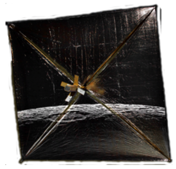
Lunar Flashlight: Mapping Lunar Surface Volatiles Using a Cubesat



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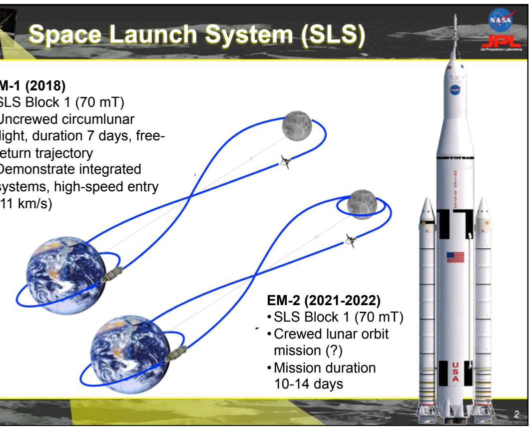
Space Launch System (SLS)

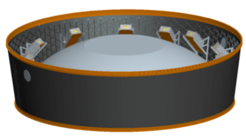
EM-1 (2018)
- SLS Block 1 (70 mT)
- Uncrewed circumlunar flight, duration 7 days, free-return trajectory
- Demonstrate integrated systems, high-speed entry (11 km/s)

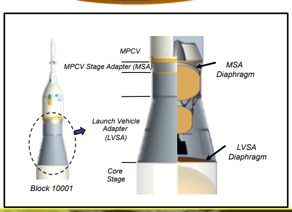


EM-2 (2021-2022)
- SLS Block 1 (70 mT)
- Crewed lunar orbit mission (?)
- Mission duration 10-14 days

Secondary payloads on EM-1

- Room for 11 6U cubesats on standard deployer
- Secondary payloads will be integrated on the MPCV stage adapter (MSA) on the SLS upper stage
- Secondary payloads will be deployed on a trans-lunar trajectory after the upper stage disposal maneuver





EM-1 Secondary Selection

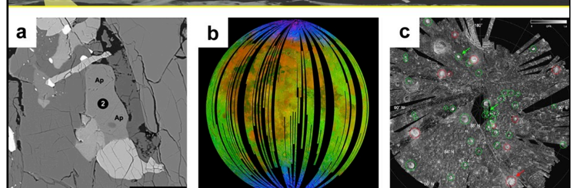
- 19 NASA center-led concepts were evaluated and 3 were down-selected by the Advanced Exploration Systems (AES) program
- Primary selection criteria:
  - Relevance to Space Exploration Strategic Knowledge Gaps (SKGs)
  - Synergistic use of previously demonstrated technologies
  - Life-cycle cost and optimal use of available civil servant workforce
- Other secondary payloads will be added
  - NASA SMD and STMD will each compete one in FY15
  - Possibly others – universities, research centers, etc?

Payload *NASA Centers*	**Strategic Knowledge Gaps Addressed**	**Mission Concept**
BioSentinel ***ARC**/JSC*	**Human health/performance in high-radiation space environments** • Fundamental effects on biological systems of ionizing radiation in space environments	Study radiation-induced DNA damage of live organisms in cis-lunar space; correlate with measurements on ISS and Earth
Lunar Flashlight ***JPL**/MSFC/MHS*	**Lunar resource potential** • Quantity and distribution of water and other volatiles in lunar cold traps	Locate ice deposits in the Moon's permanently shadowed craters
Near Earth Asteroid (NEA) Scout ***MSFC**/JPL*	**NEA Characterization** • NEA size, rotation state (rate/pole position) **How to work on and interact with NEA surface** • NEA surface mechanical properties	Slow flyby/rendezvous and characterize one NEA in a way that is relevant to human exploration

Why look for water ice?

- The Moon is highly depleted in volatile compounds, especially water
- Humans exploring the Moon will need water:
  - Option 1: Carry it there. ↵ expensive (at $10K/lb, 1 gal H_2O=$80K)
  - Option 2: Use water that may be there already. ↵ "live off the land"
- Can mine O_2 from minerals and H from solar wind implantation, however, this is very energy intensive
- **Life would be much easier and cheaper if we could use H_2O from the Moon**
  - At the surface or near surface
  - In "operationally useful" quantities

Water on the Moon

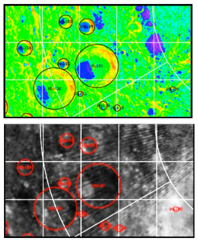


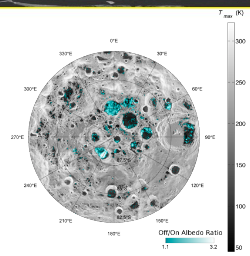
a: Volcanic glass from the Apollo 15 landing site and apatite grains from the Apollo samples and lunar meteorites contain trace amounts of water (5-50 ppm) as part of the mineral structures (e.g., Saal et al. 2008; McCubbin et al. 2010, 2013). *Too little.*

b: Moon Mineralogy Mapper (M3), EPOXI and Cassini instruments found trace H_2O and OH on the lunar surface near the poles, as a monolayer on lunar dust grains or bound into the mineral structures of surface materials (Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009). *Too little.*

c: Multiple ground-based and space assets (Clementine, Lunar Prospector, LRO, LCROSS, Kaguya) have suggested water ice resides in permanently-shadowed regions (PSRs) at the lunar north and south poles. *Too deep..*

Water ice frost in PSRs?





- Locations where Diviner measures the coldest year-round temperatures also show high albedo in LOLA at 1.064 μm, consistent with water frost
- Ultraviolet albedo data from LAMP also show evidence for water ice at the lunar surface, but are not yet definitive

What we need to know

Lunar Strategic Knowledge Gaps

I. Understand the lunar resource potential

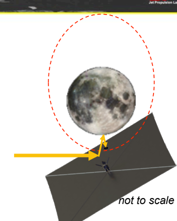
D. Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps.

Narrative: Required "ground truth" in-situ measurement within permanently shadowed lunar craters or other sites identified using LRO data. Technology development required for operating in extreme environments. Enables prospecting of lunar resources and ISRU. Relevant to Planetary Science Decadal survey.

- Lunar Flashlight will illuminate permanently-shadowed and detect water ice absorption bands in the near-infrared – **Measurement goal**
- By repeating this measurement over multiple points, Lunar Flashlight will create a map of surficial ice concentration that can be correlated to previous mission data and used to guide future missions **– Mapping goal**

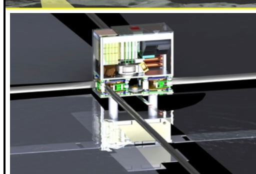
LF Mission Overview

- 6U Cubesat (form factor 10 cm x 20 cm x 30 cm)
- ~80 m² sail reflects sunlight into permanently shadowed regions
- IR 4-band point spectrometer measures H_2O absorption & continuum
- Teaming: JPL & MSFC
  - S/C (11 kg), Payload, Mission Design & Nav: JPL
  - Propulsion: MSFC
  - I&T, Ops: JPL & MSFC
- Leverages:
  - Solar sail development expertise (NanoSail-D, Sunjammer, LightSail-1)
  - CubeSat developments and standards (INSPIRE, university & industry experience)
  - Synergies with NEA Scout (bus, solar sail, comm, I&T, ops)

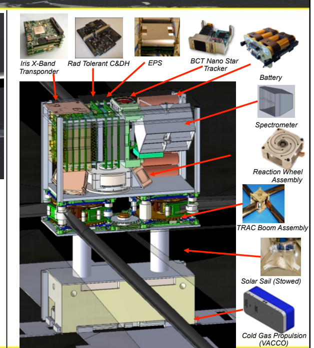


- **SLS Secondary:** EM1
- **Schedule:** Launch late 2017
- **Arrival Date**: 2018
- **Duration:** 2 years
- **MCR/SRR**: August 2014

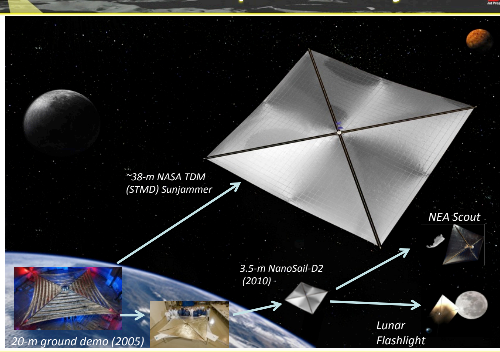
LF Flight System Overview



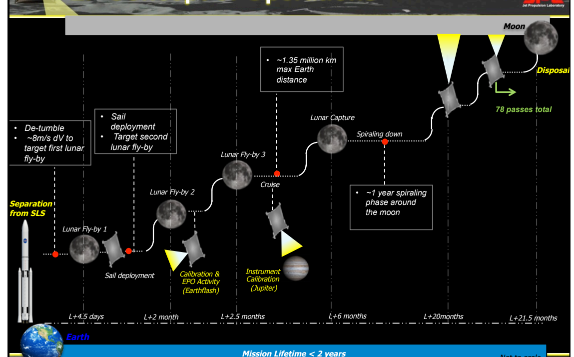
Bus: JPL Deep Space NanoSat Bus (leveraging INSPIRE)
Propulsion: MSFC ~80 m² Solar Sail (based on NanoSail-D)
Payload: COTS 4-band spectrometer
C&DH: Rad Tolerant LEON-3 architecture, JPL Protos FSW
ADCS: COTS Cold Gas, RWA, SRU, IMU, CSS
Power: ~44W
Telecom: JPL Iris X-Band Transponder + Patch Antenna (~1 kbps nominal @ Lunar Distance with DSN State)



Solar Sail Development History



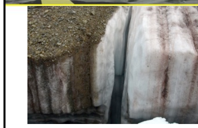
LF Concept of Operations



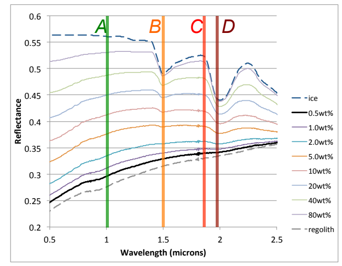
LF Goals and Objectives

NASA Goals	Lunar Flashlight Level 1 Requirements	Measurement Objectives
Human Exploration *Strategic Knowledge Gaps for the "Moon First" Human Exploration Scenario* I. Understand the lunar resource potential ID. Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps **Science** *Planetary Science Decadal Survey, Terrestrial Planets* Characterize Planetary Surfaces to Understand How They Are Modified by Geologic Processes • What are the compositions, distributions, and sources of planetary polar deposits?	Lunar Flashlight shall have the capability to address a key Strategic Knowledge Gap at the Moon	**Objective 1 (measurement)** LF shall measure the abundance of lunar volatiles present at levels ≥0.5 wt% in the lunar regolith with a precision of ±50% or better **Objective 2 (mapping)** LF shall map the distribution of exposed water ice with 1-2 km resolution within the permanently shadowed regions at the lunar south pole
Technology Demonstrate low-cost reconnaissance capability for HEOMD through the use of innovative solutions	Lunar Flashlight shall be in a 6U cubesat form factor compatible with a NASA provided cubesat deployer for launch on a NASA provided launch vehicle	

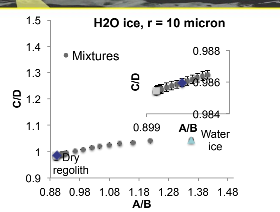
Objective 1: Measurement

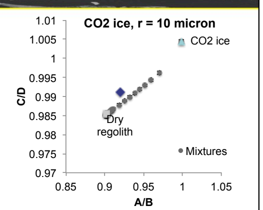


- Reflectance spectroscopy is the standard technique for identifying molecular "fingerprints" from a distance
- Measure absorption and continuum to understand ice abundance



Objective 1: Measurement





- Water ice has A/B ratio ~ 50% higher than dry regolith (and opposite spectral slope), C/D ~ 5% higher
- Baseline instrument and mission design yield detections easily within the 0.5% (by mass) water content threshold (Error bars indicate 1σ uncertainty for single measurement)
- Potential to separate H_2O ice from CO_2 ice, which will aid understanding origins and distribution of H-bearing volatiles useful as resources

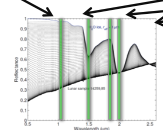
Measurement Constraints

Solar Sail
Light reflected from sail into IFOV (~22 kW onto surface)
- material reflectance
- sail tensioning & alignment
- beam co-alignment

Lunar surface
Light reflected to the instrument
- scattering characteristics
- H_2O wt% & grain size
- areal distribution
- topography

Instrument
Signal collection & processing
- band width & center
- aperture
- optical throughput
- detector & electronics performance
- detector cooling

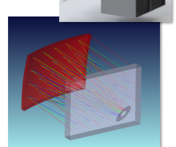
Navigation
Geometry of the reflected signal
- orbit altitude
- pointing and pointing knowledge
- offset between IFOV and spot center < 1°



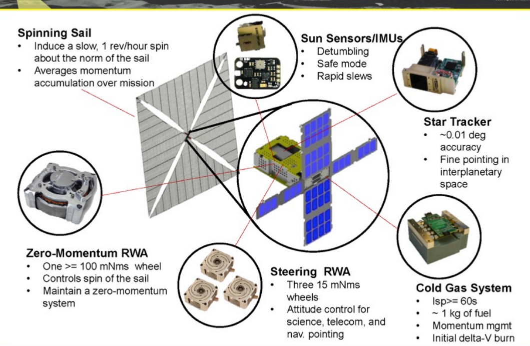
- Observations in 4 wavelength bands, with measured reflectance ratios capable of discriminating 0.5 wt.% H_2O from dry regolith with high (3σ) confidence
- Requires reasonably-achievable values for all of the contributing factors

LF Instrument Design

- Four-channel point spectrometer: all channels view the same spot simultaneously through different filters
- Off-axis parabola telescope design keeps detectors within a small footprint, which is beneficial for cooling, acceptable image quality over IFOV
  - each aperture is 30 mm x 40 mm, f/1 focal ratio
  - IFOV = 2.86°; 1-km diameter spot at 20 km range
- Judson (Teledyne) strained-lattice InGa:As PVs detectors
  - Passively cooled operation at -65C
- Passive radiator is integral with optical instrument
  - Detectors are mounted just behind filters
  - radiator is on anti-sun side of solar sail
  - thermal isolation from instrument
  - K-Core thermal link to detectors
- Considering addition of small camera to aid pointing reconstruction along track

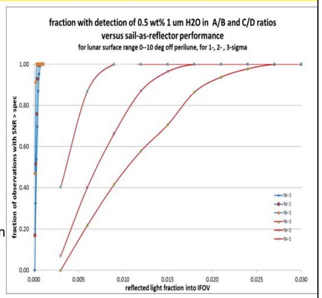


LF Attitude Control Subsystem



Measurement prediction

- Given educated constraints for spacecraft subsystems capabilities (ACS, trajectory, navigation, thermal, instrument, etc.)
- For 2.1% of the light incident on the sail reflected into the IFOV, 94% of observations give>3σ detection capability in the long-wave band, for H_2O ice of 1μm grain size present at 0.5 wt.%.
  - The average observation has higher confidence: 8.3σ for 1μm grain size
- Need 10% "reflectance" to achieve an average observation of 3σ in the short-wavelength bands



Solar sail testing this summer, but 10% (or better) seems very likely to be reasonable for LF: measurement achievable

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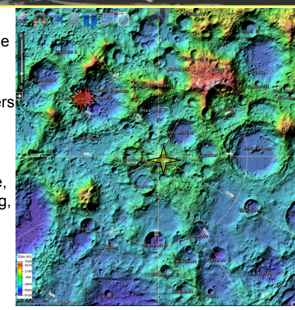
Objective 2: Mapping

- Measure water ice at multiple locations within PSRs at one pole at ~1-2 km footprint per spot
- This is an *operationally useful* scale for future landers and rovers
- Enables prediction of other ice deposits by correlating data with other mapped geologic characteristics, including latitude, temperature, topography, lighting, proximity to young fresh craters, etc.



LOLA topographic map for the South Polar region from 80S showing large craters and PSRs

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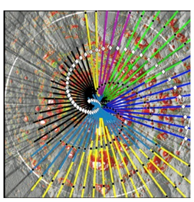
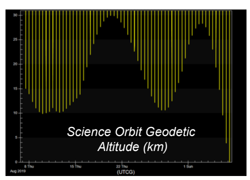
Mapping Constraints

- All ground tracks are the same length (10 degrees latitude around pole), with varying width (spot size).



- Initial Orbit: 9000 x 200 km
- Spiral down to 9000 x <20 km
- Distance to surface varies with latitude and orbit perilune. Spot size on the surface depends on distance from S/C to the surface.



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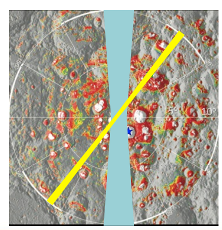
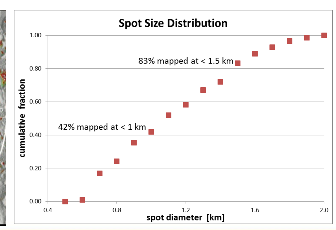
Mapping Prediction

- Given educated constraints for spacecraft subsystems capabilities (ACS, trajectory, navigation, instrument, etc.
- 10% of PSRs within 10° of pole are observed (60 orbits), covers Shoemaker Crater and LCROSS site
- ~50% of observations will have 1-km footprint; >95% will be 2 km





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Lunar Flashlight summary

- Cost-constrained Cubesat+ (nanosat) mission to detect and map lunar surface ice in permanently-shadowed regions of the lunar south pole
- Furthering the maturity of CubeSats
  - Long-lived CubeSat bus for deep space missions (C&DH, EPS, ADCS, Deep Space Transponder)
  - Further characterization of deep space environment effects on CubeSats (building on INSPIRE)
  - Mature CubeSat Solar Sail propulsion
- Future potential of small missions for science & exploration
  - Part of 1st generation of cubesat-style planetary missions to conduct real science measurements
  - Secondary spacecraft hosted on interplanetary missions

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