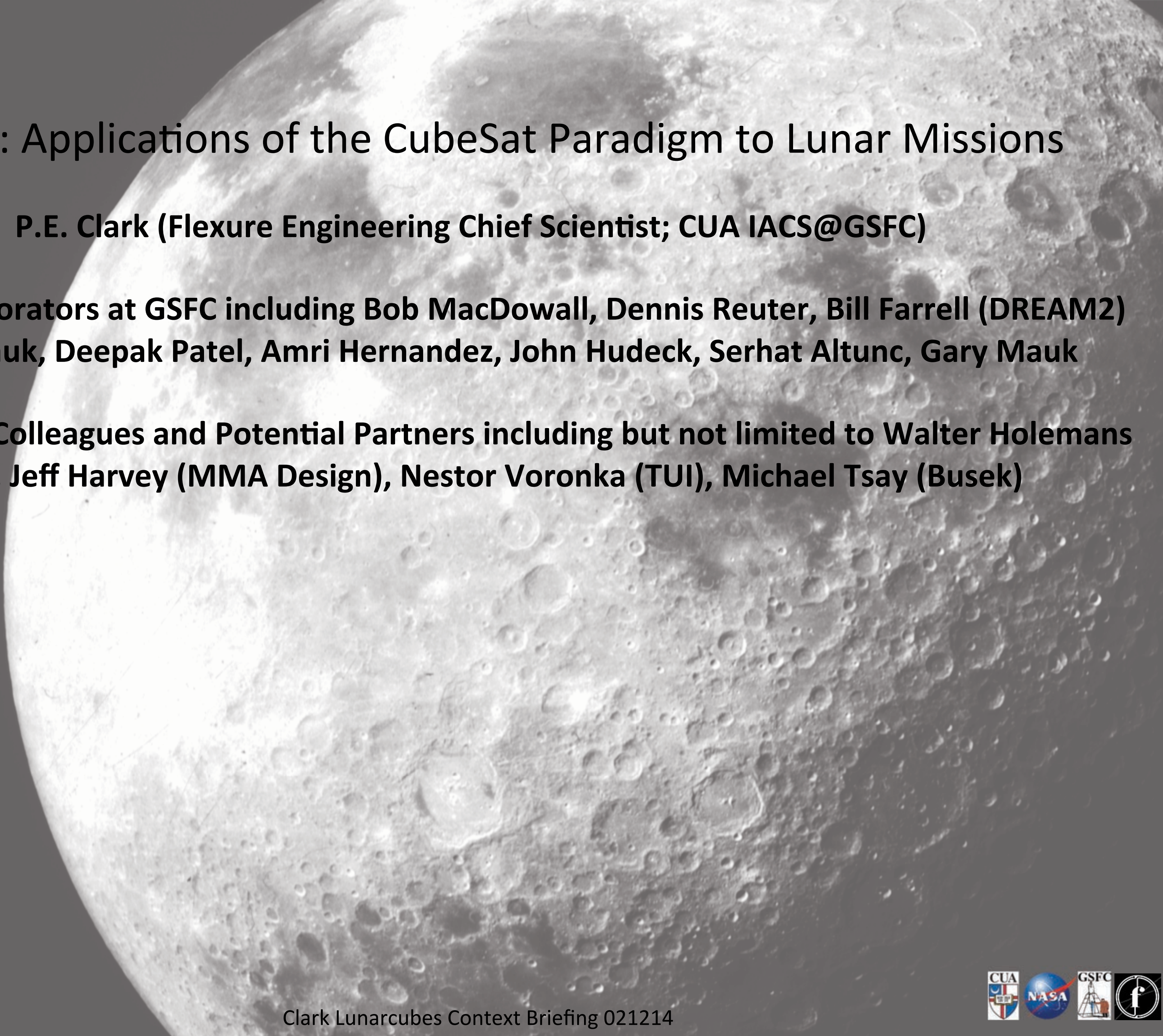


LWaDi: Applications of the CubeSat Paradigm to Lunar Missions

P.E. Clark (Flexure Engineering Chief Scientist; CUA IACS@GSFC)

Many Collaborators at GSFC including Bob MacDowall, Dennis Reuter, Bill Farrell (DREAM2)
Robin Mauk, Deepak Patel, Amri Hernandez, John Hudeck, Serhat Altunc, Gary Mauk

Many Other Colleagues and Potential Partners including but not limited to Walter Holemans
(PSC), Jeff Harvey (MMA Design), Nestor Voronka (TUI), Michael Tsay (Busek)

Solar System Exploration Context

Though cubesats not specifically mentioned in the planetary decadal survey, interest in:

- studying interactions (dust/volatiles/charged particles/radiation)
- within or between systems (exosphere/surface/magnetosphere)
- Requiring temporally/spatially measurements need acquired simultaneously/sequentially,
- imply the need for distributed networks
- inexpensively provided by nanosats w/ common bus w/ similar or different payloads.

- for understanding planetary evolution and origin,
- constraining planetary interior and surface processes,
- understanding the role of volatiles.

Roadmaps within the various target communities (LEAG, MEPAG, etc.)

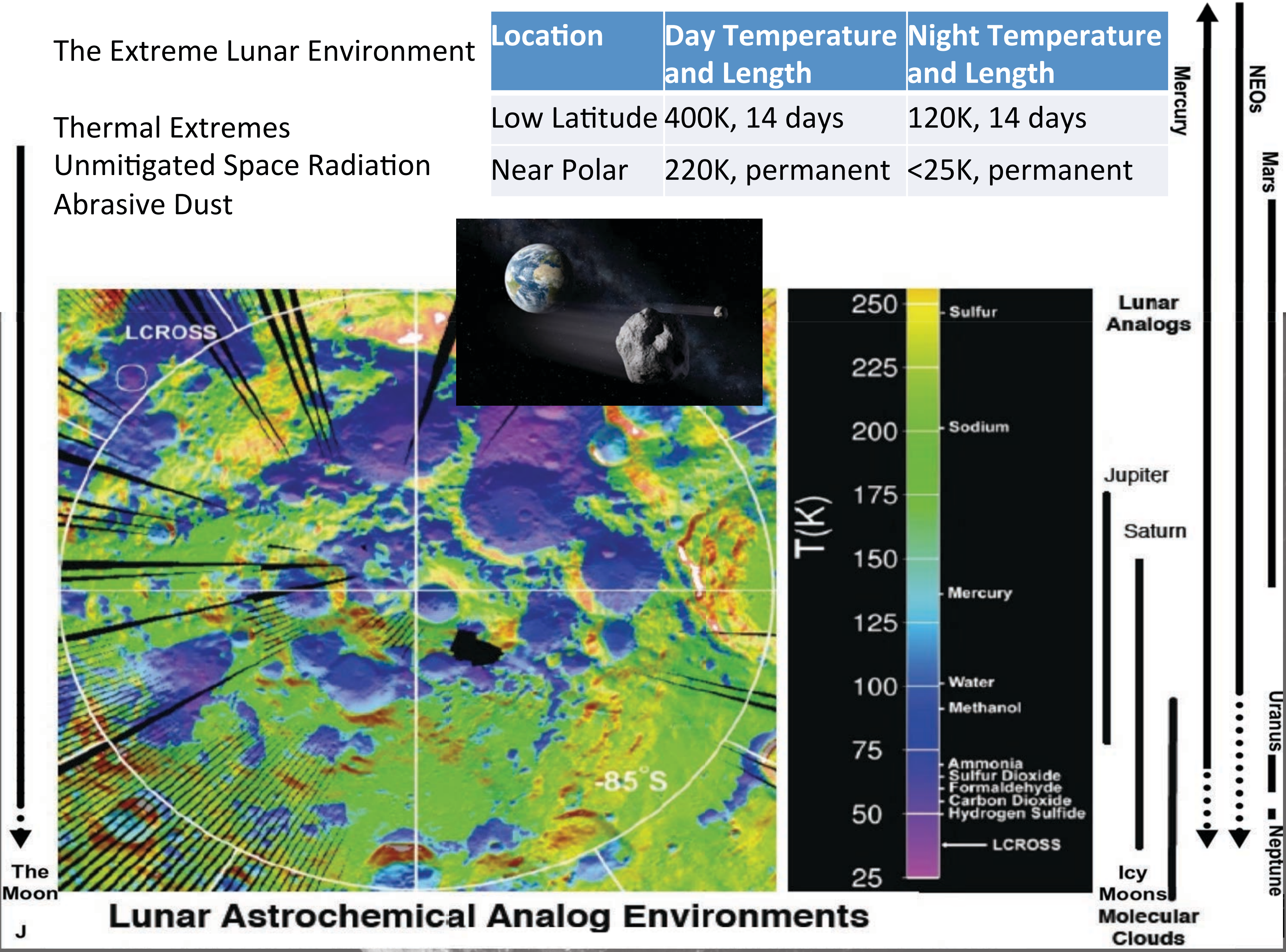
- mention the need for observations
- monitoring these interactions or characterizing places associated with volatile activity
- that could be met particularly well by networks of
  - impactors,
  - in situ compact surface packages for environmental or geophysical monitoring,
  - orbiters for monitoring temporal and spatial changes in dynamic systems.

Compact in situ instruments will also play a crucial role in one of the highest priority goals: sample selection, characterization, and return.

The Extreme Lunar Environment

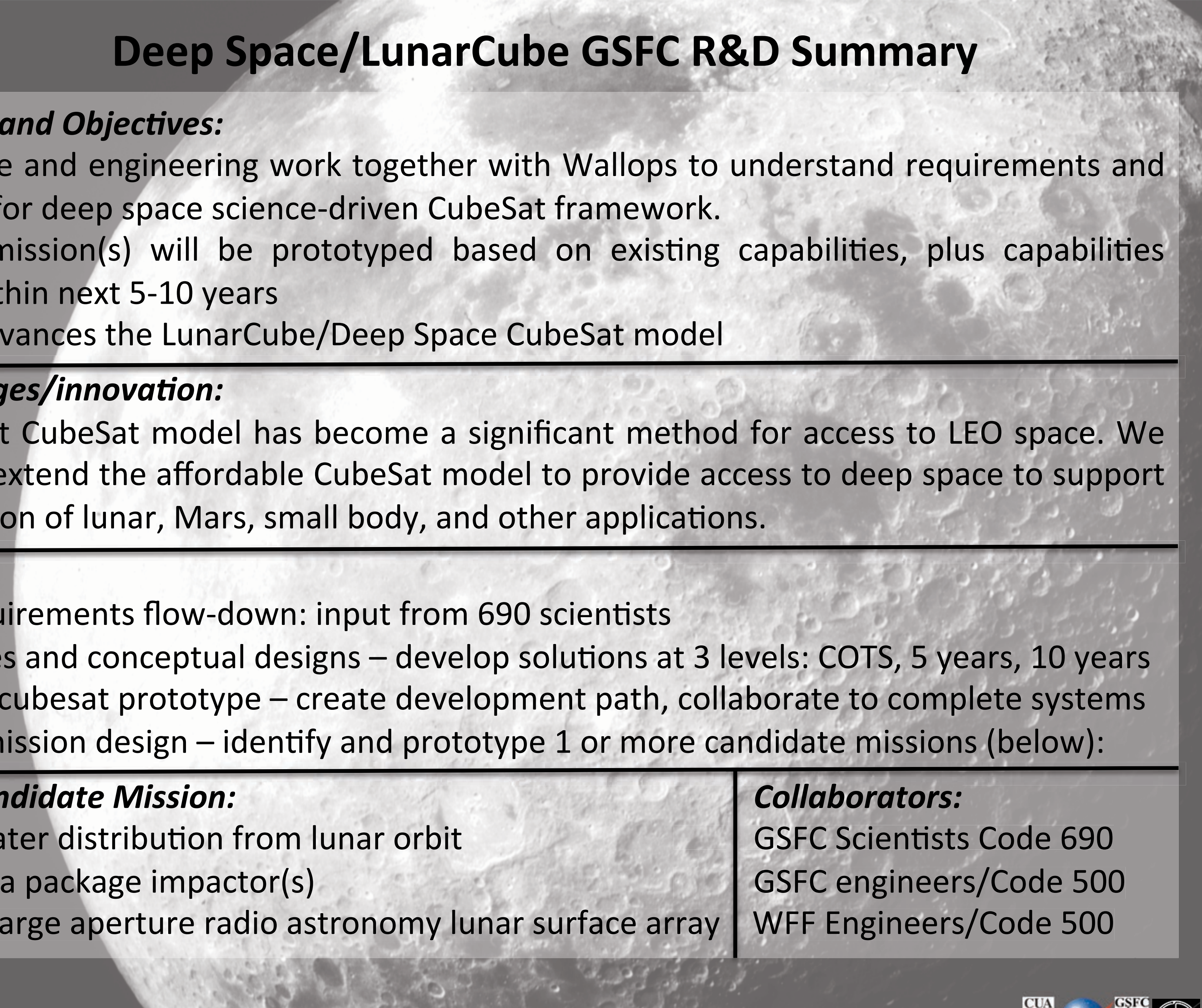
Thermal Extremes
Unmitigated Space Radiation
Abrasive Dust

Location	Day Temperature and Length	Night Temperature and Length
Low Latitude	400K, 14 days	120K, 14 days
Near Polar	220K, permanent	<25K, permanent



Lunar Astrochemical Analog Environments

Deep Space/LunarCube GSFC R&D Summary



Description and Objectives:

GSFC science and engineering work together with Wallops to understand requirements and constraints for deep space science-driven CubeSat framework.

Candidate mission(s) will be prototyped based on existing capabilities, plus capabilities available within next 5-10 years

The IRAD advances the LunarCube/Deep Space CubeSat model

Key challenges/innovation:

The low-cost CubeSat model has become a significant method for access to LEO space. We propose to extend the affordable CubeSat model to provide access to deep space to support a cross-section of lunar, Mars, small body, and other applications.

Approach:

Science requirements flow-down: input from 690 scientists

Trade studies and conceptual designs – develop solutions at 3 levels: COTS, 5 years, 10 years

Deep space cubesat prototype – create development path, collaborate to complete systems

Candidate mission design – identify and prototype 1 or more candidate missions (below):

Selected Candidate Mission:

NIR lunar water distribution from lunar orbit

Dusty plasma package impactor(s)

Pathfinder Large aperture radio astronomy lunar surface array

Collaborators:

GSFC Scientists Code 690

GSFC engineers/Code 500

WFF Engineers/Code 500

Representative Candidates for LunarCube Missions

Candidates	**Lunar Water Distribution**	**Lunar Polar Impact Outflow**	**ROLLS Pathfinder**
Concept	Nature of water components and their distribution	Measure ion, plasma, dust, volatile outflow after impact	Radio astronomy and imaging of solar radio bursts below terrestrial cutoff (10MHz) pathfinder
Type of Measurements, Instrument(s), Heritage	Near IR, 1 to 4 microns, .01 micron spectral resolution (240 8-bit channels), SNR 10dB, detection of features (wavelength, band center and width) associated with water type and component, imaging not required. Super compact NIR spectrometer with cryocooler.	1) Low E ion analyzer being developed for CubeSat (Mariner 2 ion spectrometer, AMPTE IRM, CATS MEMS 0-30 KeV electrostatic optics; 2) ULF electric field and plasma density DC to 20kHz (electric field .2 mV/M) plus optional Langmuir probes (Dynamic Ionosphere CubeSat Experiment); 3) UV spectrometer (LADEE UV spectrometer), 150-400nm, .5 nm spectral resolution	Radio receiver/riometer, 1 to 10 MHz (Lazio et al, Advances in Space Research 48, 1942-1957, 2011). supported by radio astronomy antenna(s) – wire of ~50 m total length or less, antenna deployer, preamp, CPU, data storage, downlink antenna and controller, thermal system, power system, solar arrays, housing. Subsequent versions of ROLSS are anticipated
Resources	2 kg, 2W, <2U, <10 mbits/day	1) <1 kg, <1W, <1U; 2) <1W, 1U stowed (2 10-m wire booms for plasma, 2 8-cm booms for Langmuir), 1kg; 3) 2kg, 3W, 4U.	4 kg, 5W, additional peak power for one-time antenna deployment, periodic data downlink. 1U, data volume could be reduced to <100 bits per sec. Desirable: higher datarate.
Operation Location, Modes, Duration	lunar orbit; minimum 9 (3 latitudes x 3 times of day) measurements/day for three lunar cycles, 6 month baseline.	Operating on limited (10% duty cycle in cis-lunar space, 100% duty cycle on 'last leg' capture by Moon's gravitation field until impact polar crater baseline. Desirable: fly small 'swarm' to generate greater detectable signal to be seen remotely. <hours for 'last leg'.	Lunar surface, nearside, near lunar equator. Survive at least one diurnal cycle (baseline), multiple cycles through several duty cycles desirable. Data collection and downlink modes.
Tall Poles, Special Needs	Optics, temperature monitored, nominal operation 150K via passive thermal. In-space propulsion. Protect windows from contamination. Comm drives pointing requirements.	Greater Volume required than 6U. Electromagnetic shielding. Nominal operation -50 to 50 degrees C with knowledge of temperature. Comm not science drives pointing requirements.	Thermal: surviving lunar night. Deployment of antenna. baseline single low mass wire. Desirable: tens of meters of polyimide antenna perhaps using 1D solar sail deployment mechanisms.

Why CubeSats for Deep Space

Funding is declining, costs increasing for conventional planetary exploration.

Very low-cost CubeSat model now significant in LEO, evolving from standardized kits to science-driven, multi-institutional, multi-platform, second generation standardized platforms.

NSF and NASA subsidized use in academia has created ‘hands on’ experience for this generation of students.

Interest in this approach for deep space applications growing rapidly (4th International Workshop on Lunarcubes October, 2014).

CubeSat	1st Generation	LunarCube
Environment	LEO	Earth to Moon
Form Factor	</= 3U	>/= 6U
Mass	<4 kg	>/= 6 kg
Power	Watts to 10’s of Watts	10’s to 100’s of Watts
Bandwidth	Several kbps	10’s to 100’s of kbps
Cost	10,000’s to 100,000’s	1,000,000’s to 10,000,000’s
Risk	< Class D	Class D

What do we mean by LunarCubes?

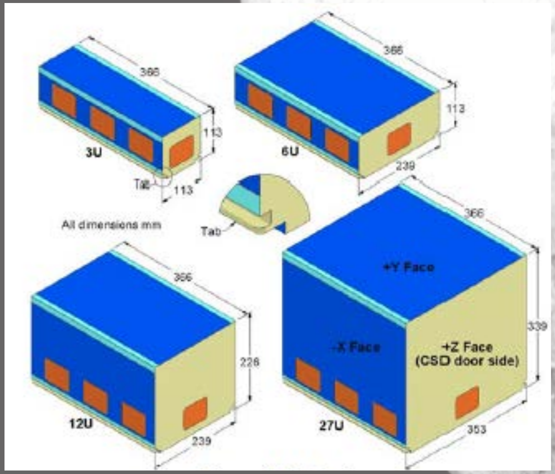
GSFC, WFF, and collaborators (See 6U Layout) are:

examining use of analogous framework for access to deep space, supporting representative cross-section of lunar, Mars, and other applications at varying degrees of difficulty (flyby, probe, orbiter, lander)

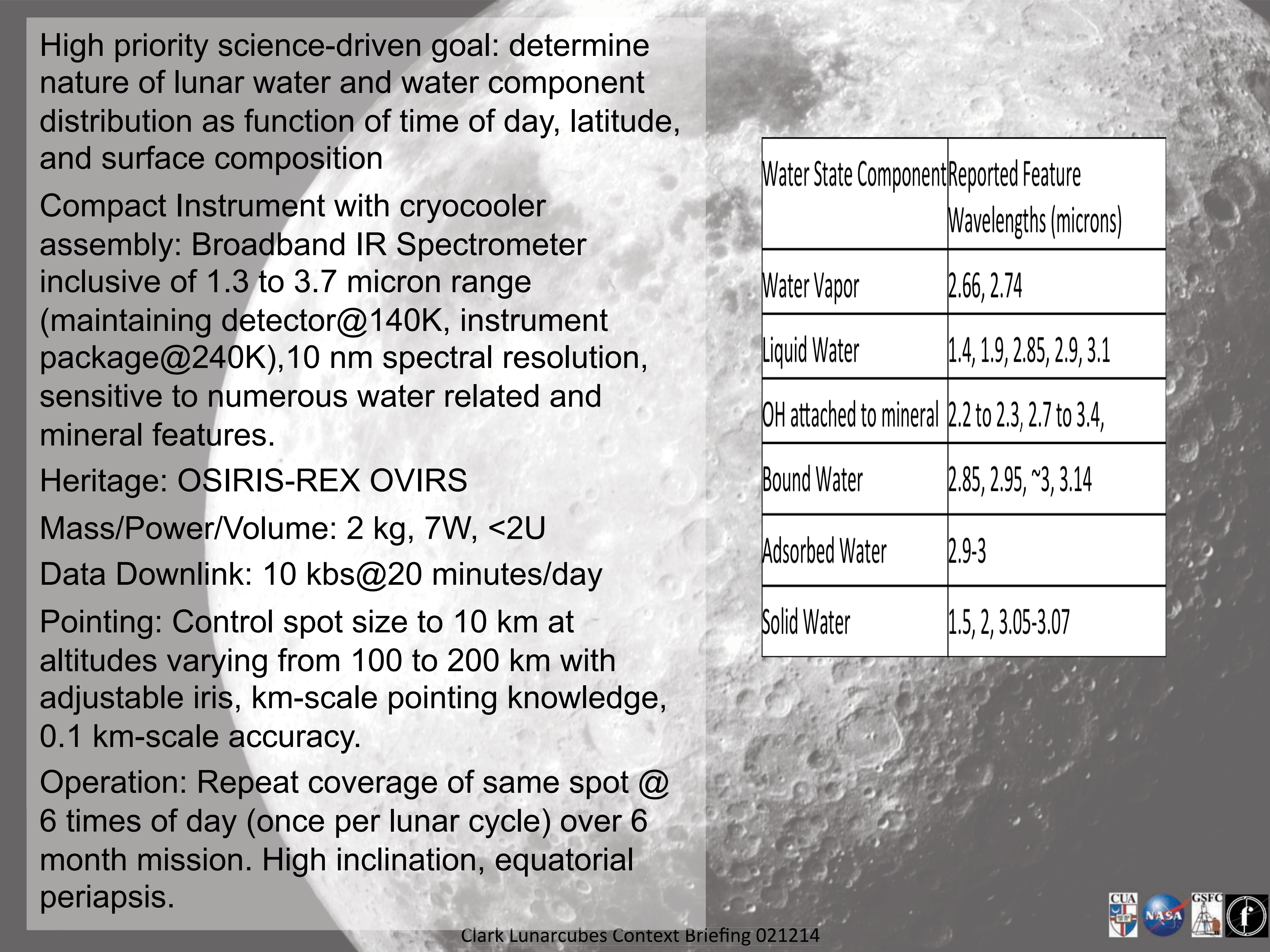
Incorporating science concepts and requirements framework,

identifying modifications and new technology needed to support a science-driven deep space model,

designing a deep space prototype bus, and prototype for a candidate mission



PSC 6U packing Option



High priority science-driven goal: determine nature of lunar water and water component distribution as function of time of day, latitude, and surface composition

Compact Instrument with cryocooler assembly: Broadband IR Spectrometer inclusive of 1.3 to 3.7 micron range (maintaining detector@140K, instrument package@240K),10 nm spectral resolution, sensitive to numerous water related and mineral features.

Heritage: OSIRIS-REX OVIRS

Mass/Power/Volume: 2 kg, 7W, <2U

Data Downlink: 10 kbs@20 minutes/day

Pointing: Control spot size to 10 km at altitudes varying from 100 to 200 km with adjustable iris, km-scale pointing knowledge, 0.1 km-scale accuracy.

Operation: Repeat coverage of same spot @ 6 times of day (once per lunar cycle) over 6 month mission. High inclination, equatorial periapsis.

Water State Component	Reported Feature Wavelengths (microns)
Water Vapor	2.66, 2.74
Liquid Water	1.4, 1.9, 2.85, 2.9, 3.1
OH attached to mineral	2.2 to 2.3, 2.7 to 3.4,
Bound Water	2.85, 2.95, ~3, 3.14
Adsorbed Water	2.9-3
Solid Water	1.5, 2, 3.05-3.07

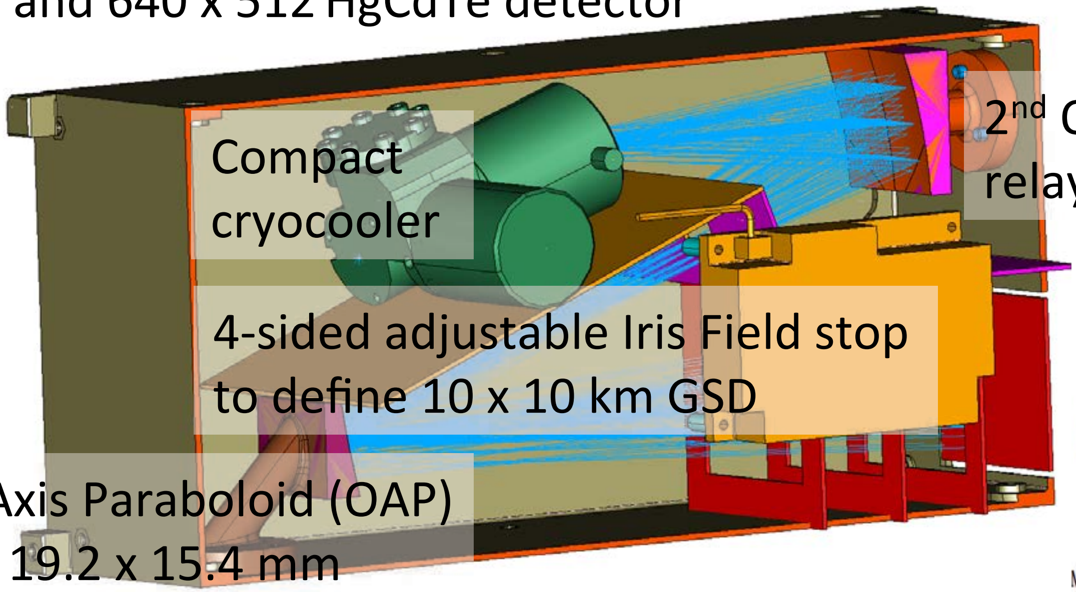
LWaDi Optical System Concept

HgCdTe Detector with compact cryocooler

Optical system with two off-axis paraboloid mirrors separated by field stop to define 10 x 10 km GSD, generating pupil image onto Linear Variable Filters and 1024 x 1024 element HgCdTe detector (18 x 18 mm and 36 x 36 mm images)

Issues: Cooling (140K) detector, maintaining thermal Stability for optics box (<240K) maintaining uniform ‘spot size’ at different altitudes.

9.6 x 7.7 mm pupil image onto LVFs
and 640 x 512 HgCdTe detector

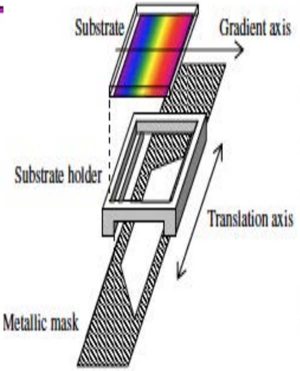


Compact
cryocooler

2nd OAP to
relay pupil

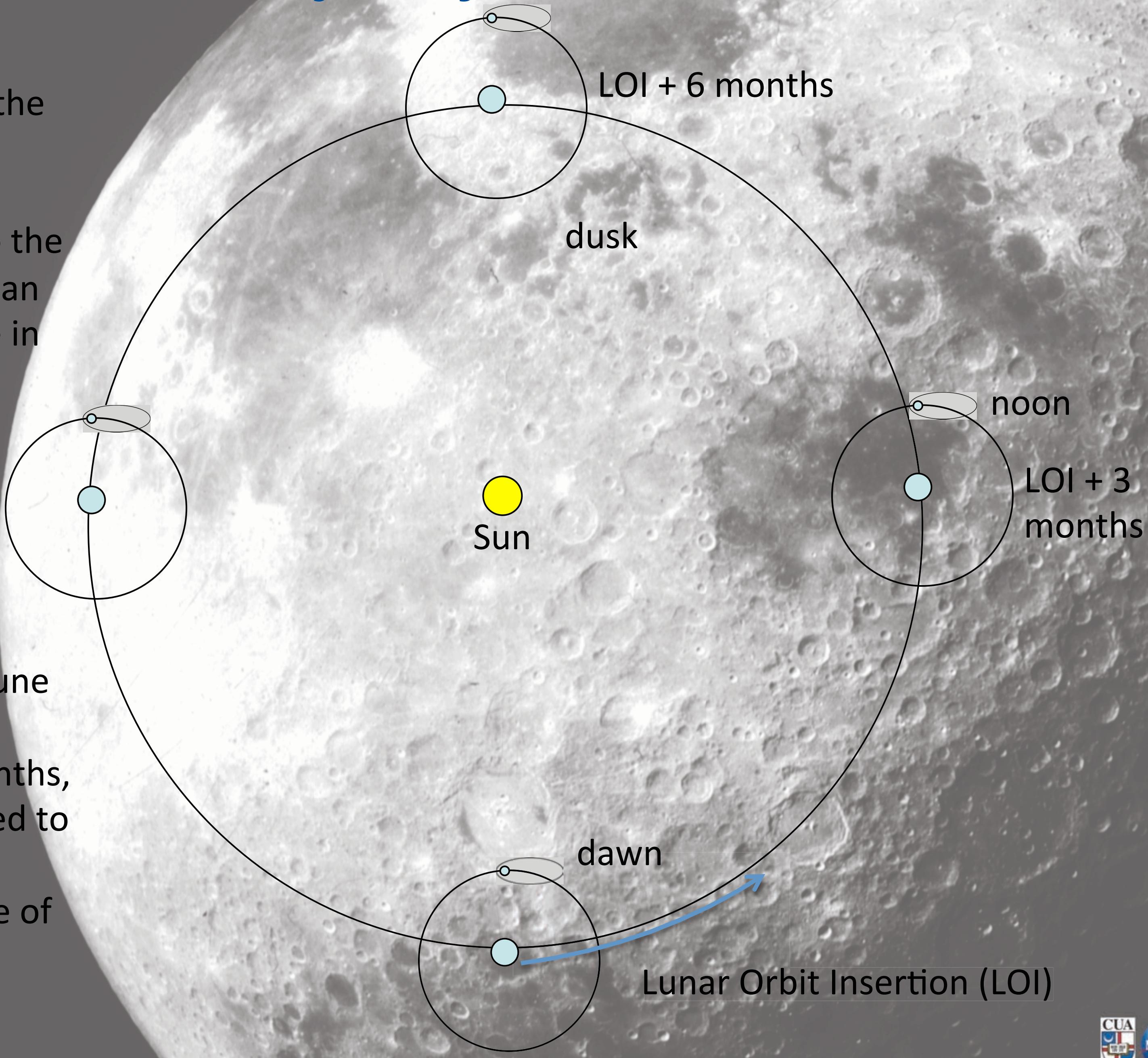
4-sided adjustable Iris Field stop
to define 10 x 10 km GSD

Off-Axis Paraboloid (OAP)
with 19.2 x 15.4 mm
Aperture Stop



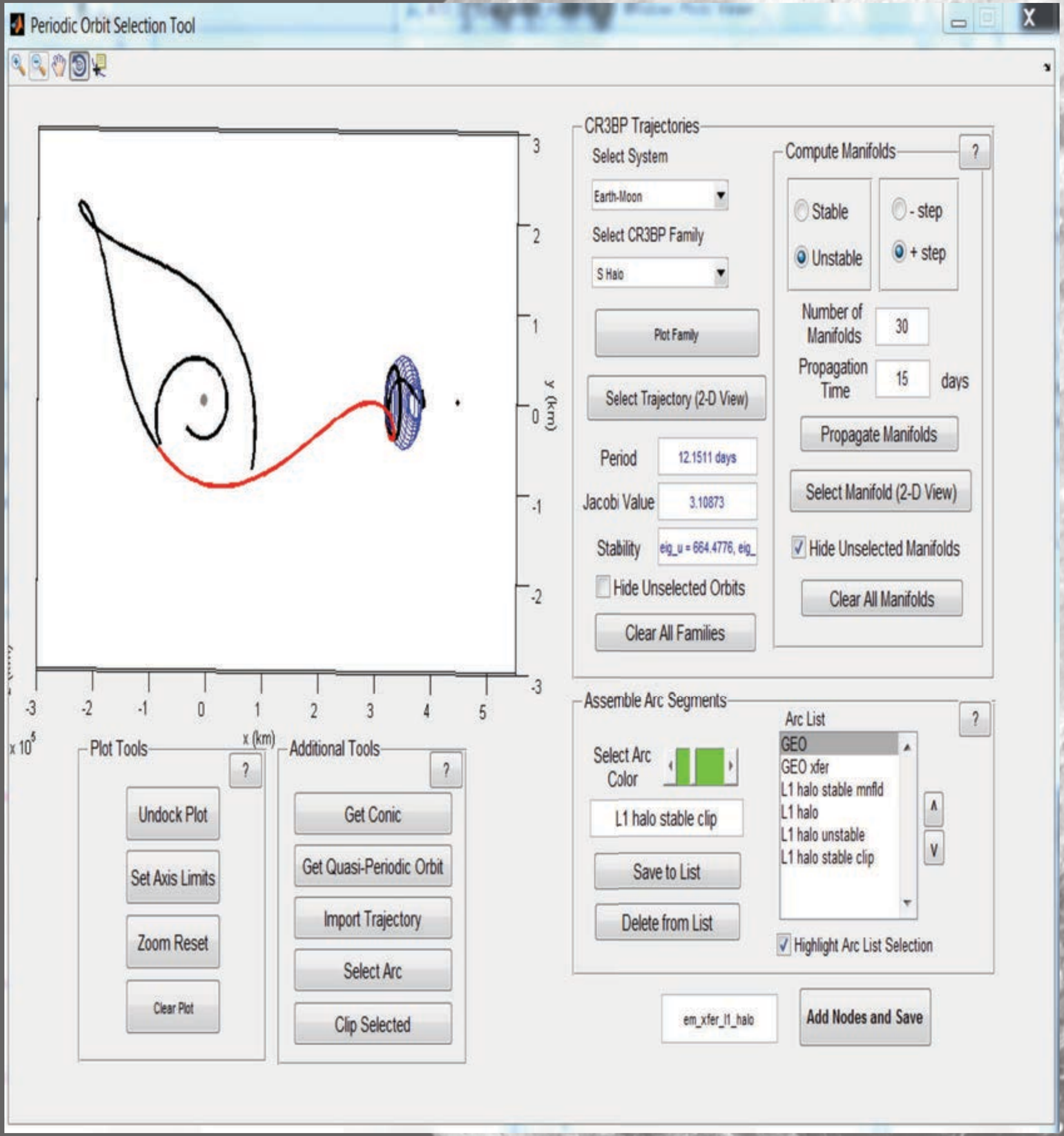
Mission Trajectory for 6 month mission

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



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

Flight Dynamics Considerations: Low Energy Transfer Trajectories



Select System: Earth-Moon

Select CR3BP Family: S Halo

○ Stable
● Unstable

○ - step
● + step

Number of Manifolds: 30

Propagation Time: 15 days

Period: 12.1511 days

Jacobi Value: 3.10873

Stability: eig_u = 664.4776, eig_

☐ Hide Unselected Orbits

☑ Hide Unselected Manifolds

Select Arc Color: 🟩

L1 halo stable clip

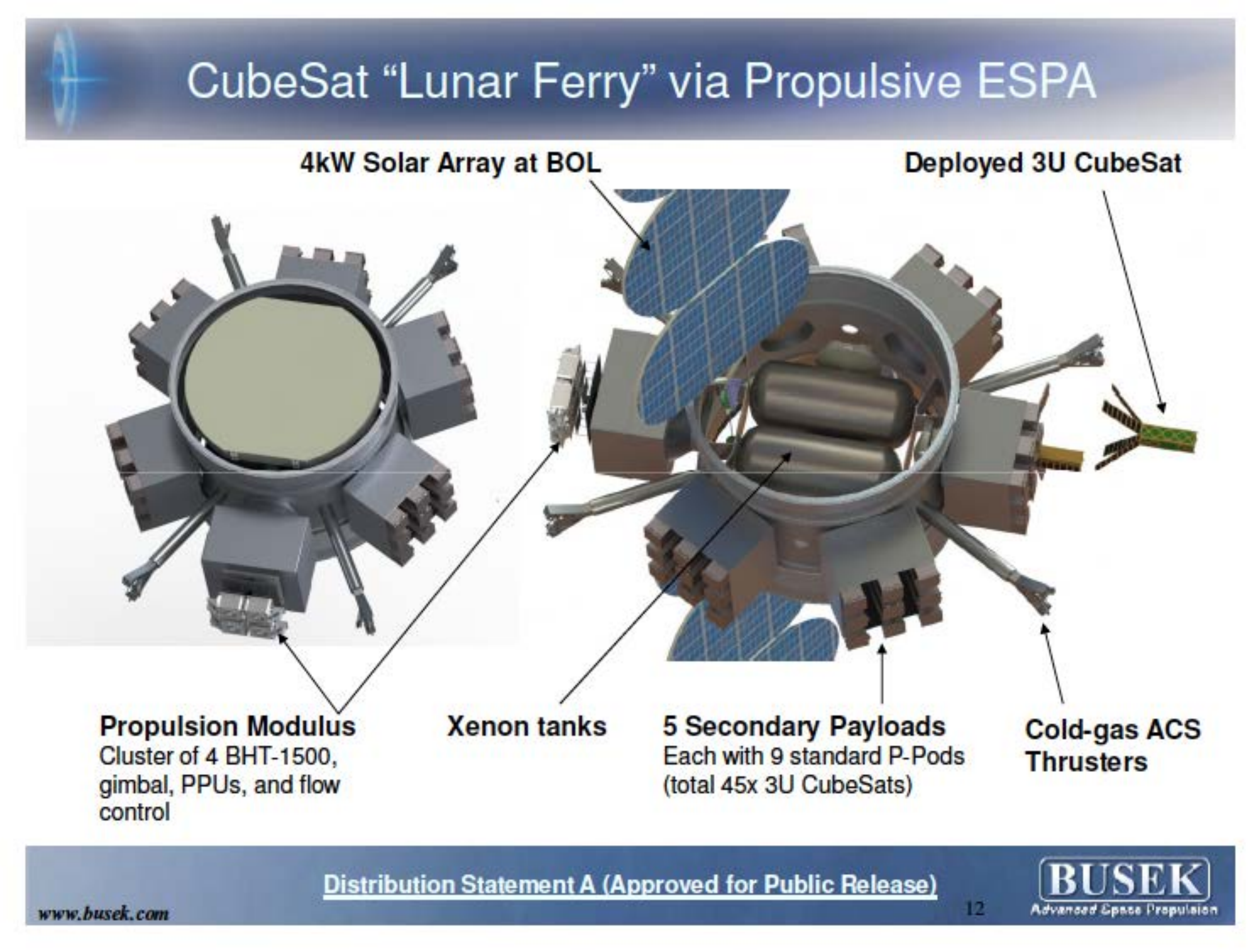
Arc List:
GEO
GEO xfer
L1 halo stable mnfld
L1 halo
L1 halo unstable
L1 halo stable clip

☑ Highlight Arc List Selection

em_xfer_l1_halo

- Transfer from GEO to stable manifold (red) of L1 Libration Point Orbit (LPO) – Southern halo in this case
- Ride manifold to LPO
- Hop off LPO onto unstable manifold toward Moon
- Insert into lunar orbit (100 x 900 km, high inclination)
- Total delta-V 1.5 to 1.7 km/sec. Time of Flight several weeks

Propulsion: Carrier Option



CubeSat “Lunar Ferry” via Propulsive ESPA

4kW Solar Array at BOL

Deployed 3U CubeSat

Propulsion Modulus
Cluster of 4 BHT-1500, gimbal, PPUs, and flow control

Xenon tanks

5 Secondary Payloads
Each with 9 standard P-Pods (total 45x 3U CubeSats)

Cold-gas ACS Thrusters

Distribution Statement A (Approved for Public Release)

www.busek.com

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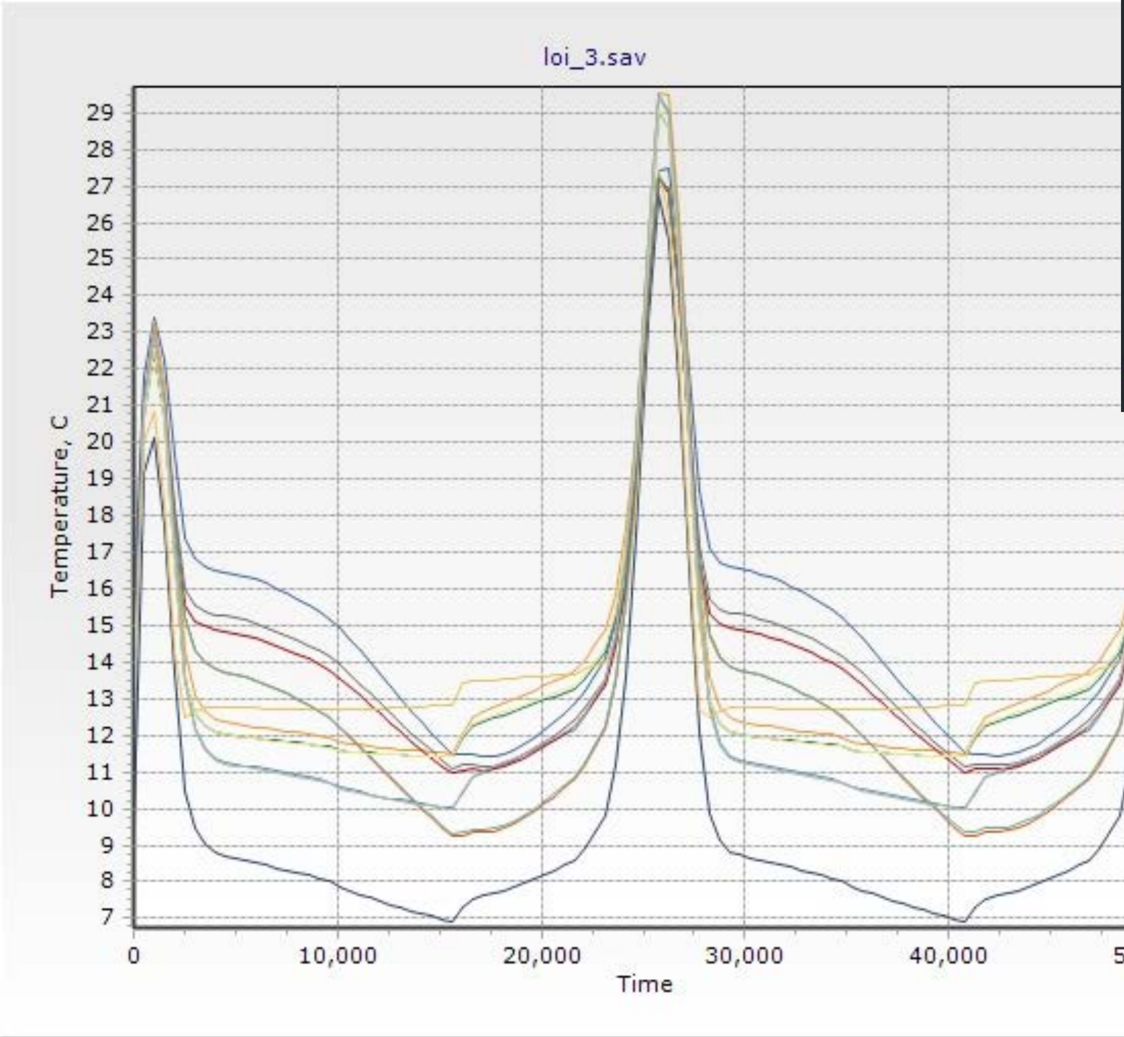
BUSEK
Advanced Space Propulsion

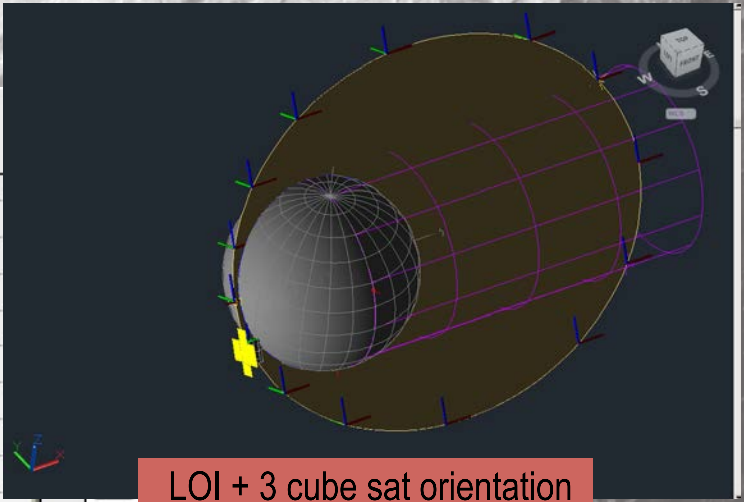
Thermal Design: Worst Case Scenario LOI+3 months

As cold 7, as warm as 29: requiring no special provisions for spacecraft as a whole

Operational Range electronics: -20 to 40 degrees C

Operational Range batteries: -10 to 30 degrees C





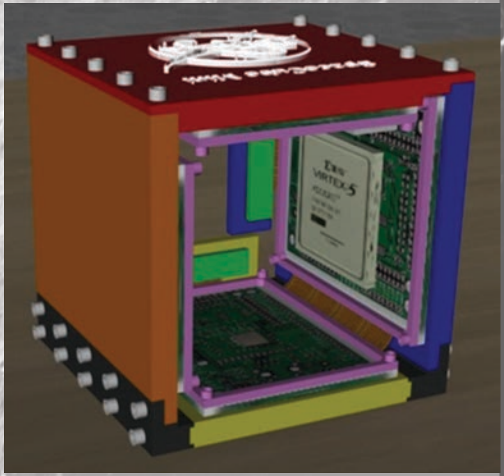
LOI + 3 cube sat orientation

This case has 2 orbits (50000sec), to verify that the temperatures are repeatable

C&DH and Processing

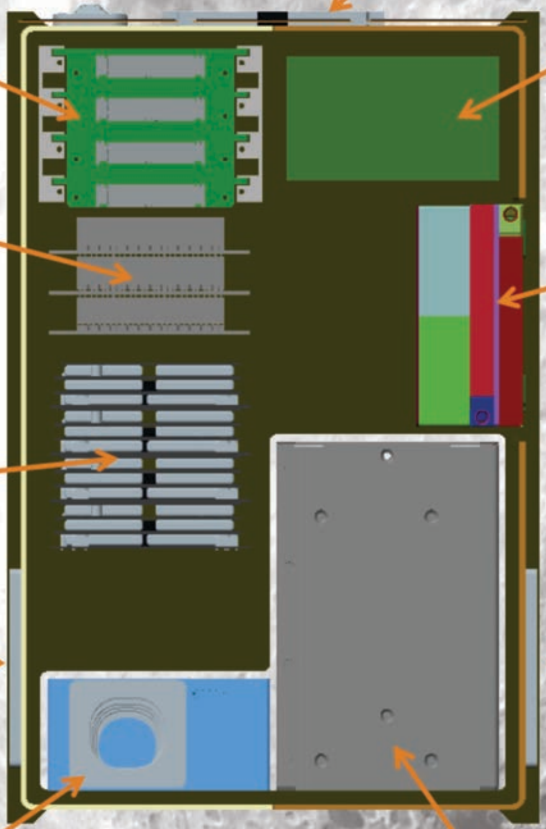
GSFC SpaceCube 2.0 Mini Processor

- High-performance flight processor for high-end instrument and payload processing
- All Rad-Hard/Rad-Tolerant components to support various orbits/ environments and multi-year missions
- (1) Xilinx Virtex-5 Commercial or Rad-Hard by Design SIRF/QV FPGA
- (1) Aeroflex Rad-Hard Monitor FPGA
  - Xilinx Configuration, Scrubbing, Watchdog, Core Spacecraft interface functions
- Small Size: Fits within 1U CubeSat Form Factor
- Low Power: 5-10W
- Low Mass: < 400 grams
- Developed through IRAD and ESTO funding



System	Description	Heritage	Mass kg	Volume U	W (peak)
ACS/GNC	Star tracker, nanocam, Momentum Wheels, uPPTs	BCT XACT, GOM nanocam, plus Busek mPPTs	1.5	1.5	5 XACT 10 mppts
C&DH/ Processing	Science and engineering management, processing	SpaceCube mini, controller (sc) and science processer (sp)	0.5	0.5	2 SC 5 SP
Thermal/ Radiation	Heaters for battery and electronics, passive blankets, reflective paint	In-house	1	0.5	0 (best case) to 5 (worst case)
Structures/ Mechanisms	Frame, deployer, deployables (Gimballed, stowable Solar panel array, antennas	PSC 6U deployer, COTS (30W), MMA Design 2-wing 3-panel EHawk	1 (WOP) 2 (WP)	1 (WOP) 2 (WP)	
Comm	Dual Xband patch Antenna, transceiver	INSPIRE dual x-band patch antenna and transceiver	1	1	5
Power	Electrical system, conversion, regulation, wiring, solar panels automated solar tracking	In-house, GOMspace batteries	1.5	1	
Instrument	Detector, optics, associated electronics, cryocooler	Sofradir or equivalent 1-4u HgCdTe package with tactical cryocooler	2	1.5	7 (4W cryocooler)
Total w/out propulsion (WOP)			9	6 (internal)	35
Propulsion	Unit with tank + fuel	Xe RF ion thruster	3.2	3.4	70
Total w/ propulsion (WP)			12.2	9.4 (internal)	105

LWaDi 6U Configuration without Main Propulsion



Sun Sensor

MMA Hawk Solar Panel Gimbal

SpaceCube Mini

X-Band Transceiver

Telemetry PC-104 Stack

Busek uPPT Thruster Unit

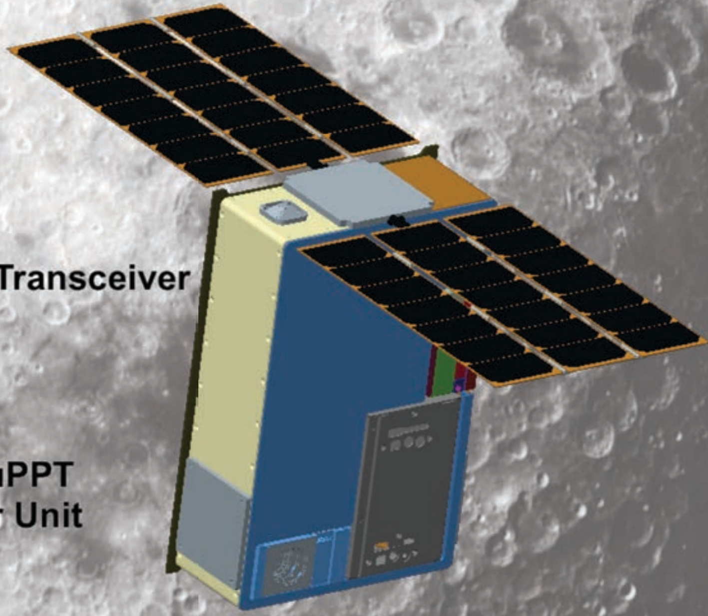
Clyde Space Battery Board Stack

X-Band Patch Antenna

X-Band Patch Antenna

BCT XACT

LWaDi Instrument



Some Deep Space Science Cubesat Missions Under Development

Target(s)	Description	Payload	Example
Moon, Asteroids, Mars	LWaDi (Lunar Water Distribution orbiter. Volatile forms and components systematics)	broadband IR cryocooled.	GSFC (Clark et al)
Moon, Asteroids	Lunar Flashlight orbiter. (Surface ices in permanently shadowed 'cold traps')	NIR instrument.	JPL (Staehle et al)
Moon	Magnetic Swirl Anomaly impactor	Magnetometer.	UCSC (Garrick-Bethel et al)
Moon, asteroids	Cold Trap Characterization Impactor Series.	Imager, dust detector, NIR and neutron spectrometers.	U Hawaii (Hermalyn et al)
Moon, asteroids, Maras	Polar Crater Impact Environment Impactor Series.	ion spectrometer, plasma wave detector, UV spectrometer.	GSFC (Farrell et al)
Moon, Mars, Mercury	Surface Geophysical Network with impactor(s).	Geophone network followed by impactor	Modified by Clark from UND (Neal et al)
Moon, asteroids, Mars, Mercury	Surface Environmental Network.	photometer, neutral/mobile ion mass spec, particle analyzers, fields, dust, radiation detectors	GSFC (Clark et al)
Moon	Large aperture low frequency radio Surface Network. Solar radio bursts, early universe studies	radio astronomy receiver, riometer, deployable antennas	GSFC (MacDowall et al) JPL (Lazio et al)
Moon, asteroids, Mars, Mercury	In Situ Surface/Sample Characterization via mobile robotic/human deployables.	'Noses' on chips or wires, next gen Combined XRF/XRD, mass spec, chromatography	Concepts requiring no sample handling

Potential Cubesat Instrument Payload Status

Type	Resources	Status
X-ray	3.5kg, 2.5U, 5W	Solid state collimated compact XRS. TRL 6 concepts for in situ sample characterization combined XRF/XRD (DCIXS, MICA)
γ-ray	<5kg, 5U,<10W,	Mid-TRL Concepts for compact GRS and NS components (Parsons et al)
neutron	<5kg, 5U,<10W,	Mid-TRL Concepts for compact GRS and NS components (Parsons et al)
Vis/NIR Imaging spectrometers	<2kg, ~2U, 5W	Work underway to fly prototype with facilitating microcryocooler to increase sensitivity. mid-TRL (UCIS)
IR (near to mid)	<2kg, 1.5U, 5W	1-4 micron broadband IR compact high spectral resolution, broadband IR workhorse with critical microcryocooler under development (LWaDi)
UV	3kg, 4U, 3W	Unaware of work to make compact version for deep space.
Longwave	2.5kg, 5W, 4U (IR), 16kg, 25W (SAR)	thermal, radio, need work on microsizing components. Work is underway on microsizing TES further
fields	<1kg, <1U, <2W. Boom improves.	Many groups working on compact magnetometers and compact transponders/ transceivers/software radios (CINEMA, INSPIRE)
Mass spectrometry (MS) (molecular component)	MS <2 kg, <2U, 5-10W; LIBS 2 kg, 2U, 5-10W	Chip-scale MEMS MS under development. Mini-libs under development.
Energetic particle analyzer	3kg, 4-5U, 2W, 30 eV – 30 KeV	State of art. MEMs based multi-cube module concepts under development. ESA Amotek series
Dust detectors, on spacecraft	0.5 kg, 2U, 5W	Dustbuster novel compact time of flight concept
Cosmic Ray Detectors	1 kg, 1U, <1W	Full field of view State of art Cherenkov/LET detector characterizing direction, energy, mass, and speed of particle in 1 to 1000 MeV/amu range. (Wrbanek et al)

Summary

We have identified and responded to major design challenges for applying CubeSat framework for high priority science requirements driven lunar orbital missions.

Critical design challenges include low delta V Earth to Moon transportation, detector cryocooling and low volume optics, as well as compact, efficient communication, C&DH/processing systems supporting adequate bandwidth, and radiation hardening of all components.

Technologies required to meet these challenges are either available or under development. Development of compact in situ monitoring or measurement instrument capability (e.g., sufficiently sensitive isotope ratio measurement to support geochronology) is still a major challenge.

Mission candidates that lend themselves to that format could meet or exceed decadal survey objectives for lunar, Mars, or small body exploration, providing development of more compact instruments, particularly for in situ monitoring to alleviate the need for sample handling, continues.

We are looking at a design (6U, 9 kg, <40W) which uses available technologies and should fit within the definition of CubeSat, with the major challenge being volume. Continued technology development in critical areas should result in considerable reduction in both mass and volume.

The Next Frontier: CubeSats for Deep Space

4th International Workshop on LunarCubes

October 7-10, 2014 – Mountain View, CA

Questions?

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