Developments in Lunar Compact Instrumentation for Small-scale Applications.

Pamela E. Clark[1], Robert L. Staehle[1], David Bugby[1]

Acknowledgements: Contributions from the following in compiling information on instruments under development: Robert L. Staehle[1], David Bugby[1], Abigail Fraeman[1], Robert O. Green[1], R. Glenn Sellar[1], Stojan Madzunkov[1], Frank Maiwald[1], Nan Yu[1], Adrian Tang[1], Corey Cochrane[1], Craig Hardgrove[2], Michael Collier[3], Vassilis Angelopoulos[4]

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[3]NASA/GSFC

[4]UCLA, Institute for Geophysics and Planetary Physics

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 Nebular/Accretion Processes, Early Solar System, Bulk compositions, volatile budgets, differentiation Crust/mantle/core materials, new rock types, robust sampling, Early planetary evolution, external processes, and origin and evolution of life	in situ isotopic, elemental, volatiles (molecular), mineralogical, textural, geochonrological, regolith, rocks, 'new' sites, dealing with contamination. Reverse stratigraphy observed from mobile platforms.	X-ray spectrometer X-ray imaging Gamma-ray spectrometer Neutron spectrometer Active mass spec (LIBS, LAMS) Active Gamma-ray/Neutron Compact IR spectroscopy Compact IR imaging Compact active near IR imaging In Situ geochronology Mass spec w/ in situ chromatography	MIT REXIS JPL PIXL PSI GRAND U of A LunaHMap LANL ChemCam (JPL MSL) GSFC SINGR GSFC/JPL BIRCHES JPL UCIS, SILVIR JPL Lunar Flashlight JPL RbSr KAr concepts GSFC SAM; JPL QIT-MS
Internal processes involving volatiles, polar deposits Crust/mangle/core materials, interior structure, stratigraphic record, dynamics, heat loss	Deployable network interior characterizers, lander or rovers with special attention to past or current 'active' regions. Cryogenic sampling.	Compact Cameras MicroImager Ground Penetrating Radar Magnetometer Seismometer Heat Flow Laser Reflector	JPL EECAM, JPL MMI JPL, Natl A&S Museum, GPR JPL/UCLA Fluxgate, VHS JPL SEIS, uSeismometer JPL ALGEP (Banerdt) JPL (Turyshev)
Surface Processes: regolith character and formation, impact processes		Geotechnical sensors (Mech, EM, thermal) Regolith particle analyzer	KSC MECA, SWRI DART COTS Microbrook Eyetech
Environmental processes: solar wind, plasma, IMF, micrometeoroid, radiation, exosphere interactions	Deployable environmental/ surface safety network monitoring surface dynamics	Mass Spectrometers Particle analyzers (ion/electron) Electric Field Instrument Dust Detector UV Spectrometer Radiation Detector	JPL QIT MS GSFC HALO, SIMS GSFC EPDA GSFC EPDA ARC LADEE UVS UNH DOSEN
technology development, new directions, human exploration	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 cm3
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) abd 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, MicroImager

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

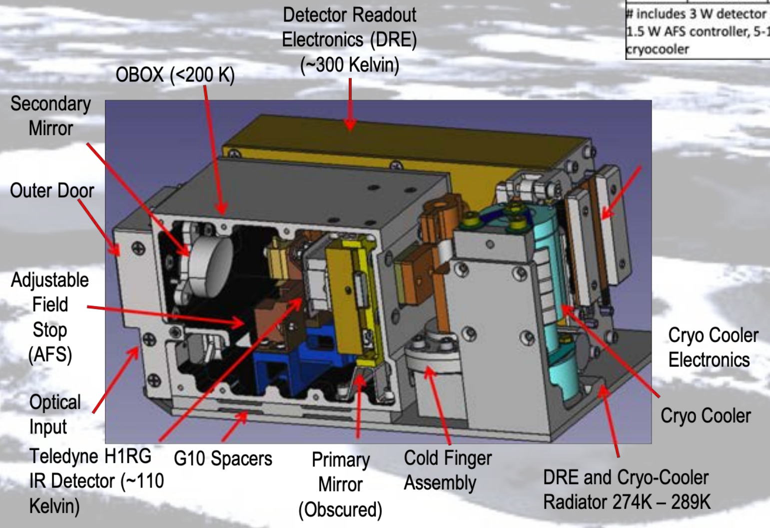
Measurement Advances: Measure forms and components of lunar water as function of time of day, latitude, and terrain from orbit requiring encompassing broad 3 micron band with detection limit >100 ppm and up to 10 km spatial resolution. Applicable as surface monitoring instrument.

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.

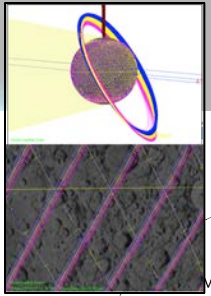
Approach/Milestones
Leverage OVIRS (OSIRIS REx) flight spares, utilize first cubesat-scale cryocoolers (AIM/IRIS).
Final Testing of instrument by late winter 2020, Final integration with spacecraft by early autumn 2020.

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

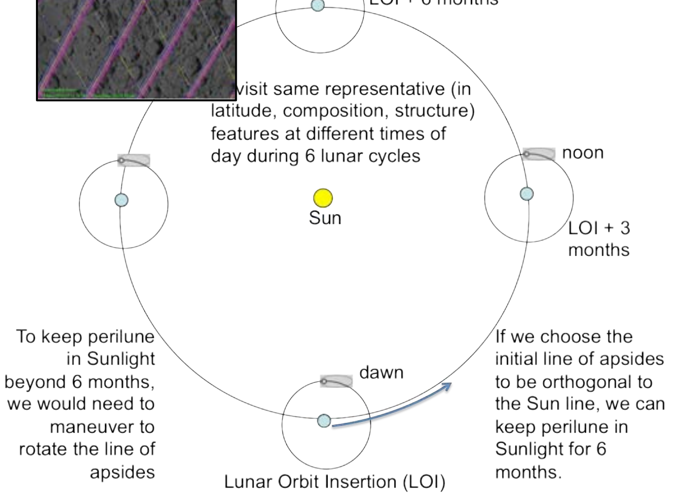
BIRCHES IR Spectrometer HW Architecture



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		



6 Month Mission Concept



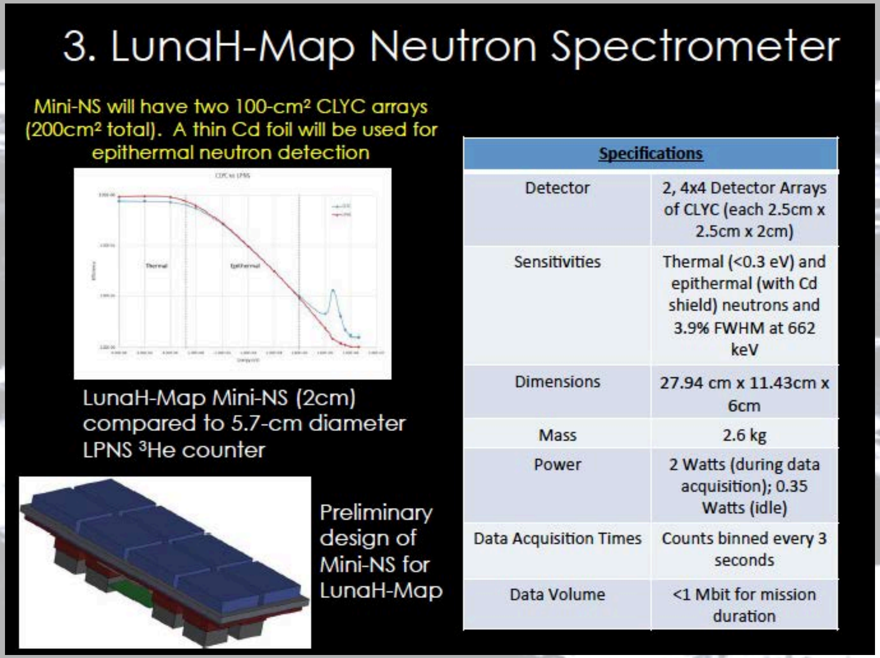
Description: Compact Neutron Spectrometer on LunaH-Map mission.

Measurement Advances: Measure decrease in epithermal neutron flux (>/= 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.

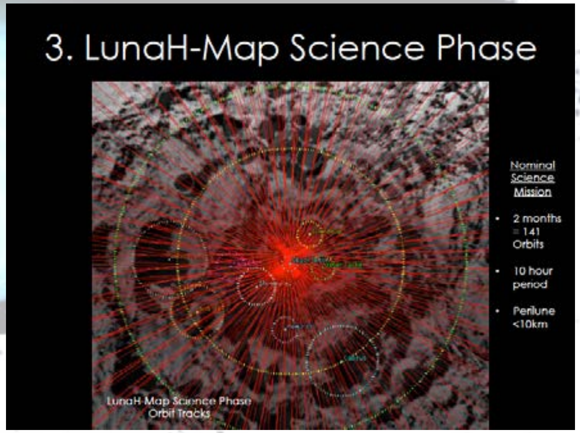
Technology Advances: Cubesat scale (6U) neutron spectrometer, with more efficient, and thus compact, CLYC detector.

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)



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



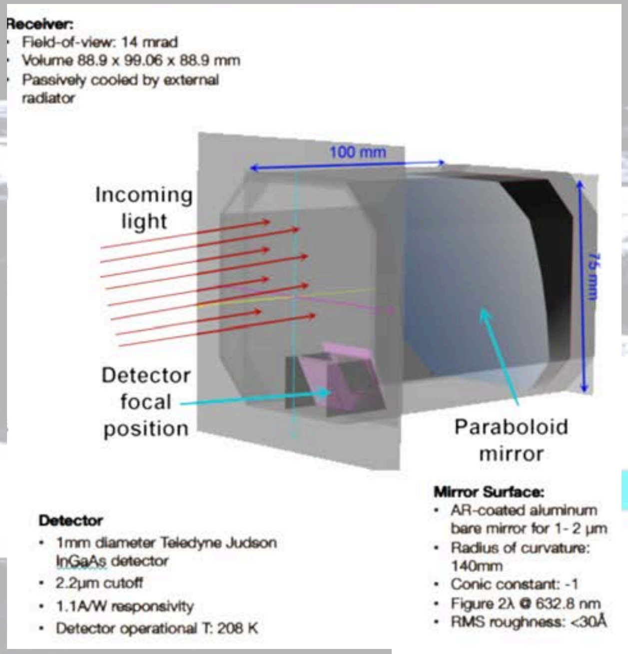
Description: Compact instrument for ice detection through use of optical receiver aligned with lasers emitting at wavelengths associate with water ice absorption and continuum on Lunar Flashlight mission

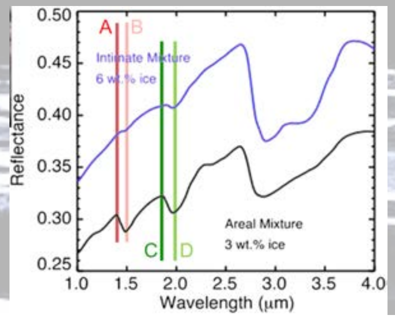
Measurement Advances: Ratio continuum and absorption reflectance bands to quantify surface ice abundance in permanently shadowed areas at for >0.5 wt % ice with 1 km spatial resolution with. 10 degrees of South Pole. Applicable as surfacd prospecting instrument.

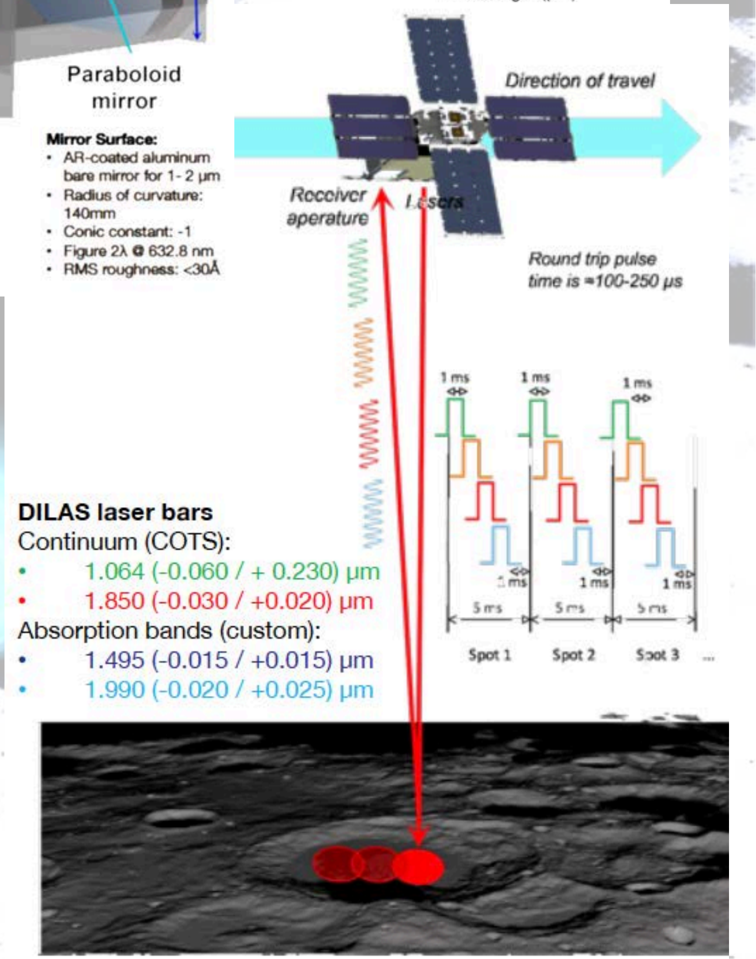
Technology Advances: Cubesat scale (6U) active near IR spectrometer. Use of laser technology in extremely challenging thermal environment.

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).







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

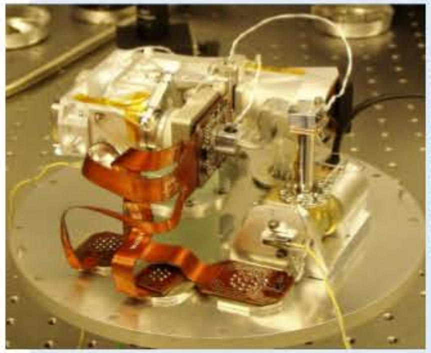
PI: Abigail Fraeman/JPL

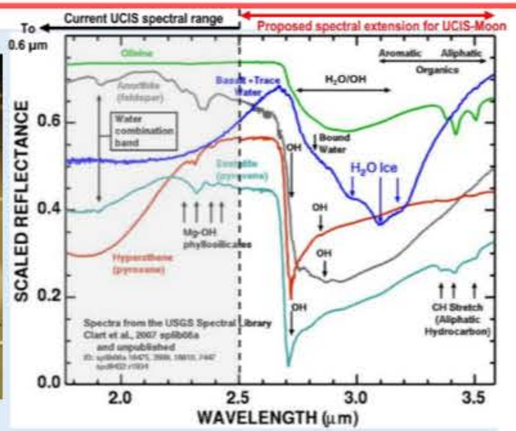
Platform: Lander or Rover

Science:
- Uses well-established SWIR imaging spectroscopy to map H_2O, 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

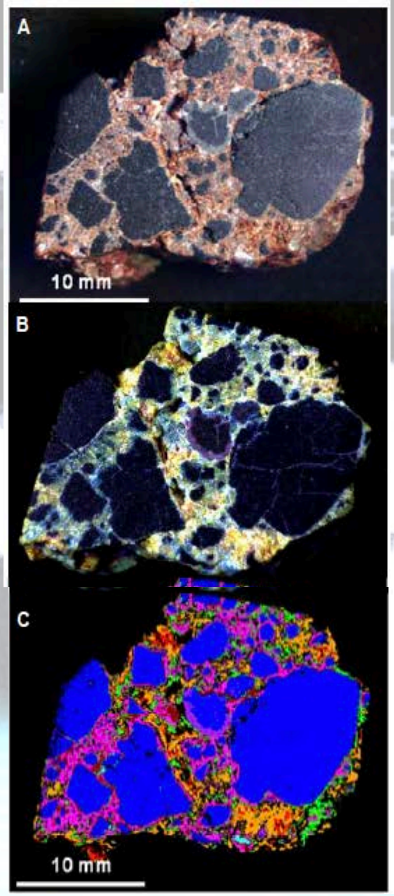
Description: Compact, low-cost Multispectral Microscopic Imager (MMI) to provide petrographic (microtextural) information on composition and color to reveal origin and history of sample.

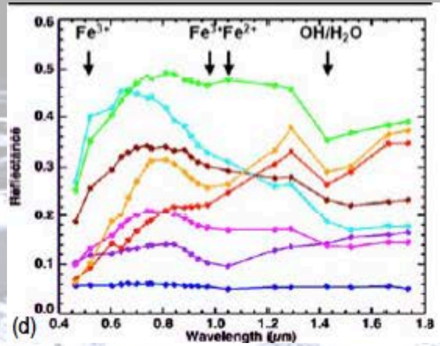
Measurement Advances: Spectrometric capabilities added to MER microscopic imagers (MI). Multiple bands and range (visibile to near IR) extend ability to characterize mineralogy and allow more effective sample screening

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 deploy 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

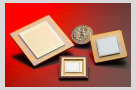
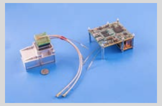
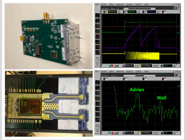
Mini Water Prospector

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 ext raction 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_2O / 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)

Jet Propulsion Laboratory
California Institute of Technology

Multi-agent Autonomous Roving Ground-penetrating radar Explorer MARGE

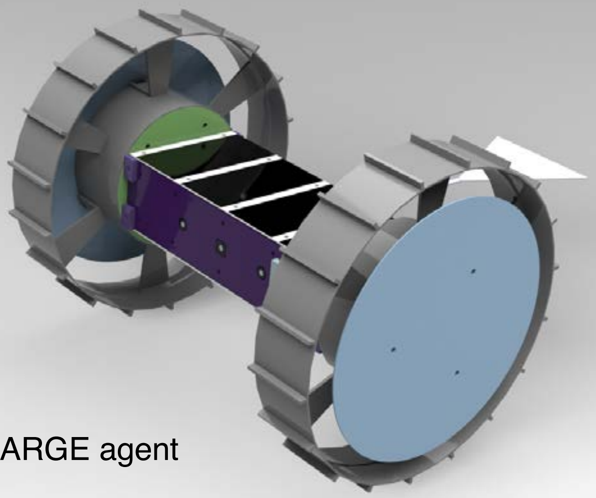
PI: Daniel Nunes, Jet Propulsion Laboratory

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

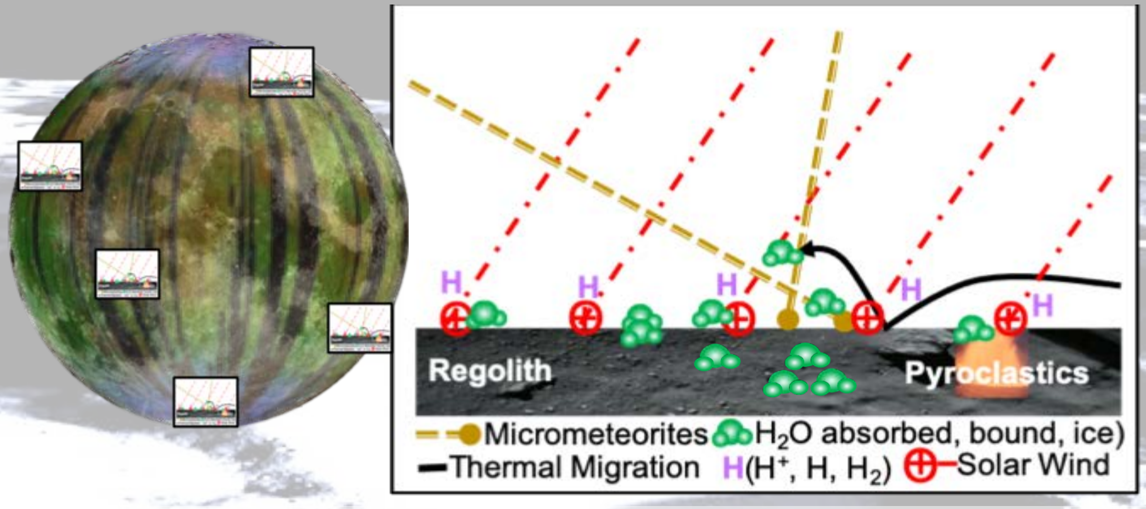
Key Milestones:
- Test integration of TRL-4 subsystems into the prototype platform (Yr-1) and functionally test it.
- Develop MARGE-1 agent, followed by environmental and field testing.
- Develop MARGE-2 agent, followed by environmental and field testing.
- Field multi-agent test MARGE-1 and MARGE-2

TRL 4 to 6

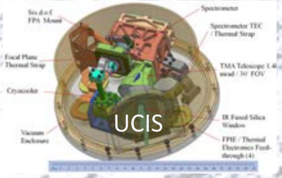
Development and Advancement of Lunar Instrumentation Program (DALI)

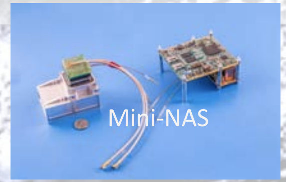
Mini Water Cycle Monitor

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 protoype-based packages

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

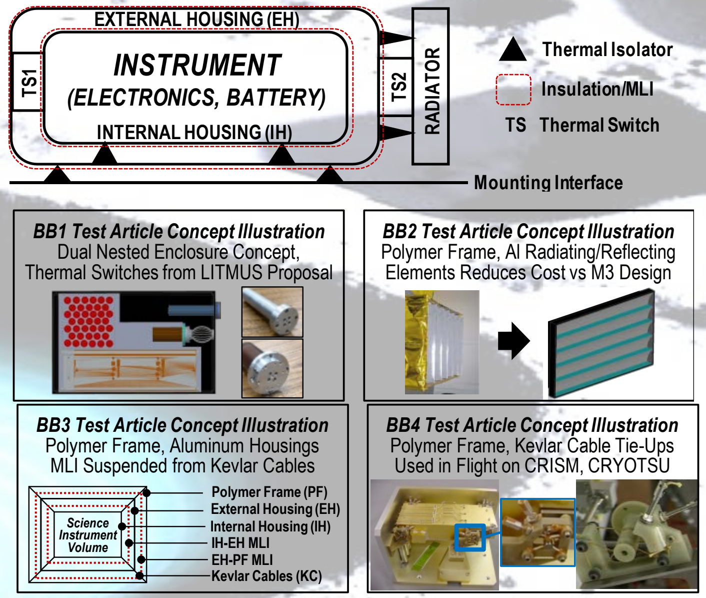
Types of Instrumentation and Challenges

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?

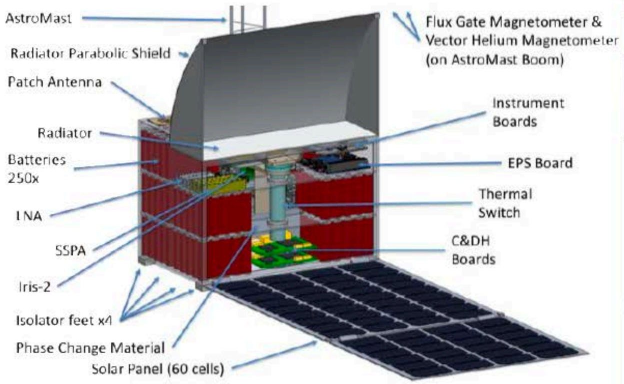
High performance thermal component packaging based on passive thermal design that will allow operation on at least limited duty cycle during lunar night is now being developed and tested through the STMD-funded Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project.



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



DASHBOARD

	Dry Mass Fraction %	CBE Mass (kg)	Subsys. Cont. %	MEV Mass (kg)
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%	16.88	15%	19.41
Mechanical	13%	3.00	30%	3.90
BUS TOTAL		22.14	16.7%	25.85

S/C DRY CBE: 23.918

3.97 | 16.6% | Subsystems

SPACECRAFT MEV (DRY): 27.89

7.11 | 25.5% | Systems Cont./NASA 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 Subsytem 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.