

Developments in Lunar Compact Instrumentation for Small-scale Applications.

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Acknowledgements: Contributions from the following in compiling information on instruments under development: Robert L. Staehle¹, David Bugby¹, Abigail Fraeman¹, Robert O. Green¹, R. Glenn Sellar¹, Stojan Madzunkov¹, Frank Maiwald¹, Nan Yu¹, Adrian Tang¹, Corey Cochrane¹, Craig Hardgrove², Michael Collier³, Vassilis Angelopoulos⁴

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Note: This is predecisional information for planning purposes only.

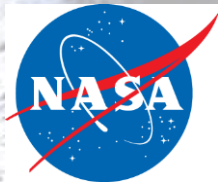
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Why now?

Goals: High priority interests of NASA HEOMD, SMD, STMD, and Commercial space science and exploration, as well as cislunar space operation interests coincide driven by unexpected discoveries and lunar initiative

Objectives:

- determining the global distribution and origin, as well as resource inventory, for water and other potential in-situ resources at local-scale resolution;
- Monitoring and modeling the nature of the radiation/charged particle /exosphere/micrometeorite/surface/subsurface interactions constituting the lunar environment and impacting performance and health of the crew and their equipment;
- Monitoring and modeling the lunar interior and constraining the Moon's history and origin with implications for evolution of the Earth Moon system.
- Establishing communication and transportation infrastructure in support of assets used to achieve these goals

In response:

- JPL and others developing a diverse set of compact instruments and instrument suites, as well as high performance adaptable packaging options suitable for a wide range of instruments
- Applicable to orbital or surface handheld, crew-deployed or rover-mounted devices to achieve wide range of goals

Matching Planetary Goals with Instrumentation via the Moon

Planetary Decadal Survey Goal	Measurement Context	Instruments	Examples
Origin of and relationship between terrestrial planets, extrasolar systems	in situ isotopic, elemental, volatiles (molecular), mineralogical, textural, geochronological, regolith, rocks, 'new' sites, dealing with contamination. Reverse stratigraphy observed from mobile platforms.	X-ray spectrometer	MIT REXIS
Nebular/Accretion Processes, Early Solar System, Bulk compositions, volatile budgets, differentiation		X-ray imaging	JPL PIXL
Crust/mantle/core materials, new rock types, robust sampling,		Gamma-ray spectrometer	PSI GRAND
Early planetary evolution, external processes, and origin and evolution of life		Neutron spectrometer	U of A LunaHMap
Internal processes involving volatiles, polar deposits	Deployable network interior characterizers, lander or rovers with special attention to past or current 'active' regions. Cryogenic sampling.	Active mass spec (LIBS, LAMS)	LANL ChemCam (JPL MSL)
Crust/mantle/core materials, interior structure, stratigraphic record, dynamics, heat loss		Active Gamma-ray/Neutron	GSFC SINGR
Surface Processes: regolith character and formation, impact processes		Compact IR spectroscopy	GSFC/JPL BIRCHES
Environmental processes: solar wind, plasma, IMF, micrometeoroid, radiation, exosphere interactions		Compact IR imaging	JPL UCIS, SILVIR
technology development, new directions, human exploration		Compact active near IR imaging	JPL Lunar Flashlight
		In Situ geochronology	JPL RbSr KAr concepts
		Mass spec w/ in situ chromatography	GSFC SAM; JPL QIT-MS
		Compact Cameras	JPL EECAM,
		MicroImager	JPL MMI
		Ground Penetrating Radar	JPL, Natl A&S Museum, GPR
		Magnetometer	JPL/UCLA Fluxgate, VHS
		Seismometer	JPL SEIS, uSeismometer
		Heat Flow	JPL ALGEP (Banerdt)
		Laser Reflector	JPL (Turyshev)
		Geotechnical sensors (Mech, EM, thermal)	KSC MECA, SWRI DART
		Regolith particle analyzer	COTS Microbrook Eyetech
		Mass Spectrometers	JPL QIT MS
		Particle analyzers (ion/electron)	GSFC HALO, SIMS
		Electric Field Instrument	GSFC EPDA
		Dust Detector	GSFC EPDA
		UV Spectrometer	ARC LADEE UVS
		Radiation Detector	UNH DOSEN
	landing low cost, compact deployable packages with 24/7 operation (dynamics, ground truth) or sampling downselect	All in situ instruments especially needing to operate in the dark (polar volatiles)	See Above

Compact Instruments: The table summarizes the target characteristics, including mass, power, and volume, of certain instruments of primary interest already under development via NASA DALI, CLPS/NPLP, GCT and SIMPLEX programs, supplemented by JPL internal funding in some cases.

Some Lunar Surface Instrument and Instrument Suite Candidate Characteristics

Instrument	Type	Mass	Power	Volume
UCIS-Moon	IR Imaging spectrometer 600-3600 nm	4 kg	20 W when operating	4U
NRVSS (VIPER)	Vis to Mid IR Imager, neutron spectrometer	??	??	??
HVM3	IR Imaging spectrometer	12 kg (includes radiator)	15 W	56 cm ³
QITMS	Mass Spec	7 kg	24W when operating	8U
MMI	microimager	1 kg	5 W when operating	1U
HOLMS	OH heterodyne spectrometer	??	??	??
miniGPR	Ground penetrating radar	1.5 kg	1W when operating	2U
miniNS	Neutron spectrometer	0.5 kg	5W when operating	1U
miniENA, miniESA	Electrostatic analyzer and energetic neutral analyzer	<1 kg each	1W each	1U each
Dual magnetometer	VHM and FGM	0.5 kg FGM, 2 kg VHM + booms	<1W FGM, 2.5 W VHM when operating	<0.5U FGM, 2U VHM
Mini water prospectors	Mini IR camera (filter), miniNS, miniGPR	<3 kg	8W when operating	3U
water cycle monitoring stations	IR imager, miniESA, miniENA, miniNS	5 kg	2 W night, 9W day when operating	5U

Types of Instrumentation and Challenges

Physical and compositional properties of local terrains.

- Vis/IR cameras and spectrometers, High energy spectrometers, surface to subsurface compositional and mineralogical and volatiles assessment.
- Artemis 1 instruments (Lunar Flashlight, LunaH-Map, Lunar Ice Cube (BIRCHES), from which spin-offs proposed
- UCIS (DALI) and HVM3 examples of IR imagers, UCIS with emphasis on selected water absorption bands
- NRVSS VIPER Vis to IR and neutron spectrometer package
- MMI at soil particle scale mineralogical and petrological assessment, handheld to rover mounted applications

Operational Challenges: viewing apertures (thermal); temperature stability for optics, cryocoolers for Vis/IR

Exospheric species abundances.

- Tunable Laser Spectrometer or Mass Spectrometer to assess nature and cyclic variability of exosphere as well as human impact.
- Deploy as exosphere monitor network.
- could quantify the fall-off in gas emissions from equipment left behind as “atmospheric” conditions return to the natural background.
- If surface-exposed volatiles are present, diurnal signal could be detected through the lunar day and night, especially near local sunrise.

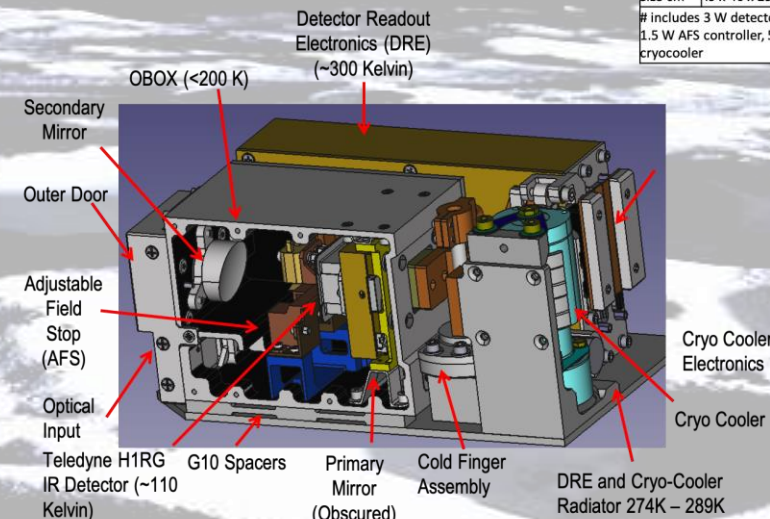
Operational Challenges: 24/7 operation, power, apertures (thermal)



ARTEMIS Cubesat Pioneers, DALI example, Microlmager

BIRCHES compactness		
Property	Ralph	BIRCHES
Mass kg	1.1	3
Power W	5	#10-20 W
Size cm	49 x 40 x 29	110 x 10 x 15
# includes 3 W detector electronics, 1.5 W AFS controller, 5-10 W cryocooler		

BIRCHES IR Spectrometer HW Architecture



Description: Broadband IR Compact High Resolution Exploration Spectrometer (BIRCHES) on Lunar Ice Cube.

Measurement Advances: Measure forms and components of lunar water as function of time of day, latitude, and terrain from orbit requiring encompassing broad 3 micron band with detection limit >100 ppm and up to 10 km spatial resolution. Applicable as surface monitoring instrument.

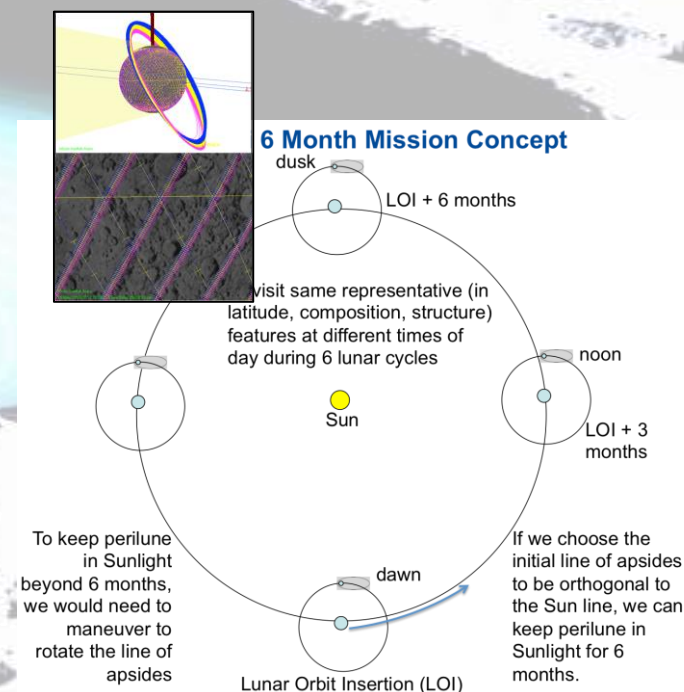
Technology Advances: Cubesat (6U) scale point spectrometer, based on Reuter line of LVF/MCT instruments with cryocooler necessary to operate out to 3.5 microns in extremely challenging thermal environment for measuring water components and forms.

Approach/Milestones

Leverage OVIRS (OSIRIS REx) flight spares, utilize first cubesat-scale cryocoolers (AIM/IRIS).

Final Testing of instrument by late winter 2020, Final integration with spacecraft by early autumn 2020.

Team: Clark (Science PI), GSFC: Instrument build and test (Brambora, Hurford, Patel). Morehead State University: Lunar Ice Cube mission (Malphrus PI, Brown)



Description: Compact Neutron Spectrometer on LunaH-Map mission.

Measurement Advances: Measure decrease in epithermal neutron flux ($\geq 20\%$) associated with protons (ice) to 10's cm depth at south pole within <2 degrees of pole with 7.5 km spatial resolution. Applicable in surface prospecting.

Technology Advances: Cubesat scale (6U) neutron spectrometer, with more efficient, and thus compact, CLYC detector.

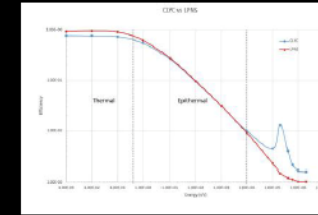
Approach/Milestones

Leverage advances in neutron detectors (CLYC).
Final Testing of instrument by late winter 2020, Final integration with spacecraft by early autumn 2020.

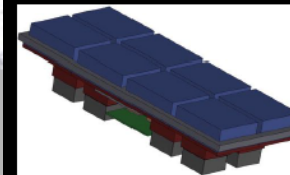
Team: Hardgrove (PI) (ASU)

3. LunaH-Map Neutron Spectrometer

Mini-NS will have two 100-cm² CLYC arrays (200cm² total). A thin Cd foil will be used for epithermal neutron detection



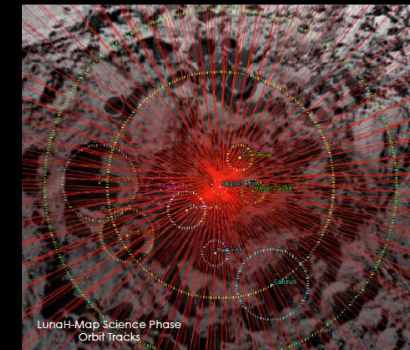
LunaH-Map Mini-NS (2cm) compared to 5.7-cm diameter LPNS ³He counter



Preliminary design of Mini-NS for LunaH-Map

Specifications	
Detector	2, 4x4 Detector Arrays of CLYC (each 2.5cm x 2.5cm x 2cm)
Sensitivities	Thermal (<0.3 eV) and epithermal (with Cd shield) neutrons and 3.9% FWHM at 662 keV
Dimensions	27.94 cm x 11.43cm x 6cm
Mass	2.6 kg
Power	2 Watts (during data acquisition); 0.35 Watts (idle)
Data Acquisition Times	Counts binned every 3 seconds
Data Volume	<1 Mbit for mission duration

3. LunaH-Map Science Phase



Nominal Science Mission

- 2 months = 141 Orbits
- 10 hour period
- Perilune <10 km

LunaH-Map Science Phase Orbit Tracks

Description: Compact instrument for ice detection through use of optical receiver aligned with lasers emitting at wavelengths associate with water ice absorption and continuum on Lunar Flashlight mission

Measurement Advances: Ratio continuum and absorption reflectance bands to quantify surface ice abundance in permanently shadowed areas at for >0.5 wt % ice with 1 km spatial resolution with. 10 degrees of South Pole. Applicable as surfacd prospecting instrument.

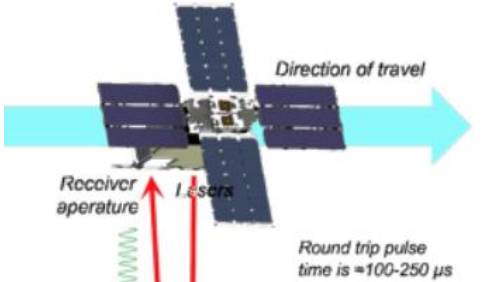
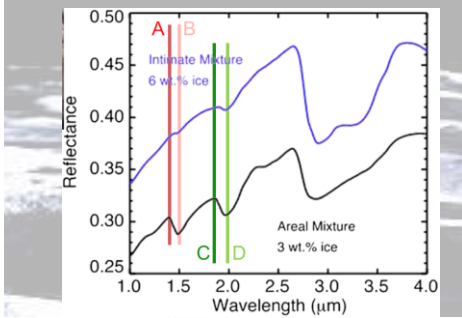
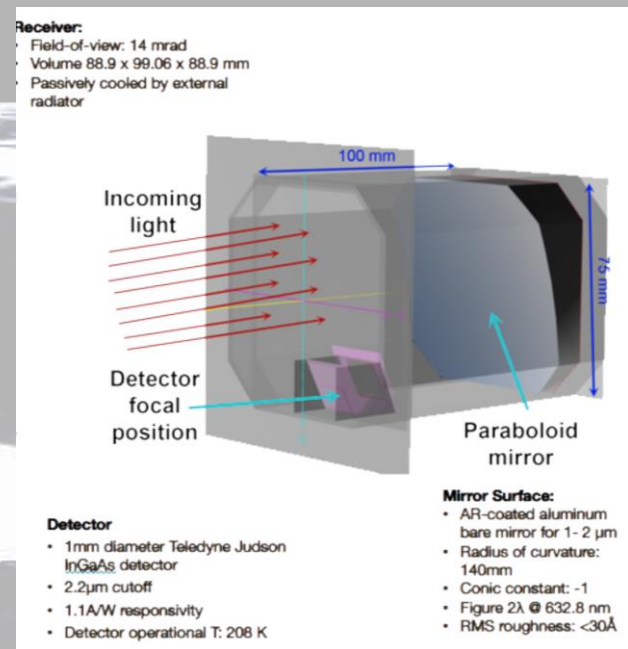
Technology Advances: Cubesat scale (6U) active near IR spectrometer. Use of laser technology in extremely challenging thermal environment.

Approach/Milestones

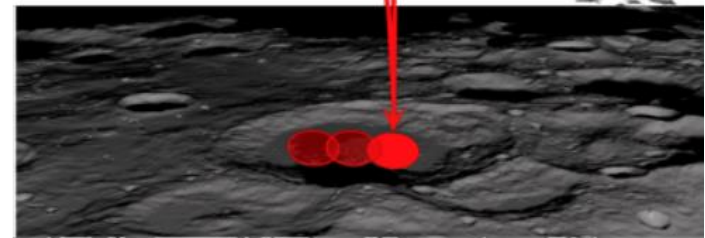
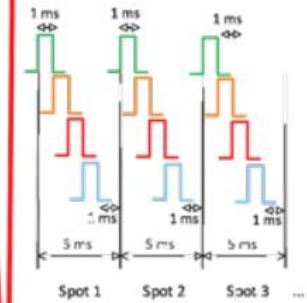
Leverage advances in laser technology.

Final Testing of instrument by late winter 2020, Final integration with spacecraft by early autumn 2020.

Team: Baker (JPL), Cohen (GSFC).



- DILAS laser bars**
- Continuum (COTS):
- 1.064 (-0.060 / + 0.230) µm
 - 1.850 (-0.030 / +0.020) µm
- Absorption bands (custom):
- 1.495 (-0.015 / +0.015) µm
 - 1.990 (-0.020 / +0.025) µm





An Ultra-Compact Imaging Spectrometer for the Lunar Surface: Enabling Volatile Mapping and Unraveling the Moon's Geologic History

PI: Abigail Fraeman/JPL

Platform: Lander or Rover

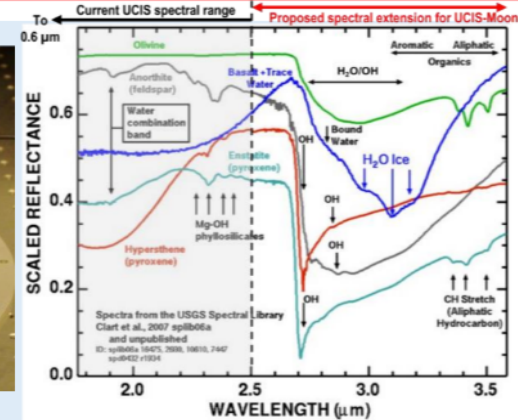
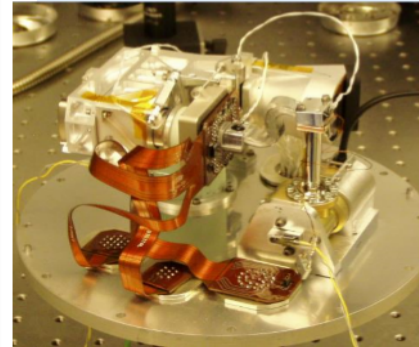
Science:

- Uses well-established SWIR imaging spectroscopy to map H₂O, OH, organics, and igneous compositions from spatially contiguous spectra
- Understand the sources, distribution, temporal variability, and ISRU potential of lunar volatiles
- Understand igneous processes on the Moon
- Understand lunar stratigraphy
- Understand space weathering on the Moon

Objectives:

- Mature the Ultra Compact Imaging Spectrometer (UCIS) to TRL6 optimized for lunar volatile science via three tasks:
 1. Incorporate a new detector array that supports a 0.6 - 3.6 μm spectral range.
 2. Advance thermal design to allow operation in lunar environment.
 3. Develop on board processing algorithms to enable rapid return of most important products.

CoIs: Diana Blaney, Robert Green, Ian McKinley, Pantazis Mouroulis, David Thompson - JPL; Bethany Ehlmann - Caltech.



(left) UCIS prototype, initially developed and optimized for Martian geology and thermal environment. We will extend the wavelength coverage to optimize the instrument for lunar volatile science and cope with lunar temperatures. (Right) Laboratory measurements showing the character and diversity of OH species, molecular H₂O, and water ice absorptions that would be distinguishable with the expanded spectral range.

Key Milestones:

- Y1Q3: Critical design review
- Y1Q4: Algorithm methods and test datasets finalized
- Y2Q4: Integration and testing complete
- Y3Q1: FPGA implementation complete
- Y3Q3: TVAC testing complete
- Y3Q4: Full demonstration with FPGA testing, instrument TRL6 report

TRL (4) to (6)

Development and Advancement of Lunar Instruments (DALI)

Multispectral MicroImager

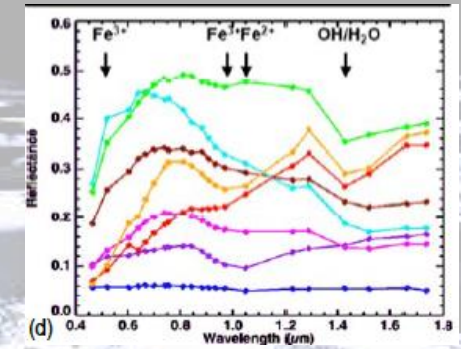
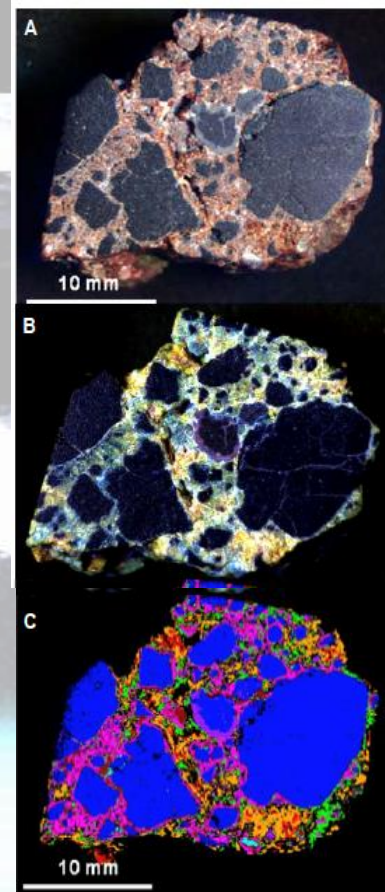
Description: Compact, low-cost Multispectral Microscopic Imager (MMI) to provide petrographic (microtextural) information on composition and color to reveal origin and history of sample.

Measurement Advances: Spectrometric capabilities added to MER microscopic imagers (MI). Multiple bands and range (visible to near IR) extend ability to characterize mineralogy and allow more effective sample screening

Technology Advances: Advance MI to be rugged, portable instrument with built in sources (LEDs) with no moving parts to be mounted on rover or tripod.

Approach/Milestones, TRL 4 to 6
Build and test prototype based on field unit.

Team: Sellar, Farmer (ASU), Nunez (ASU)



Left: MMI 25 x 30 mm subframes A. natural color composite, B. translated color composite, C. mineralogical map. Right top: reflectance spectra of end-member minerals mapped in C. Right bottom: Field unit.

Types of Instrumentation and Challenges

Internally generated and bombardment-induced seismic activity.

- Range of small spectrometers being developed via DALI or JPL internal funding, SEIS spinoff from INSIGHT.
- As in the case of the mass spectrometer, could be deployed as part of monitor network.

Operational Challenges: thermal stability, deployment including 3D alignment, 24/7 operation

External Environment Fields and particles monitoring


- Magnetometers being developed via STMD or JPL internal funding.
- Compact particle analyzers being developed elsewhere (electrostatic analyzers, energetic neutral analyzer at GSFC)

Operational Challenges: thermal: booms (magnetometer), stability; aperture (analyzers), 24/7 operation

Extended Resource Prospecting and Resource Cycle Monitoring:

- Programmable mini-rovers traverses in areas identified as 'promising' in terms of potential resources
- water prospector package characterize surface/subsurface water to a depth of 1 to 2 meters
- mini Ground Penetrating radar now under development at JPL, which would yield variations in dielectric constant (and by implication water ice) to a depth of a few meters with a resolution of 10 cm.
- Stations with IR imager and neutron spectrometer (surface/subsurface), exospheric species characterizer, solar wind analyzer constrain global water transportation, source, and sink models

Operational Challenges: high power demand, access to PSRs (rovers), 24/7 operation in situ instruments (station), thermal stability (optics) and cryocooler (IR imagers)



Instrument Suites


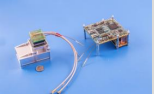
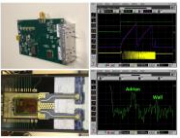
Mini Water Prospector

Description: Small fleet of prospecting mini-rovers with compact instrument package needed to prove lunar water/ice reserves by acquiring local ground truth in most probable locations (e.g., multiple PSRs).

Measurement Advances: Miniaturized instruments capable of characterizing and constraining water/ice/hydroxyl abundance from surface to ~1 meter depth:

- Multi-band InfraRed Camera (MIRC) – designed to see into PSRs using rim-scattered light. Option to add short-range IR LED illumination.
- Neutron Spectrometer (NS) – miniaturized for small rovers (leverages NASA investments in LunaHMap, MatISSE)
- Ground Penetrating Radar (GPR) – miniaturized for small rovers

Using mini-rover platforms to take measurements separated by meters (resolutions currently >100 m) along traverses to allow discovery, mapping, and grading of locations of lunar ice deposits sufficient to support extraction of tens of metric tonnes/month.

Instr	Surface		Depth		Specificity	Quantification	Mass	Power
	coverage	sampling	max	sampling				
MIRC	Map (surface)	~ 0.1 m	surface only	surface only	H ₂ O other volatiles	± 0.5 % (at surface) 	0.5 kg	5 W (peak)
NS	Discrete measurement (subsurface)	~ 10 m	1 m	integrated	H-bearing species	± 1 wt % 	0.4 kg	5 W (peak)
GPR	Continuous traverse (subsurface)	~ 1 m	2 m	0.1 m	dielectric constant	± 1 % (volume) 	1.5 kg	< 1 W

Technology Advances/Approach:

- 1) Leverage instrument development of JPL CIRAS HOTBIRD (TRL 5-6) or DALI UCIS detectors (TRL 4-6), ASU Mini-NS (TRL 5-6), JPL GPR (TRL 3-6),
- 2) Leverage Generic Compact, Low Resource, High Performance Packaging (ARTEMIS/PALETTE); compact versions relevant instrumentation (above)
- 3) Low Cost Commercial Landers

Team: Staehle, Sellar, Clark, Tang, Hayne (CU), Hardgrove (ASU)

Target: Lunar subsurface from 10's of centimeters to 10's of meters.

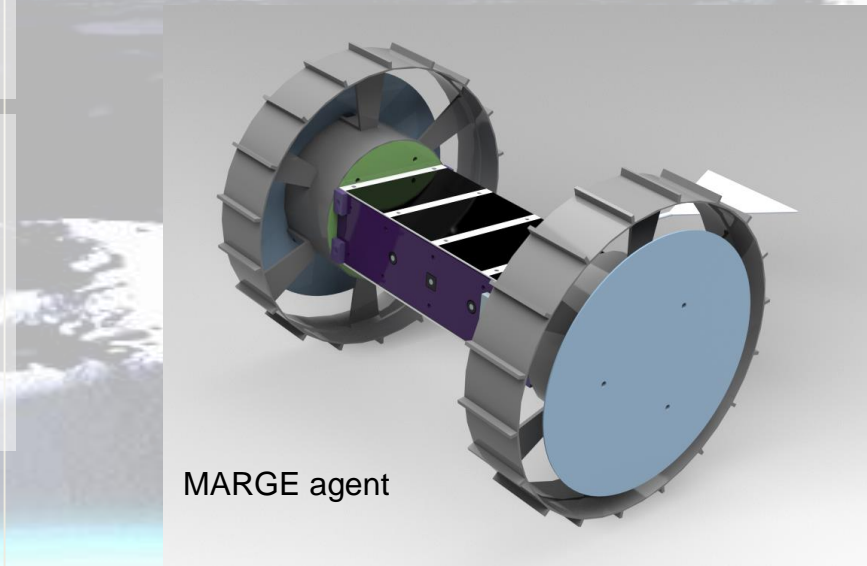
Science:

- Detect the presence and map the distribution of water ice in lunar regolith
- Detect the presence and map the path, depth and geometry of voids or lava-tubes in the lunar subsurface
- Detect the presence and map the distribution of lunar pyroclastic deposits in the regolith

Objectives:

- Integrate ground-penetrating radar, mobility and autonomy into a compact agent
- Conduct autonomous multi-agent surveys on the Moon
- Characterize the science targets with a lateral resolution of at least 0.5 m and a depth resolution of 15 cm.

CoIs: Kalind Carpenter, JPL; Neil Chamberlain, JPL; Jean Pierre de la Croix, JPL; Mark Haynes, JPL; Soon Sam Kim, JPL



MARGE agent

Key Milestones:

- Test integration of TRL-4 subsystems into the prototype platform (Yr-1) and functionally test it.
- Develop MARGE-1 agent, followed by environmental and field testing.
- Develop MARGE-2 agent, followed by environmental and field testing.
- Field multi-agent test MARGE-1 and MARGE-2

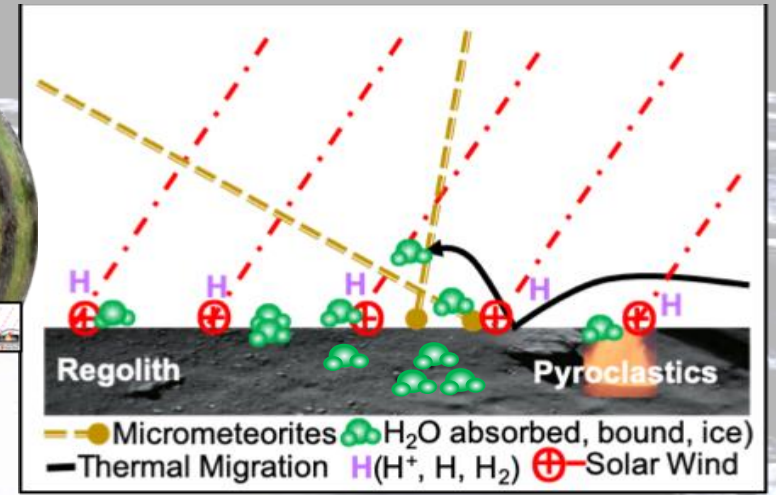
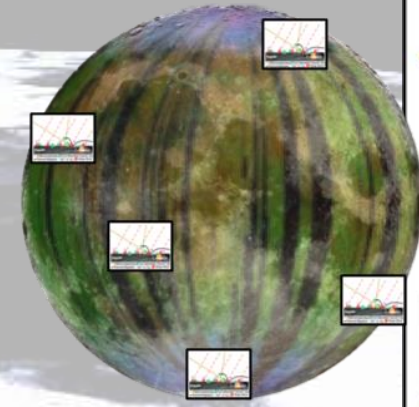
TRL 4 to 6

Development and Advancement of Lunar Instrumentation Program (DALI)

Mini Water Cycle Monitor

Description: Global Lunar Organized Water In-Situ Network (GLOWIN) is a multi-platform Lander mission concept that would provide simultaneous globally distributed lunar in situ spectral and particle measurements essential for wholistic understanding of volatile processes resulting from high energy particle/surface/subsurface/exosphere interactions.

Measurement Advances: Current understanding of lunar water is derived from spectral and remote (orbital or ground-based) observations. The nature of in situ local-scale regolith interactions is lacking. A network of lander in situ measurements for at least a year would provide the basis for a high-fidelity global water model. Lander packages would consist of instruments capable of providing: solar wind flux (source of H⁺) (ESA electrostatic analyzer e.g. ESA); the state (ice, liquid, vapor) of surface adsorbed or bound OH, H₂O (IR imager e.g. SILVIR or UCIS); exospheric hydrogen, (energetic neutral atom imager e.g. ENA); subsurface water, (neutron spectrometer e.g. mini-NS) and micrometeorite bombardment detector (candidate: acoustic detectors).



Technology Advances: Generic Compact, Low Resource, High Performance Packaging (ARTEMIS/PALETTE); compact versions relevant instrumentation (above); Low-cost commercial landers
 Approach/Milestones TRL 4-6, 2-3 years to prototype
 1 Leverage STMD GCT high performance packaging
 2 Leverage ESA, ENA, mini-NS, IR imagers already flight qualified or being flight qualified for other programs
 3 Create and qualify 'manufacturable' prototype package
 4 Have partner produce multiple prototype-based packages

Team: PI Pamela Clark, Col's Bugby, Henegan, Fraeman, Collier (GSFC), Killen (GSFC), Farrell (GSFC), Hurley (APL), LI (U Hawaii)

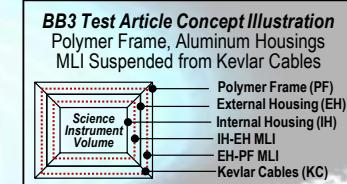
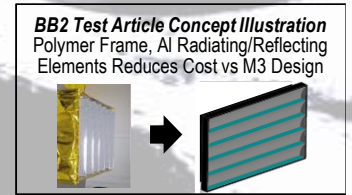
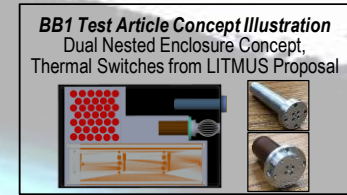
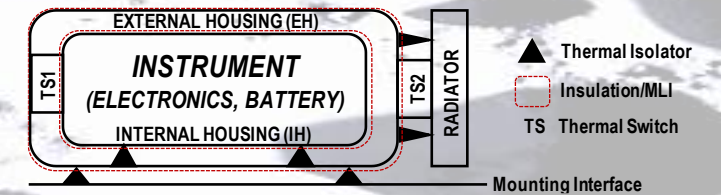
Types of Instrumentation and Challenges

Generic yet Reconfigurable Packaging for Extreme Environments:

A major challenge for small packages, particularly on the lunar surface, is thermal packaging to protect the payload from the lengthy temperature extremes without the need for active control systems requiring power and thus significantly increasing mass and volume needed for batteries during lunar night.

In addition, each type of instrument has challenges peculiar to that type, as indicated above. Is it possible to develop generic yet reconfigurable approaches widely applicable by configuring the same high performance components?

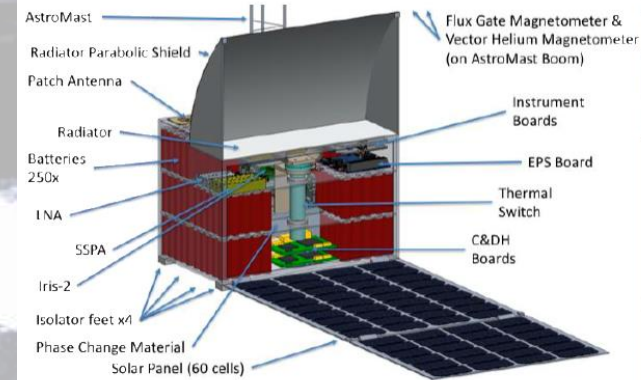
High performance thermal component packaging based on passive thermal design that will allow operation on at least limited duty cycle during lunar night is now being developed and tested through the STMD-funded Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project.



Description: Compact Stand Alone Autonomous Instrument Package utilizing Dual Magnetometer Requirements as Example (Program: Team X Study)

Point Design: Team X
Lead: John Elliott

Design



	Dry Mass Fraction %	CBE Mass (kg)	Subsys. Cont. %	MEV Mass (kg)
DASHBOARD				
PAYLOAD ON THIS ELEMENT				
Instrument	7.4%	1.78	15%	2.04
PAYLOAD TOTAL		1.78	15%	2.04
SPACECRAFT BUS				
Communications	5%	1.23	2%	1.25
C&DH	1%	0.19	21%	0.22
Thermal	4%	0.85	25%	1.06
Power	71%	16.58	15%	19.41
Mechanical	13%	3.00	30%	3.90
BUS TOTAL		22.14	16.7%	25.85
S/C DRY CBE				
		23.918		
		5.97	16.0%	
Subsystems				
SPACECRAFT MEV (DRY)				
		27.89		
		7.11	25.5%	
System Cont./Risk Margin				
SPACECRAFT MPV (DRY)				
		35.00		
SPACECRAFT MPV (WET)				
		35		
JPL Mass Margin				
		11.08		31.7%
NASA Mass Margin				

Design Requirements

- ❖ Small system size, must be under 35kg.
- ❖ One year mission life
- ❖ System must be capable of surviving Lunar Night (14 earth days).
- ❖ Two Magnetometer instrument payloads with accompanying electronics.
 - 1.78kg total mass
- ❖ Assumed 3kg for the mass of the AstroMast, lander structure, and radiator.
- ❖ Cost Target of \$3M-6M.

Design Rationale

- ❖ Power
 - The driving power mode is during Lunar Night. This requires 250 Li-Ion 18650 battery cells, which is a significant majority of the lander mass. See the Power Report for more details.
 - A folding solar array is used for power regeneration during the Lunar Day.
- ❖ Thermal
 - A thermal phase change material (PCM) will be attached to the Iris radio in order to provide passive thermal control. This means the lander can get by with a smaller radiator during the Telecom passes, and fewer heaters during the Lunar Night.
- ❖ C&DH
 - The Sphinx avionics suite has been baselined, as it has strong heritage and its capabilities exceed that required for this mission, at a reasonable cost.
 - The Sphinx will also contain a watchdog/wakeup circuit for waking up the lander from Lunar Night.
- ❖ Telecom
 - Due to its high heritage and data rate, the Iris V2 Radio has been baselined for this mission. It will communicate during the Lunar Day.
- ❖ Mechanical
 - The mechanical subsystem is equipped with a AstroMast which will deploy the two magnetometers from the lander. More details may be found in the Mechanical Report.
- ❖ The total CBE mass is estimated to be 23.9kg, which amounts to 27.9kg with the added subsystem contingency.
- ❖ Given the total allocation of 35kg, this provides a JPL mass margin of 11kg, or 32%.

Summary JPL Sensor and Supporting Subsystem Development

- JPL and others developing compact sensors and sensor suites tailored for lander decks and legs and requiring minimal sample handling.
Examples: UCIS-based Low-light imaging spectrometer, mini-QIT Mass spectrometer, INSPIRE/CuSP-derived magnetometer, SEIS INSIGHT-derived broadband spectrometer
- JPL developing supporting subsystems (mechanical/thermal/power) package for a range of minimal-resource competitive instrument suites that can survive and operate multiple lunar days without radioisotopes.
Example: PALETTE
- Implicitly development of smart strategies to mitigate the downlink bandwidth bottleneck.
Example: Operate in 'snapshot' or 'time lapse' modes.