MOREHEAD STATE UNIVERSITY

A New Era of Planetary Exploration with Small Satellite Platforms

4th IAA Conference on University Satellite Missions and CubeSat Workshop

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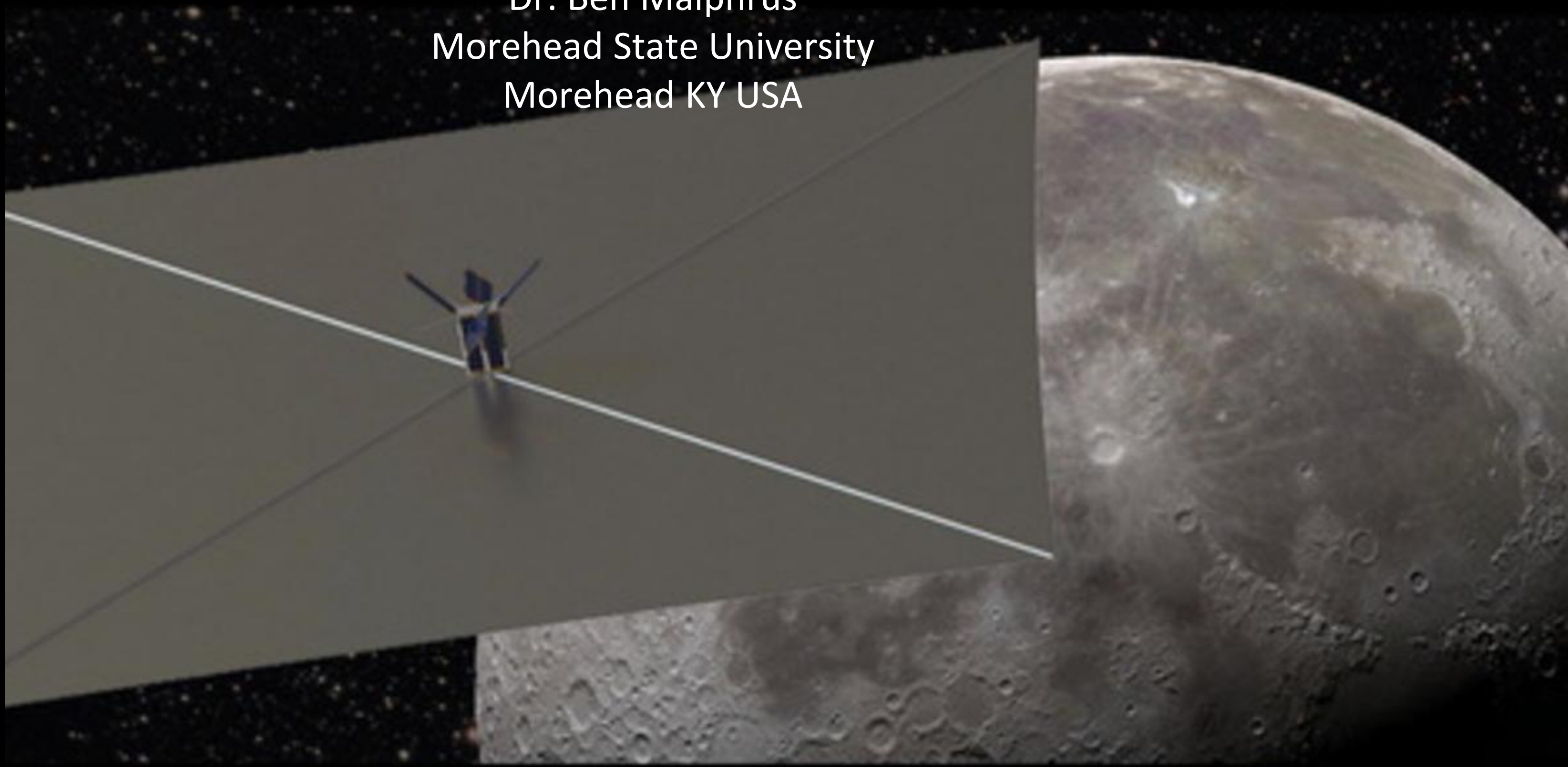
Dr. Ben Malphrus
Morehead State University
Morehead KY USA



A New Paradigm for Deep Space Exploration

CubeSats and SmallSat Form Factors

- Can Achieve Targeted Science Goals Independently
- Augment Monolithic Flagship Missions
- Low-Cost and Essentially Expendable
  - Can be sent to harsh environments
    - Radiation Belts of Jupiter
    - Ring Plane of Saturn
    - Atmosphere of Venus
    - Plumes of Enceledus

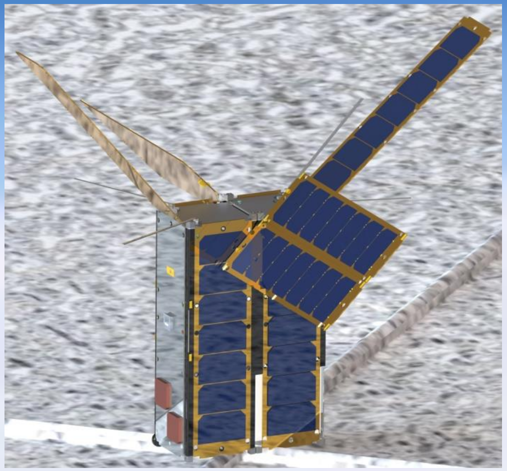
A Pandora's Box of Interplanetary CubeSats is Opening

- New Enabling Technologies will support Interplanetary Exploration with SmallSats
- NASA (and ESA to some Extent) has adopted the Interplanetary CubeSat Model, supporting missions and studies
  - NASA Interplanetary CubeSat Missions
    - MarCO
    - EM-1 (13 Interplanetary CubeSats)
  - Interplanetary CubeSat Mission Studies
    - Planetary Science Deep Space SmallSat Studies (PSDS3) program
    - Research Opportunities in Earth and Space Science (ROSES-17)
  - Numerous White Paper Studies Underway

A New Era- Enabling Technologies

- New Enabling Technologies will support Interplanetary Exploration with SmallSats:
  - New Launch Vehicles and Increased Access (Secondary Payloads to Earth Escape)
  - Miniaturized Propulsion Systems Capable of Producing Reasonable Δv
  - Small, Highly Capable Science Instruments
  - High Performance Comms and Ranging Systems
  - Radiation Hardened Subsystems
  - Use of the Interplanetary Superhighway

Each will be considered within the context of upcoming missions with a focus on Lunar IceCube….



Unique Challenges Faced by Interplanetary CubeSats

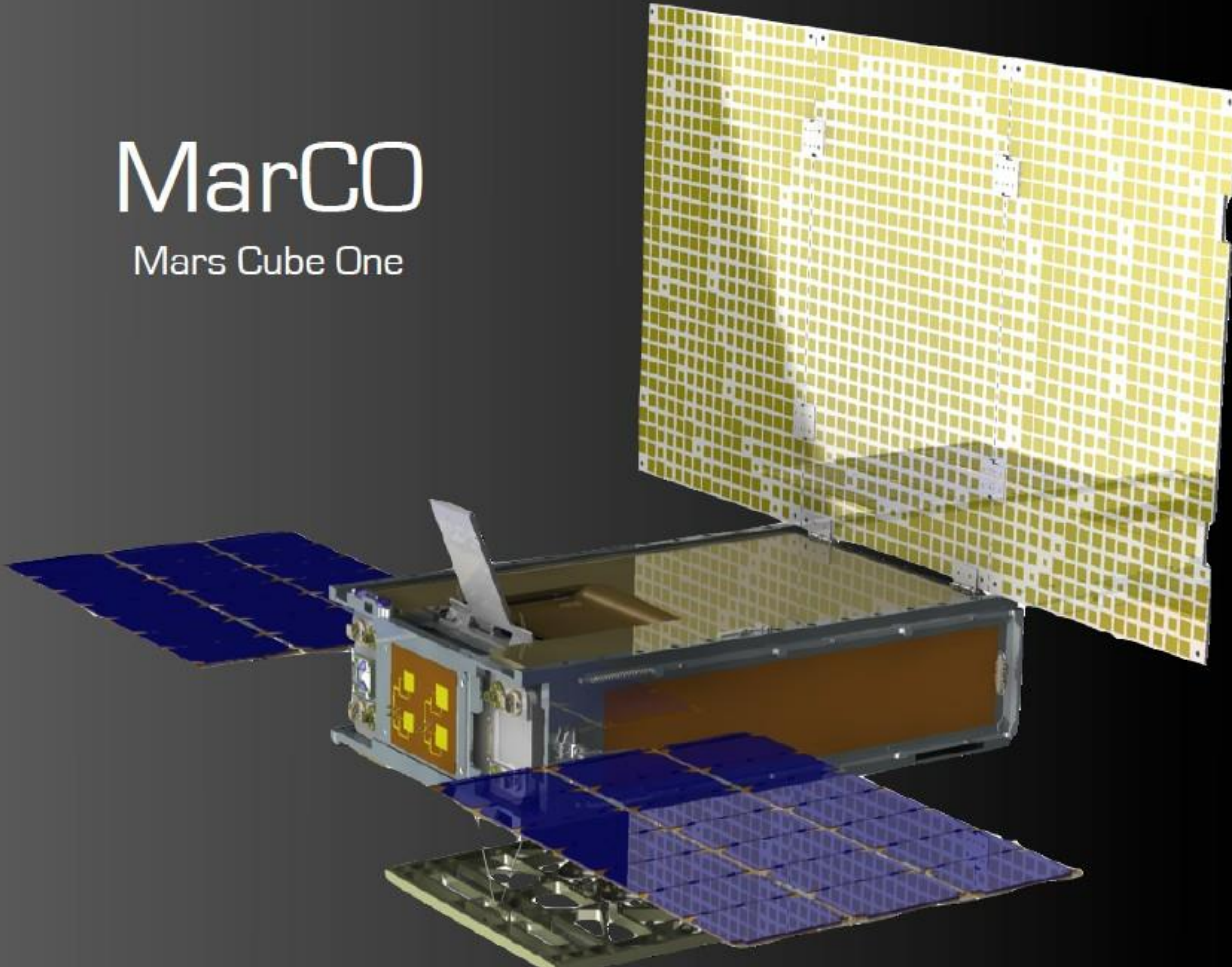
Conventional spacecraft design approaches are not applicable to CubeSats

Areas	New Challenges in Deep Space	Potential Solutions
Power	• Solar collection low a >1 AU • High power requirements (telecom, propulsion)	• Low-power modes • Power cycling • Higher energy storage capacity
Telecom	• Direct-to-Earth (DTE) challenging at large distances • Mothership relay cooperation	• On-board data compression • New Comms Designs • Disruption tolerant networking (DTN)
Orbit & Attitude Control	•Limited mass, volume, power • Reaction wheel e-sats outside Earth's geomagnetic field •ΔV tip-off	• Off-the-shelf, ACS • Cold gas thrusters (propulsion and de-sats) •Spiral Thrusting
Autonomy	• No direct link for long times	• Onboard autonomous operations • Agile science algorithms
Lifetime /Environment	• Long duration cruises • High radiation, severe thermal	•Rad-tolerant components • Short mission durations
Programmatic	• Potential risk to primary •Cost-efficient Missions ($15-40M)	• Aligning with strategic goals of Sponsor •Acceptance of Higher Risk Posture

Adapted/Updated from Spangelo et al. California Institute of Technology CubeSat Workhskop 2015

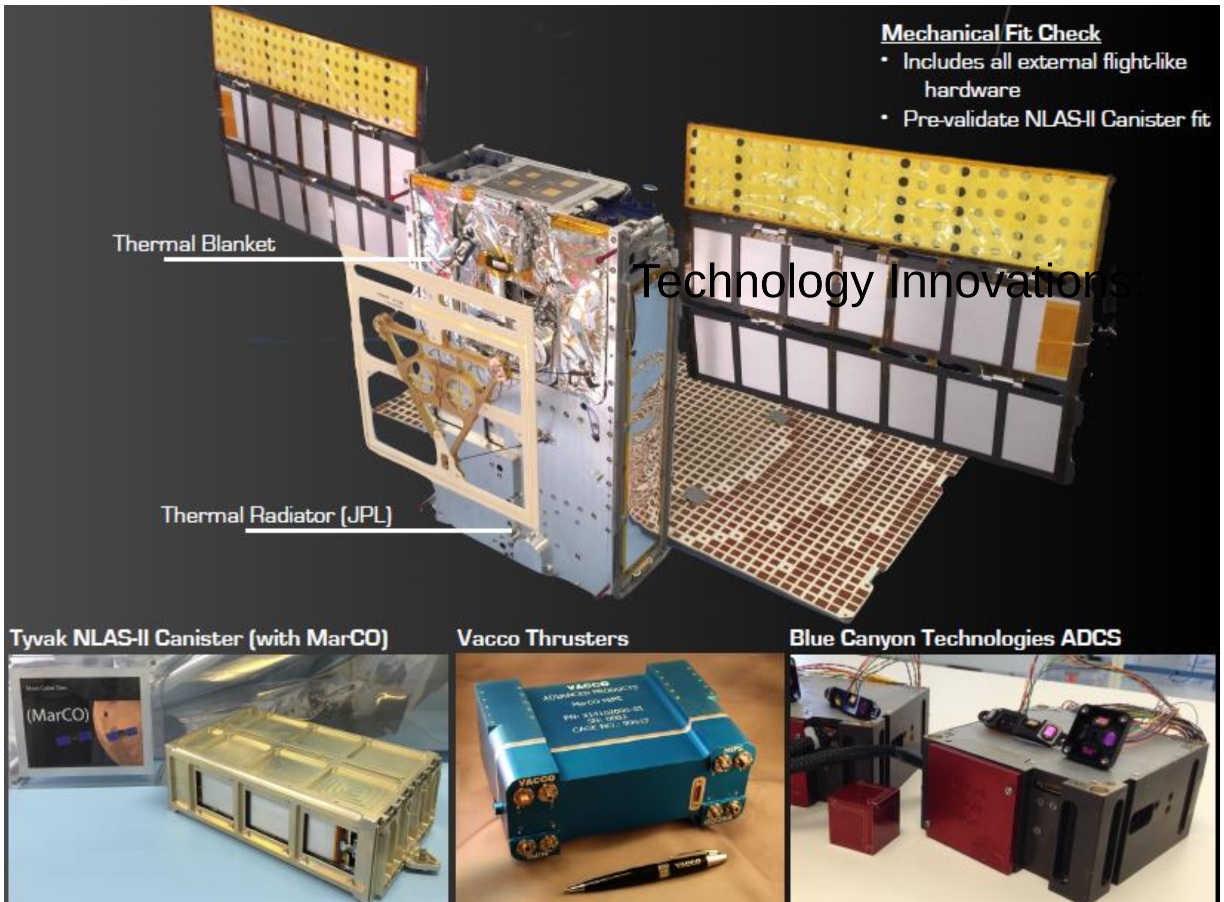
MarCO

Mars Cube One



MarCO- Mars Cube One

- JPL Mission to Observe Mars InSight Lander EDL (2018)
- 2 6U Interplanetary CubeSats- Mars Flyby



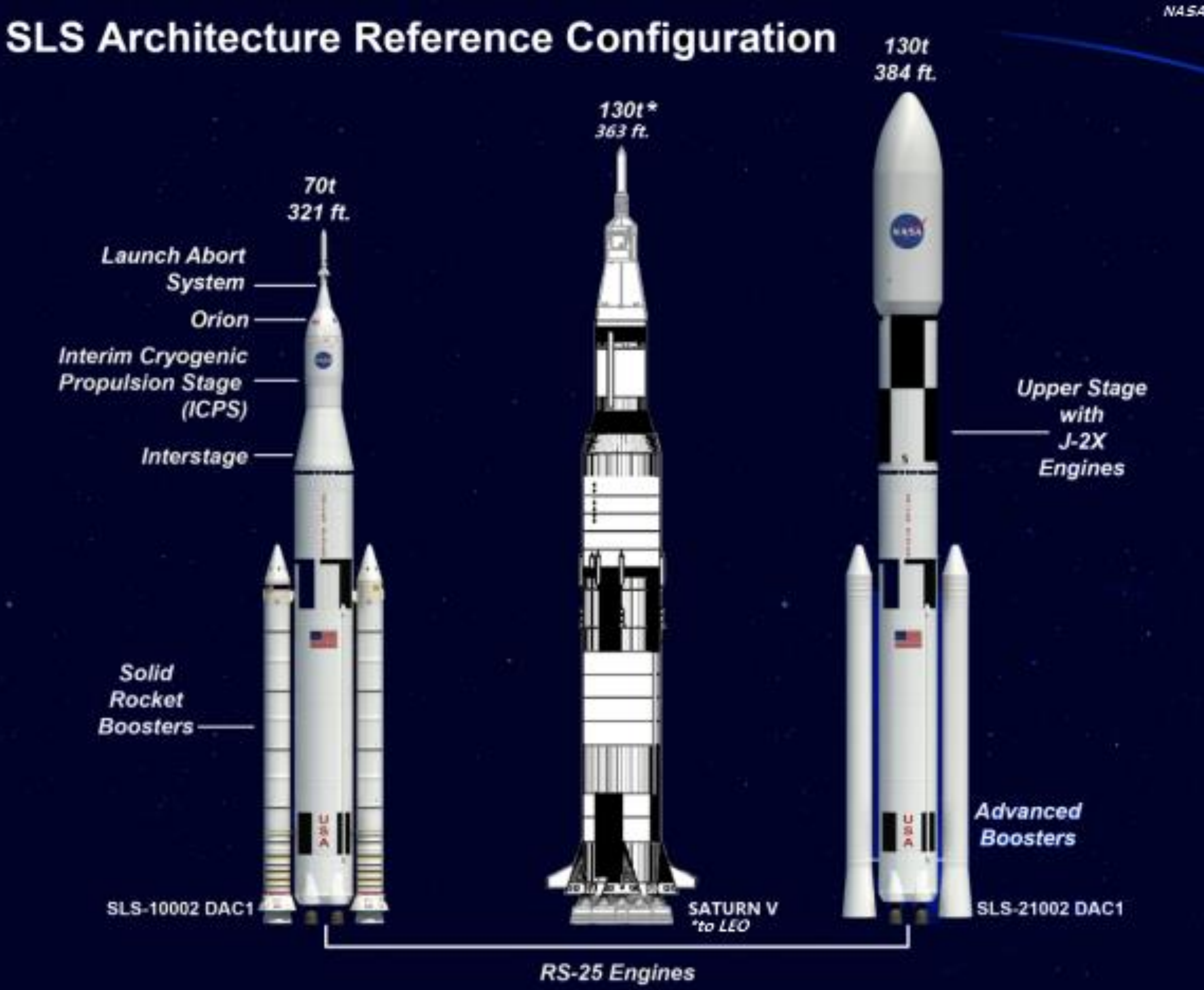
Technology Innovations:

- Deep Space Comms System
- ReflectArray Antenna
- Ranging Transponder
- ACS Thrusters
- Innovative Thermal Management
- Rad Hard Subsystems

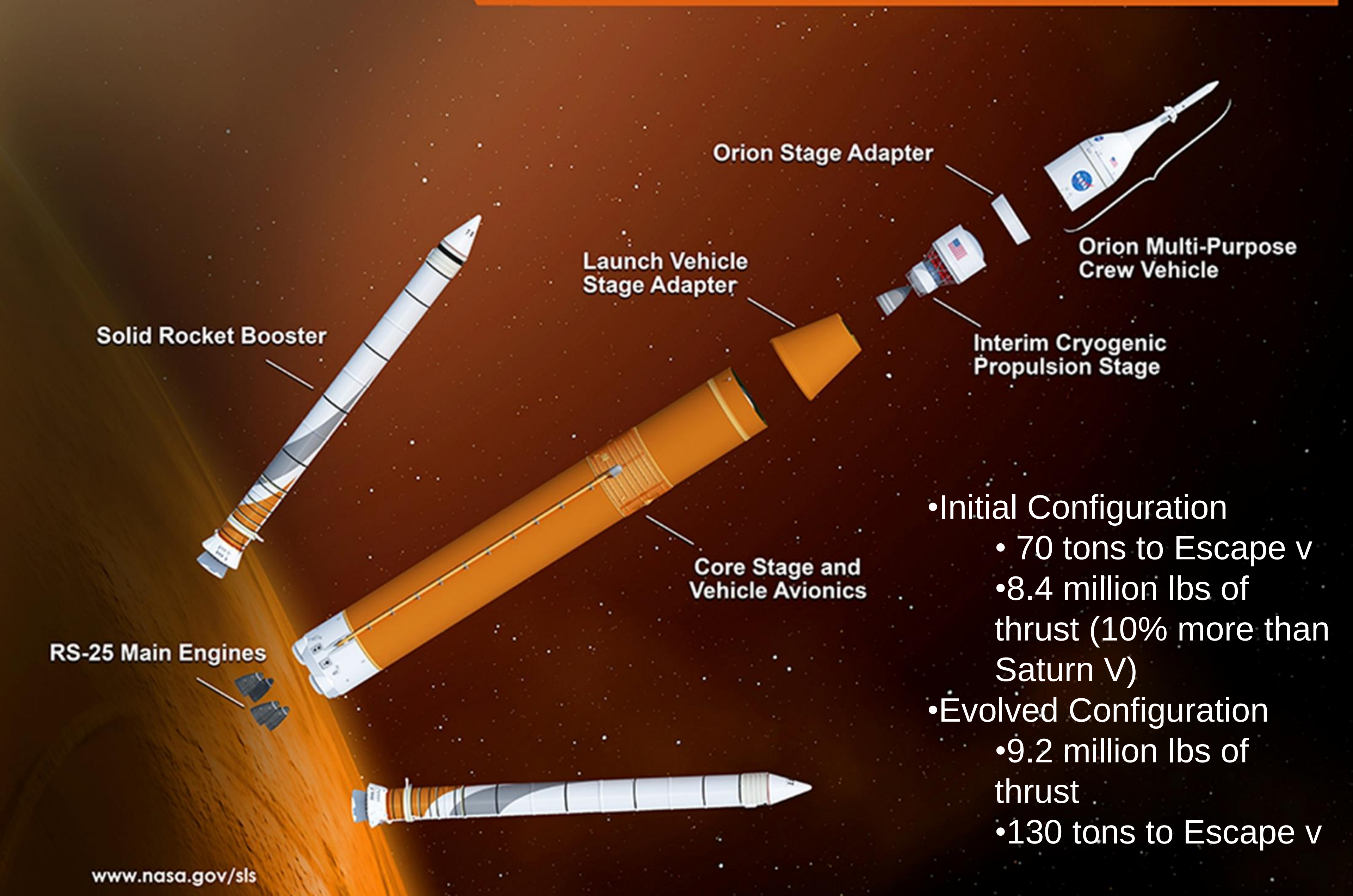
Heavy Launch Vehicle- SLS
EM-1

Space Launch System: SLS + Orion
ISS, Moon, NEAs and Beyond…
EM-1 Scheduled for 2019

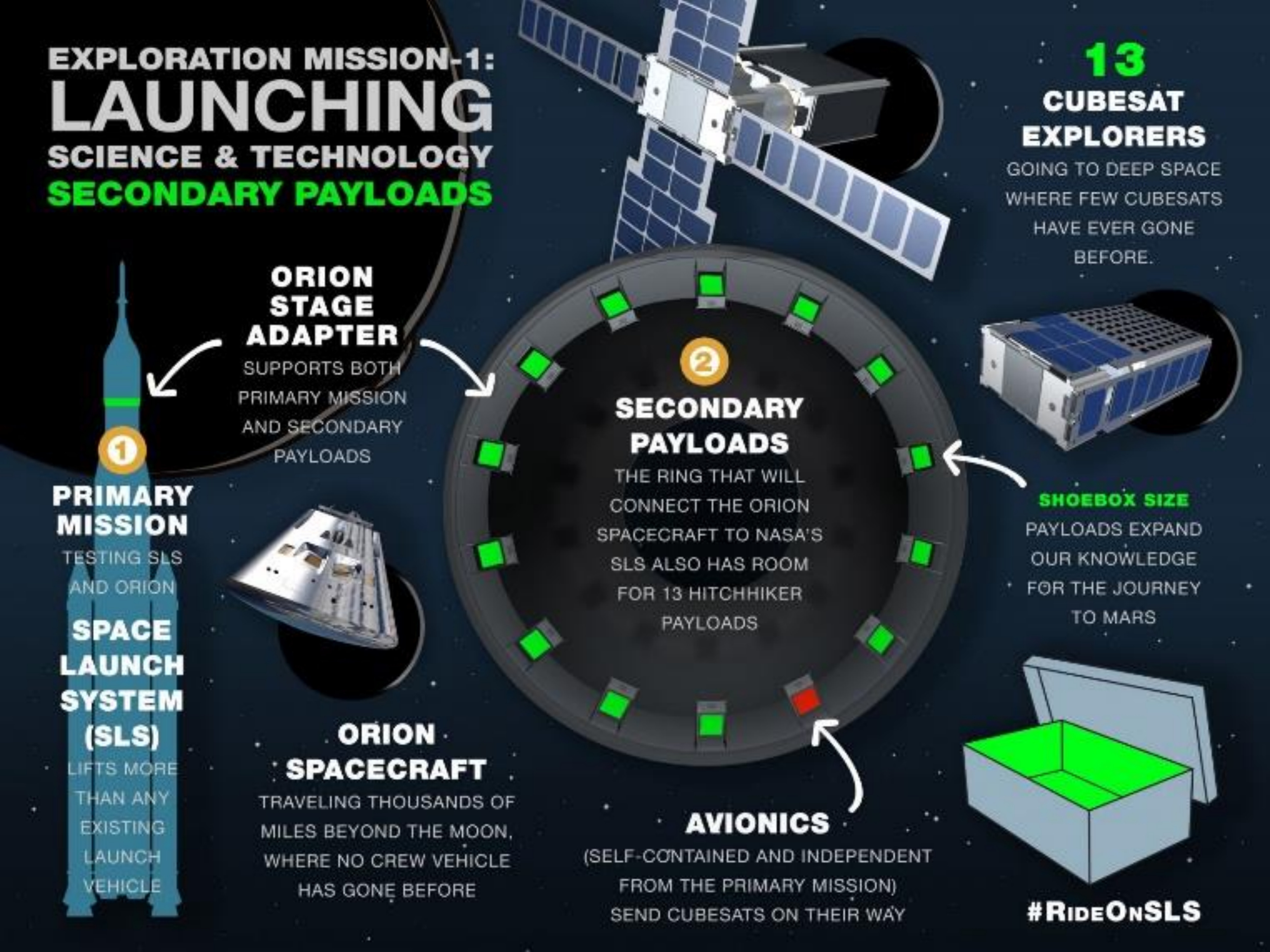
SLS Architecture Reference Configuration



Space Launch System - Block 1 Expanded View

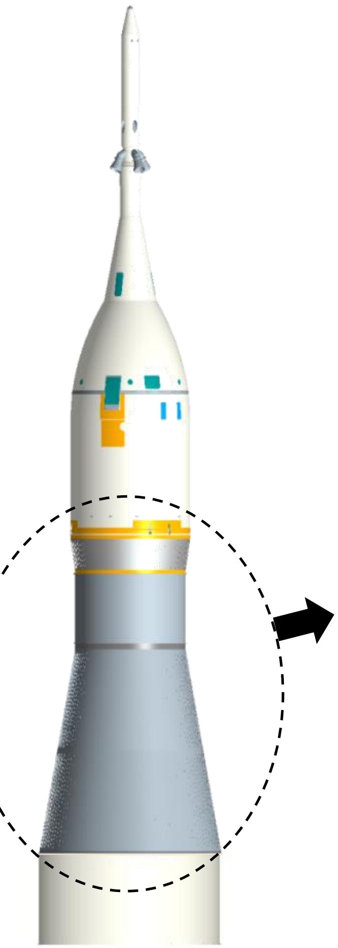


- Initial Configuration
  - 70 tons to Escape v
  - 8.4 million lbs of thrust (10% more than Saturn V)
- Evolved Configuration
  - 9.2 million lbs of thrust
  - 130 tons to Escape v

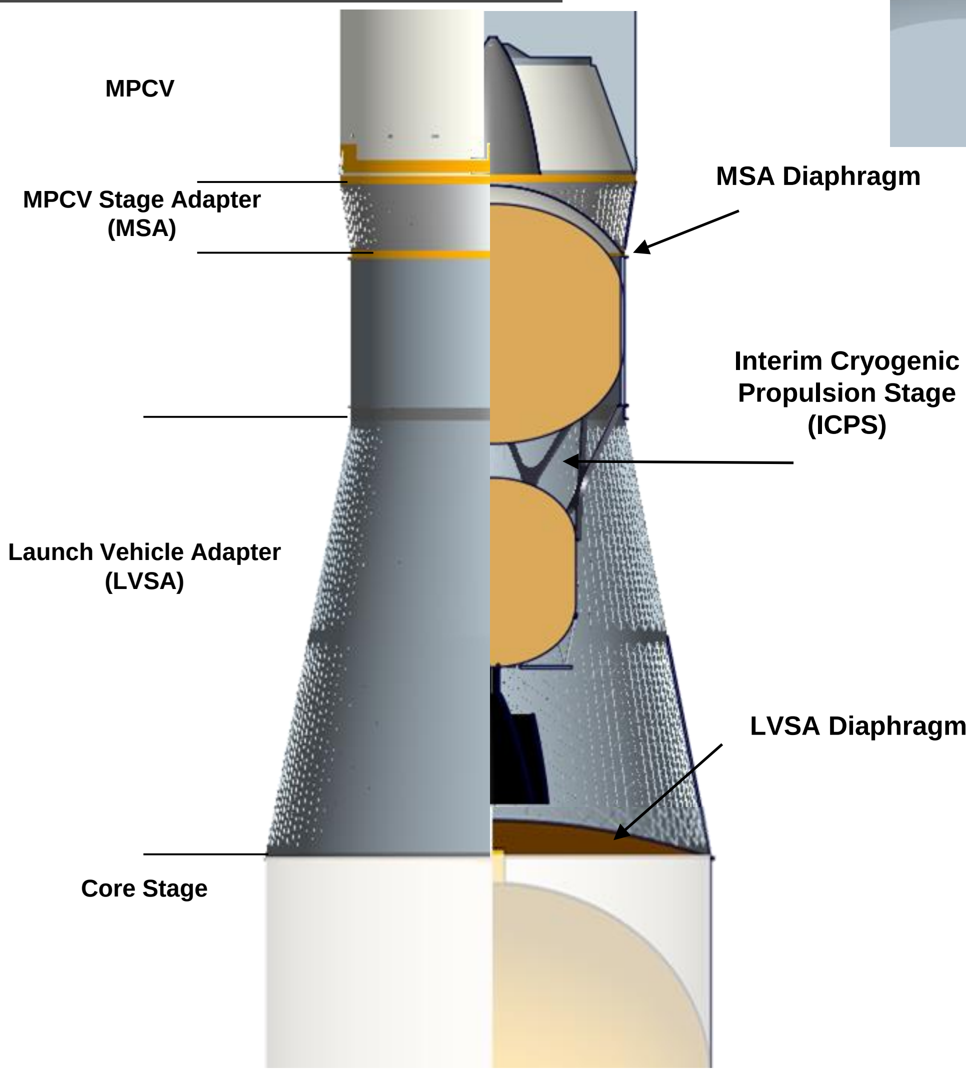

EXPLORATION MISSION-1:
LAUNCHING
SCIENCE & TECHNOLOGY
SECONDARY PAYLOADS
ORION STAGE ADAPTER
SUPPORTS BOTH PRIMARY MISSION AND SECONDARY PAYLOADS
1
PRIMARY MISSION
TESTING SLS AND ORION
SPACE LAUNCH SYSTEM (SLS)
LIFTS MORE THAN ANY EXISTING LAUNCH VEHICLE
ORION SPACECRAFT
TRAVELING THOUSANDS OF MILES BEYOND THE MOON, WHERE NO CREW VEHICLE HAS GONE BEFORE
2
SECONDARY PAYLOADS
THE RING THAT WILL CONNECT THE ORION SPACECRAFT TO NASA'S SLS ALSO HAS ROOM FOR 13 HITCHHIKER PAYLOADS
AVIONICS
(SELF-CONTAINED AND INDEPENDENT FROM THE PRIMARY MISSION) SEND CUBESATS ON THEIR WAY
13
CUBESAT EXPLORERS
GOING TO DEEP SPACE WHERE FEW CUBESATS HAVE EVER GONE BEFORE.
SHOEBOX SIZE
PAYLOADS EXPAND OUR KNOWLEDGE FOR THE JOURNEY TO MARS
#RideOnSLS

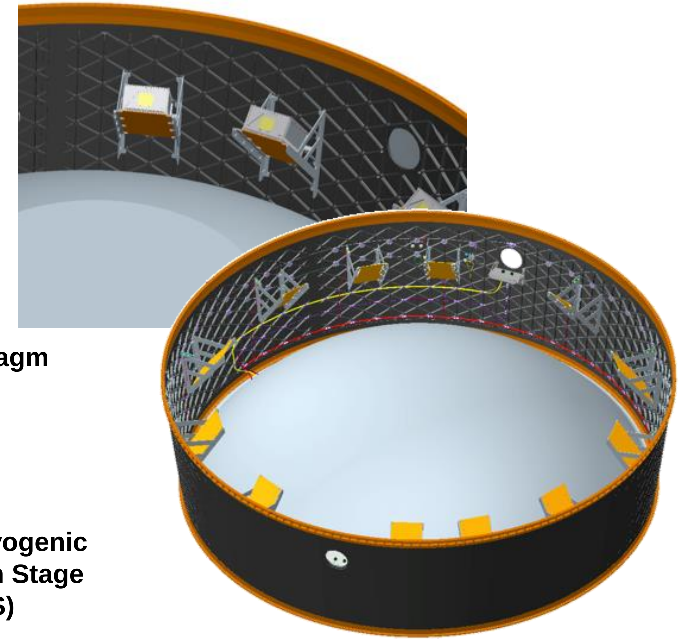
13 SmallSat Secondary Payloads on EM-1

Multi Purpose Crew Vehicle Stage Adapter (MSA)



Block 10001





EM-1 Missions

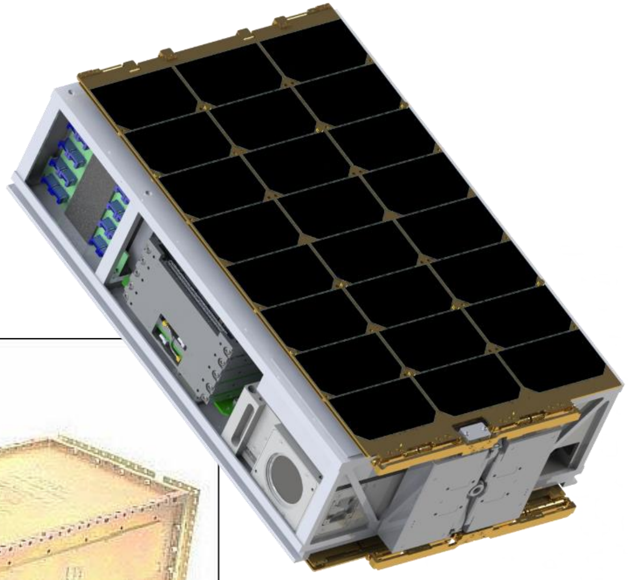
Program	Mission	Payload	Lead
HEOMD AES	Lunar Flashlight	NIR instrument Water Ice in PSRs	NASA JPL
HEOMD AES	Near Earth Asteroid Scout	Imager to characterize asteroid dynamics and surface	NASA MSFC
HEOMD AES	BioSentinel	Radiation Exposure Induced Genetic Damage Experiment	NASA Ames
SMD	CUSP	Heliophysics Experiments	SWRI
HEOMD AES	Lunar IceCube	Broadband IR cryocooled Transport Physics of Water Ice	Morehead State and Partners
SMD	LunaH- Map	Neutron Spectrometer Location and Distribution of H	Arizona State and JPL
NEXT STEP	SkyFire	Test Innovative IR Spectrometer	Lockheed-Martin
STMD	Centennial Challenge Winners	TBD- 3 Winners	TBD
EM-1	Argo-Moon	Camera	Italian Space Agency
EM-1	Omontanashi Equuleus	Various	JAXA

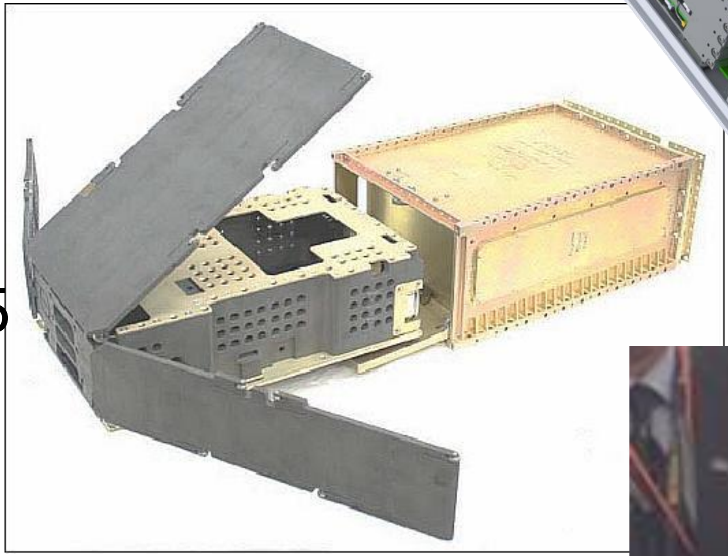
NASA Video

https://www.youtube.com/watch?v=OZvDAAI_JM0&feature=youtube

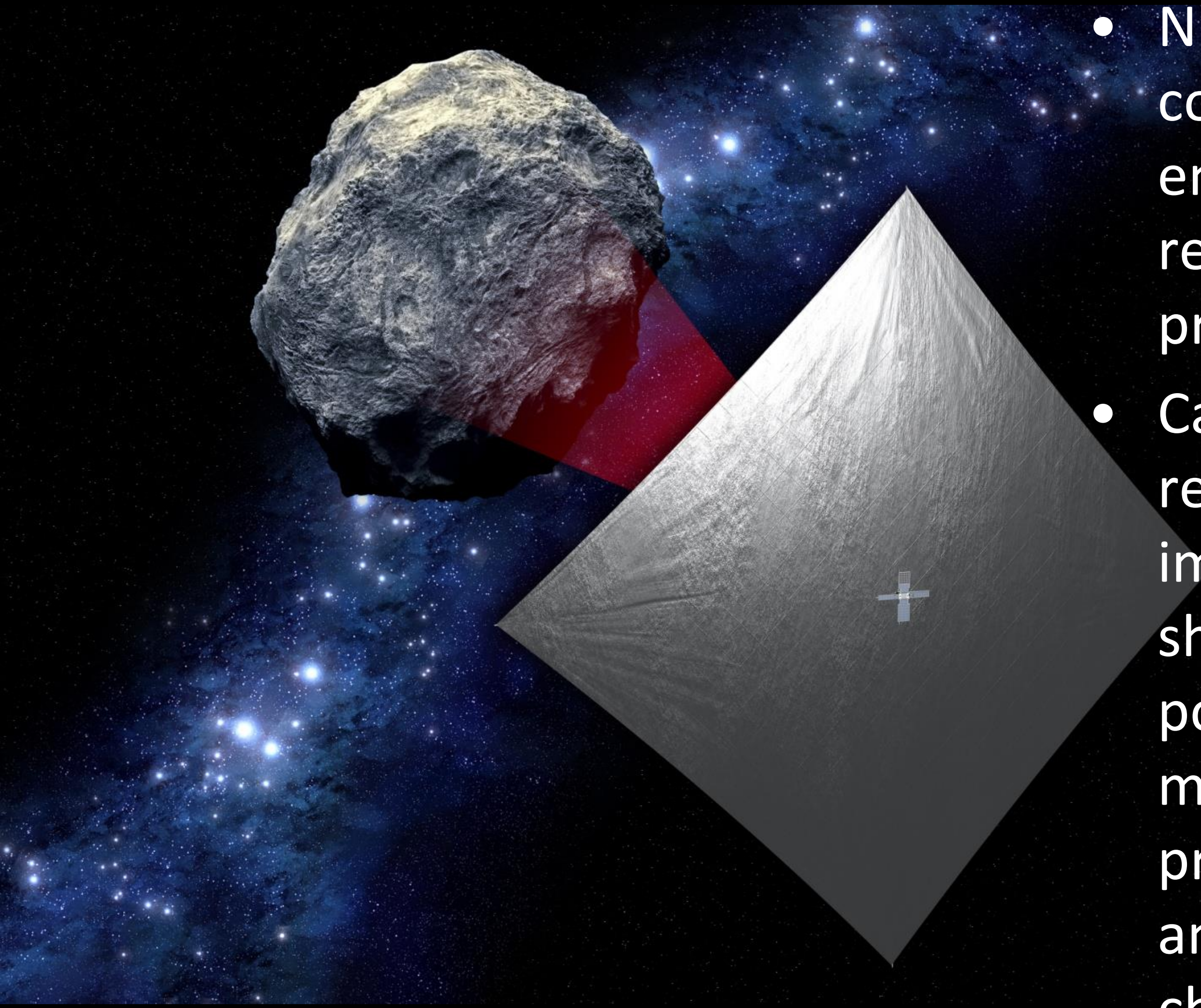
All EM-1 Missions are 6U Interplanetary CubeSats

- Small Satellites for Space Research
- Based on 10 x 10 x 10 cm units
- EM-1 Cubes are 6U
- 14 kg
- 113 mm x 239 m x 365 mm
- Canisterized PSC Deployer
- Pushing the Envelope for Tech that can Fit in a 6U



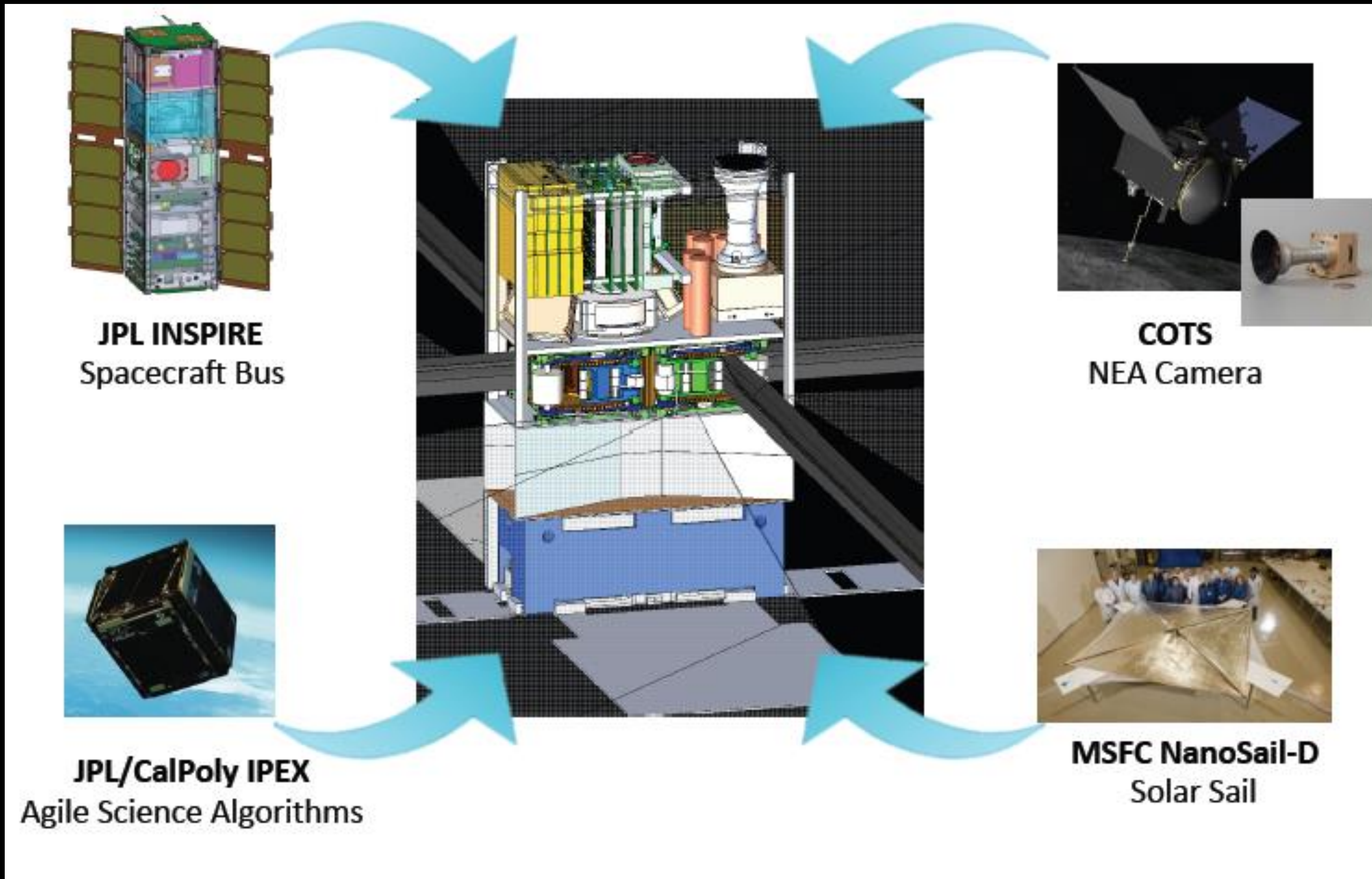


NEA Scout

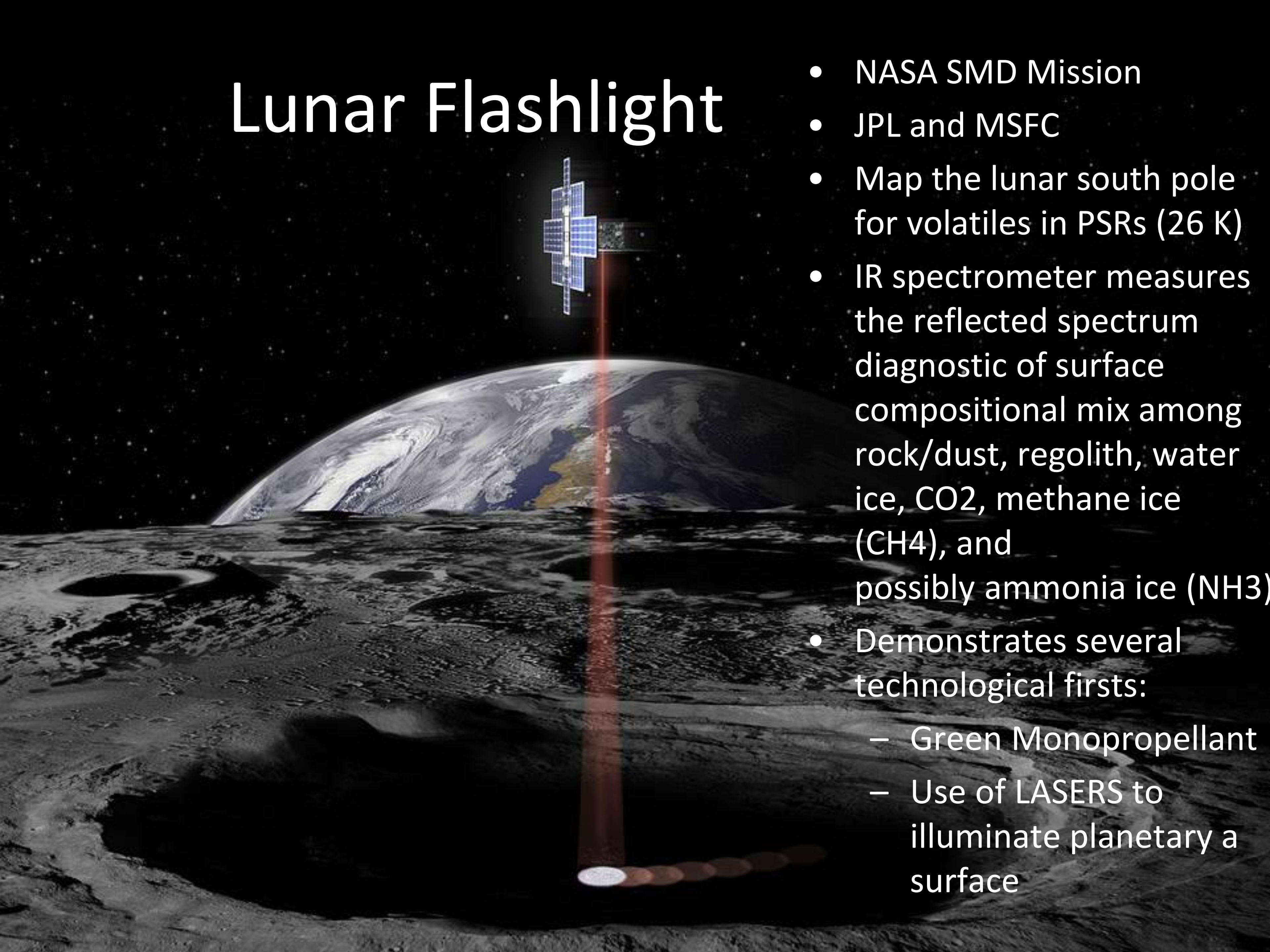


- NASA SMD Mission
- NASA MSFC and JPL
- Flyby of Asteroid 1991VG
- NEA orbit, rotation, composition, particulate environment, volatile resources, and soil properties
- Capture a series of high resolution (10 cm/pixels) images to determine global shape, spin rate, pole position, regional morphology, regolith properties, spectral class, and for local environment characterization

NEA Scout Heritage and Technology Infusion



Lunar Flashlight



- NASA SMD Mission
- JPL and MSFC
- Map the lunar south pole for volatiles in PSRs (26 K)
- IR spectrometer measures the reflected spectrum diagnostic of surface compositional mix among rock/dust, regolith, water ice, CO2, methane ice (CH4), and
  possibly ammonia ice (NH3)
- Demonstrates several technological firsts:
  - Green Monopropellant
  - Use of LASERS to illuminate planetary a surface

Payload design for the Lunar Flashlight mission:
Illuminating the Moon's South Pole

Barbara A. Cohen (NASA Goddard Space Flight Center; barbara.a.cohen@nasa.gov)

Paul Hayne, Jose Camacho, Chris Paine, Glenn Sellar, Quentin Vinckier (Jet Propulsion Laboratory); Ben Greenhagen (JHU Applied Physics Laboratory), David Paige (UCLA), Karlton Crabtree (Photon Engineering)

Water at the Lunar Poles?

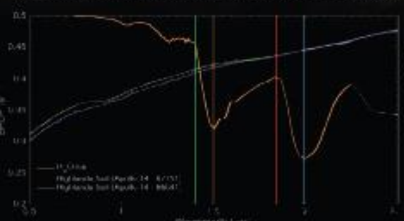
Recent reflectance data from LRO instruments suggest water ice and other volatiles may be present on the surface in lunar permanently shadowed regions, though the detection is not yet definitive [*Gladstone et al. 2012, Zuber et al. 2012, Hayne et al. 2015*]. Understanding the composition, quantity, distribution, and form of water and other volatiles associated with lunar permanently shadowed regions (PSRs) is identified as a NASA Strategic Knowledge Gap (SKG) for Human Exploration. These polar volatile deposits are also scientifically interesting, having the potential to reveal important information about the delivery of water to the Earth-Moon system.

The Lunar Flashlight Mission

The Lunar Flashlight (LF) mission is a 6U CubeSat, to be launched as a secondary payload on the first test flight (EM-1) of the Space Launch System (SLS), currently scheduled for 2018. **The goal of LF is to determine the presence or absence of exposed water ice and map its concentration at the 1-2 kilometer scale.** After being ejected in cislunar space by SLS, Lunar Flashlight maneuvers into a low-energy polar orbit with a perilune of 10-30 km above the lunar south pole.

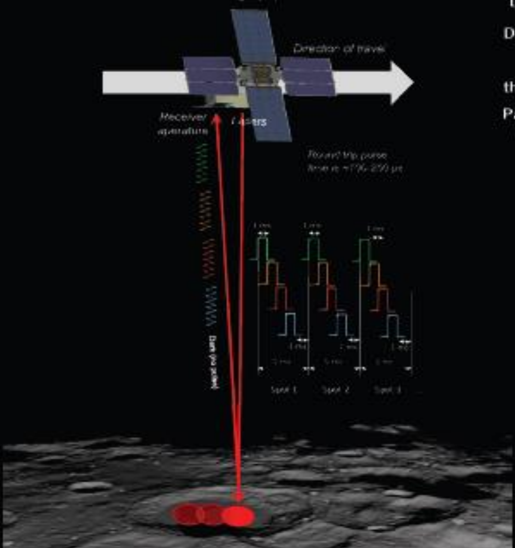
Measurement Approach

Lunar Flashlight's four-channel laser projector will illuminate permanently shadowed regions, measuring surface reflectance at wavelengths where water ice absorbs. Water ice will be distinguished from dry regolith in two ways: 1) spatial variations in albedo, and 2) reflectance ratios between absorption and continuum channels. Water ice band depths will be mapped in order to distinguish the composition of the PSRs from that of the sunlit terrain. These data will be highly complementary to other lunar datasets, including LRO.



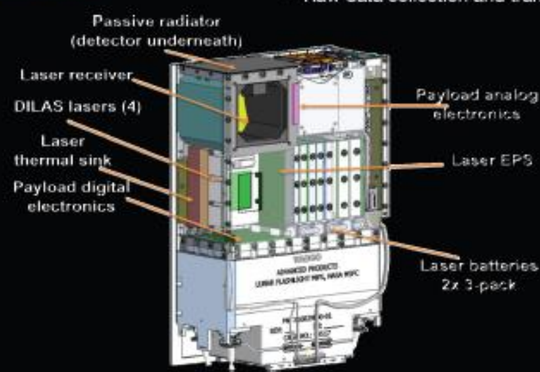
DILAS lasers
Continuum (COTS):
- 1.064 (-0.060 / + 0.230) µm
- 1.850 (-0.030 / +0.020) µm

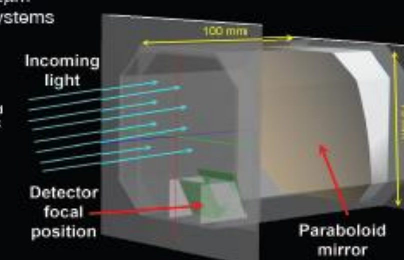
Absorption bands (custom):
- 1.495 (-0.015 / +0.015) µm
- 1.990 (-0.020 / +0.025) µm



The Lunar Flashlight Payload

Lunar Flashlight will be the first planetary mission to use an active multi-band reflectometer
- Observe permanently shadowed and eclipsed ground within 80°S
- 1ms time pulsing of 4 lasers, plus one dark ms
- Independent laser power subsystem and power monitoring
- 1-single pixel detector reflectometer sensitive over 1-2µm
- Raw data collection and transfer from SC to ground systems

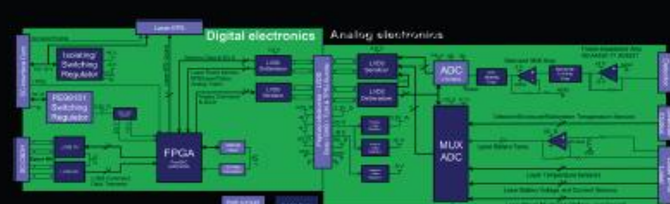




Receiver:
- Field-of-view: 14 mrad
- Volume 88.9 x 99.06 x 88.9 mm
- Passively cooled by external radiator

Detector
- 1mm diameter Teledyne Judson InGaAs detector
- 2.2µm cutoff
- 1.1A/W responsivity
- Detector operational T: 208 K

Mirror Surface:
- AR-coated aluminum bare mirror for 1- 2 µm
- Radius of curvature: 140mm
- Conic constant: -1
- Figure 2λ @ 632.8 nm
- RMS roughness: <30Å

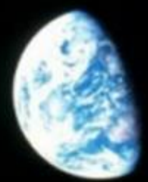


Lunar Flashlight ConOps

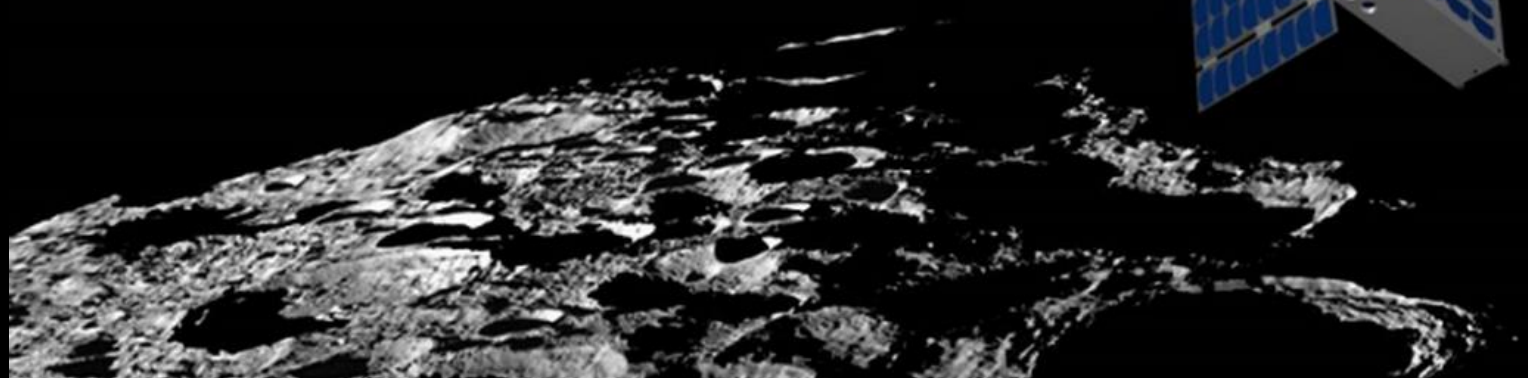
LunaH Map

LunaH-Map is a 6U CubeSat that will enter a polar orbit around the Moon with a low altitude (5-12km) perilune centered on the lunar South Pole.

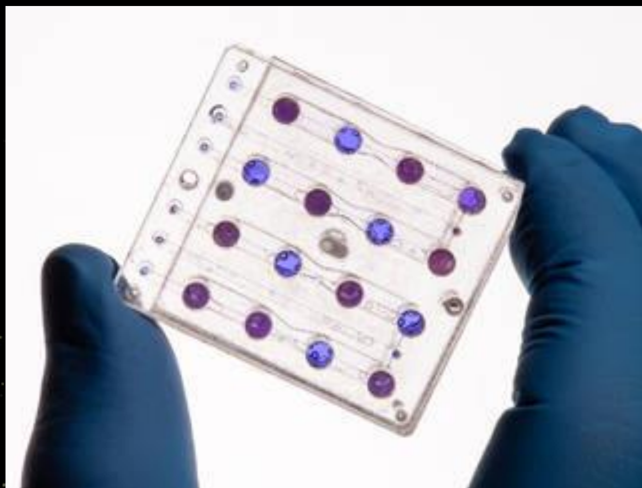
- Carries two neutron spectrometers that will produce maps of near-surface hydrogen (H)
- Maps H within permanently shadowed craters to determine its spatial distribution,
- Maps H distributions with depth (< 1 meter)
- Maps the distribution of H in (PSRs) throughout the South Polar Region
- Tech Infusion: EP, Miniaturized Neutron Spectrometers

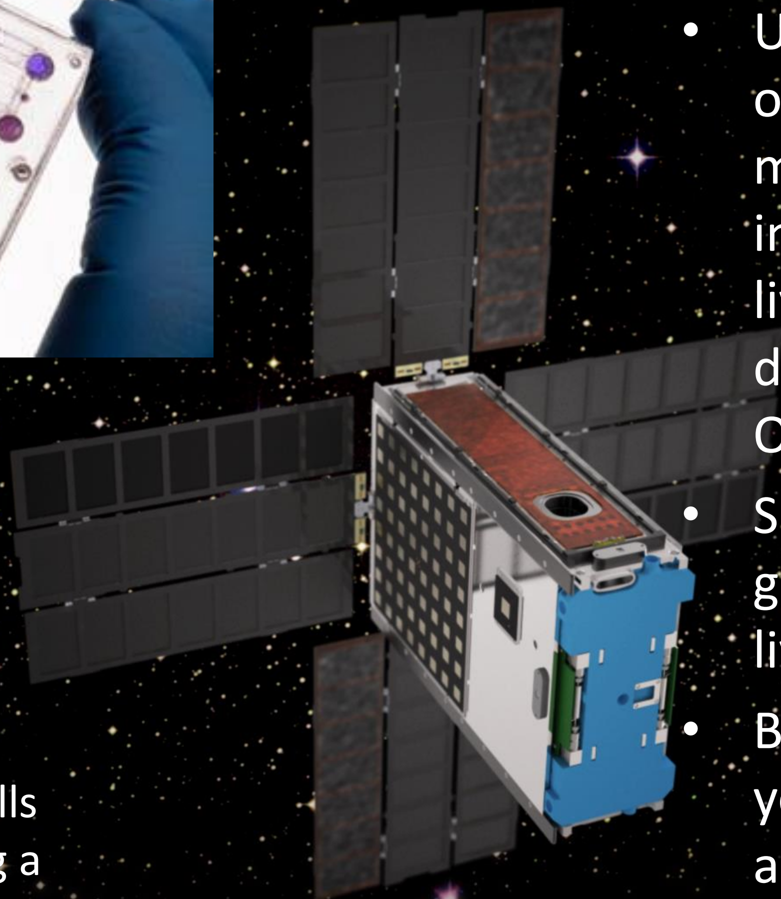


Arizona State University and Partners



Biosentinel

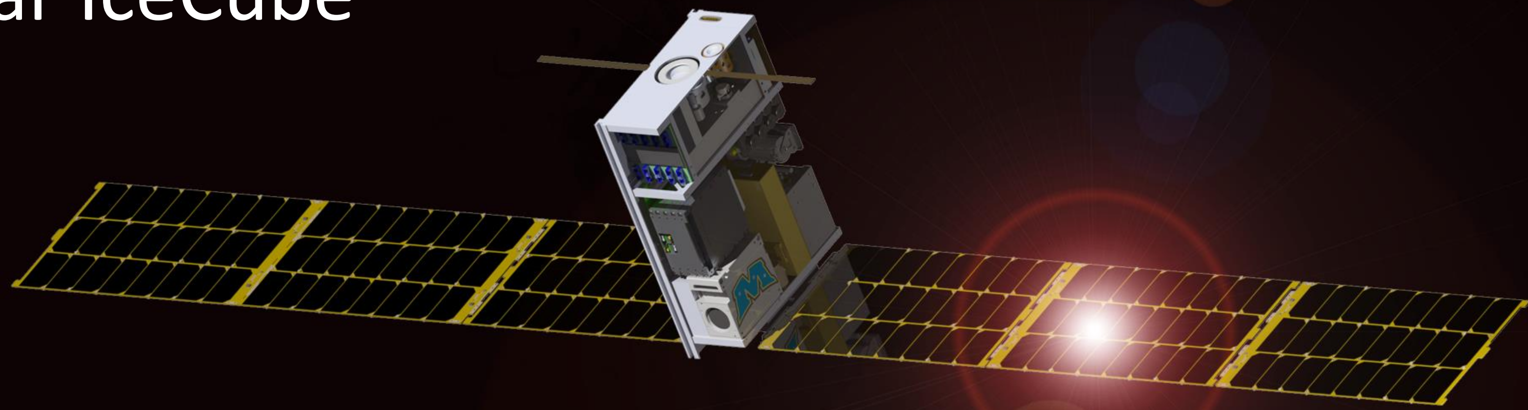




- NASA SMD Mission
- NASA Ames
- Biology above LEO
- Uses a simple model organism to detect, measure, and correlate the impact of space radiation to living organisms over long durations beyond Low Earth Orbit
- Separates the effects of gravity and radiation on living systems
- Biosensor uses the budding yeast S. cerevisiae to detect and measure double strand breaks (DSBs) that occur in response to ambient space radiation

Growth and metabolic activity of the yeast cells will be measured using a 3-color LED detection system and the metabolic indicator dye alamarBlue

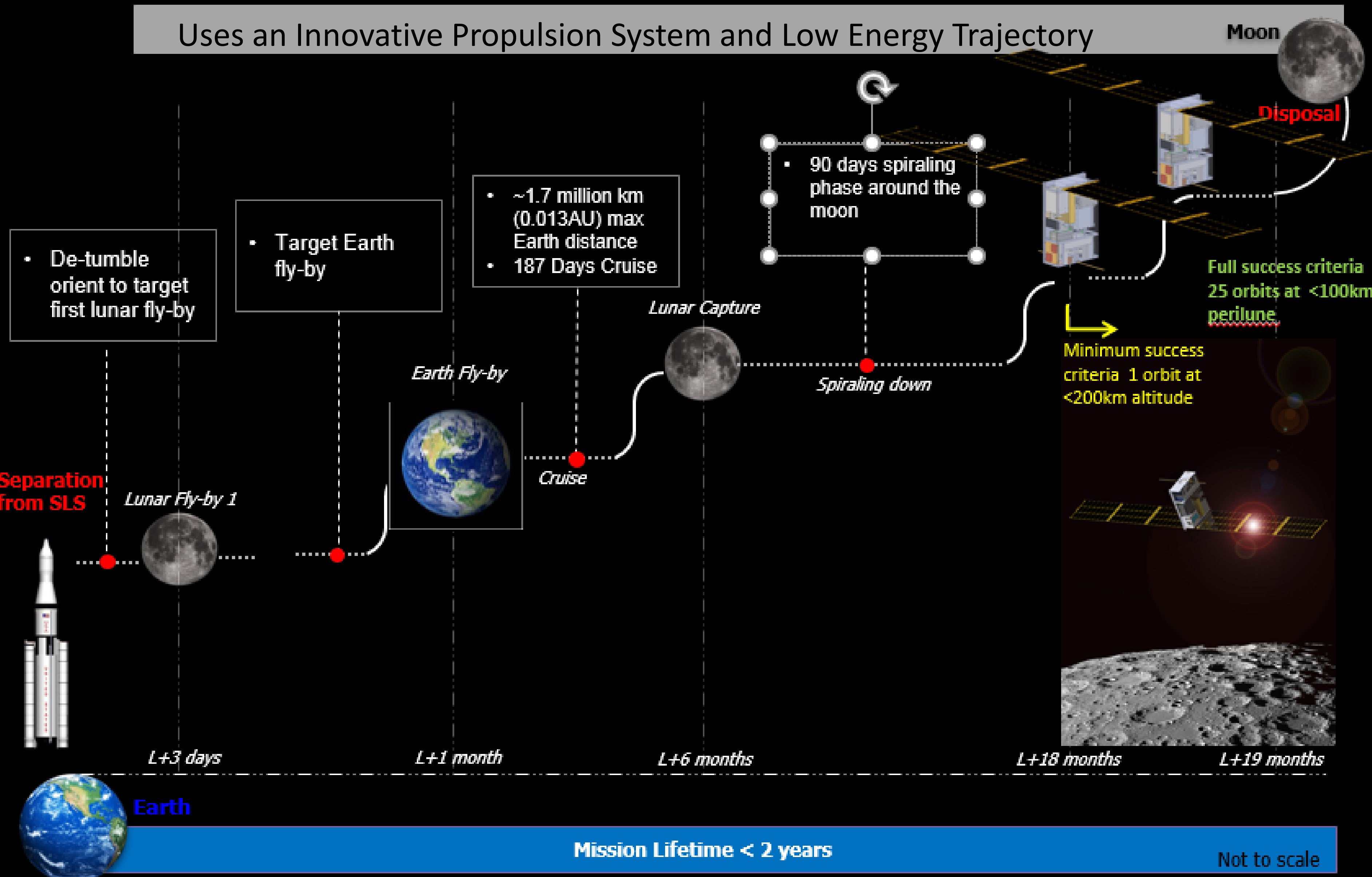
Lunar IceCube



Goal is to Investigate the Location, Abundance and Transport Physics of Water Ice from a highly inclined orbit with 100 km perilune

- Morehead State
- NASA GSFC
- JPL
- Busek

Lunar IceCube ConOps



SmallSat Propulsion Systems

New, Innovative Systems in Development including:

- Cold Gas Propulsion Systems (NEA Scout)
- Green Monopropellant (Lunar Flashlight)
- Solar Sails (NEA Scout)
- Solar Electric Propulsion
  - RF Ion Engines (Lunar IceCube, LunaH Map)
  - Pulsed Plasma Thrusters

Represents a significant challenge for small spacecraft…

SmallSat Propulsion Systems

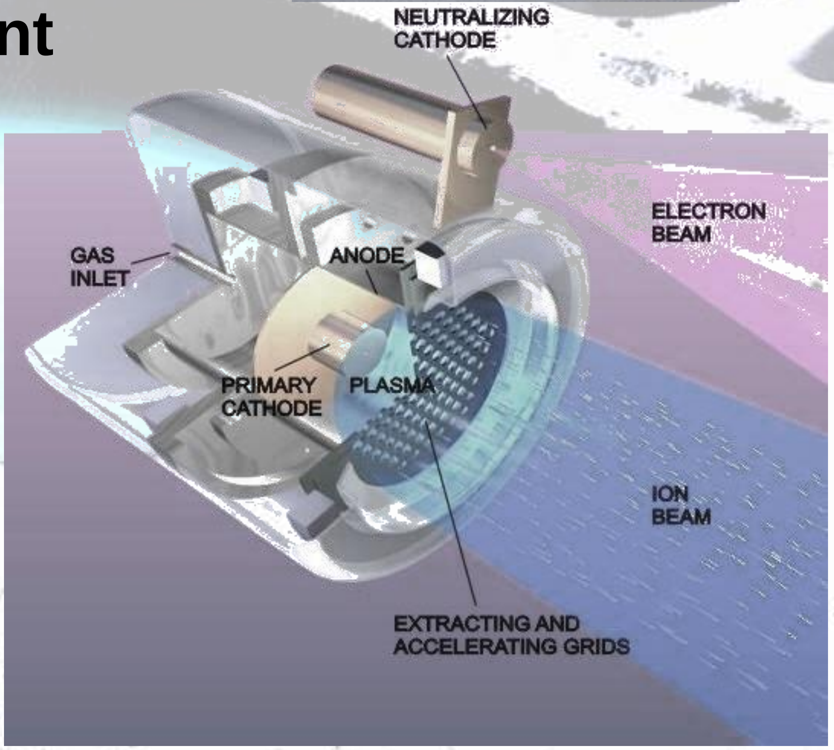
Represents a significant challenge for small spacecraft…
Lunar IceCube Example

Lunar Trajectories Require Significant ΔV

• LEO to GEO	3.95 kms^{-1} (no plane change)
• LEO to GEO	4.2 kms^{-1} (plane change - 28 deg)
• LEO to Lunar Orbit	5.9 kms^{-1}
• GEO to Lunar Orbit	3.9 kms^{-1}
• Earth Escape to Lunar	2.8 kms^{-1}

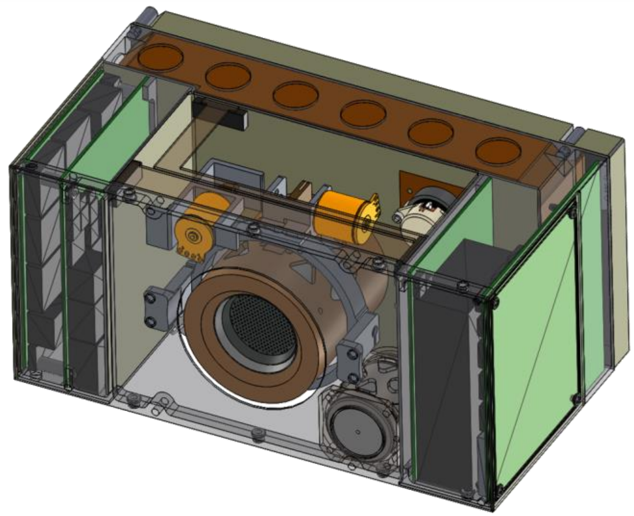
Lunar IceCube Propulsion System

- Innovative RF Ion Engine
- Electric Propulsion
- Busek Company
- Solid-State Iodine Propellant



Subsystems Accomplishments - Busek BIT-3 cm RF Ion Engine

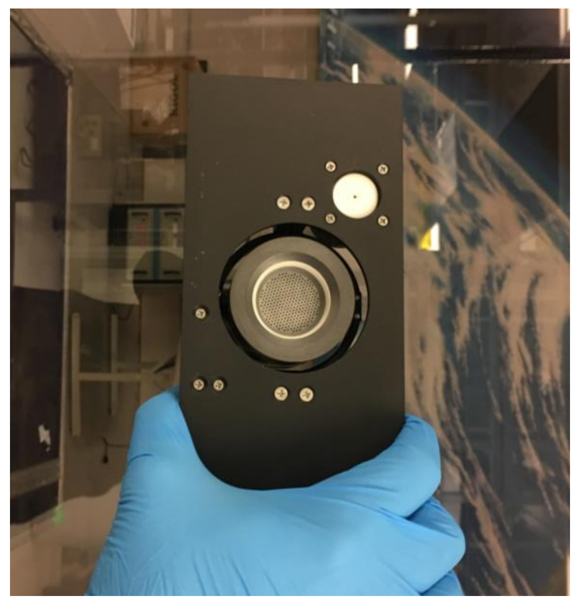
- Radiation Tolerant PPU Design and Engineering Model Complete
- Mini-RF Cathode Operational
- Test Fired with Xenon and with Iodine
- Propellant Filling Test Successful with new Hasteloy Metal Tank
- Projected Performance on Lunar IceCube:
  - ✓ ISP: 1906 sec
  - ✓ Thrust: > 0.8 mN



Lunar IceCube BIT-3 Final Design

RF cathode operating together with the BIT-3 thruster, both on xenon propellant

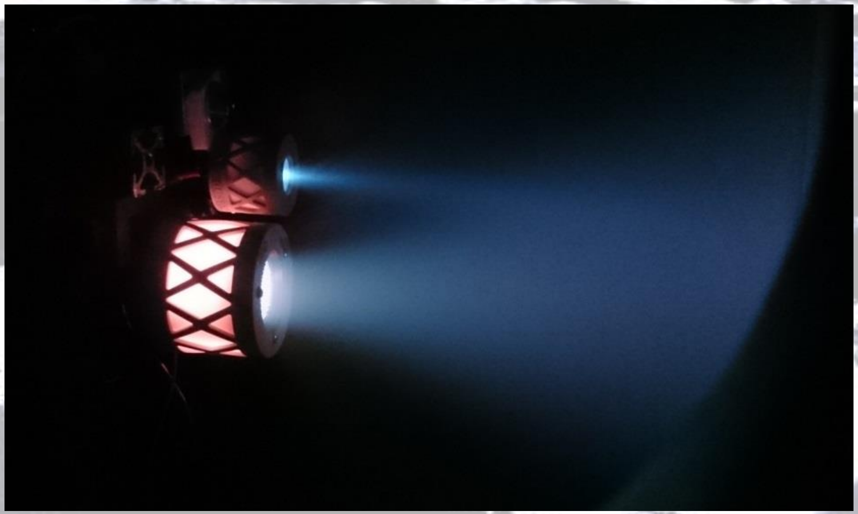
BIT-3 Firing with Iodine propellant at 58W



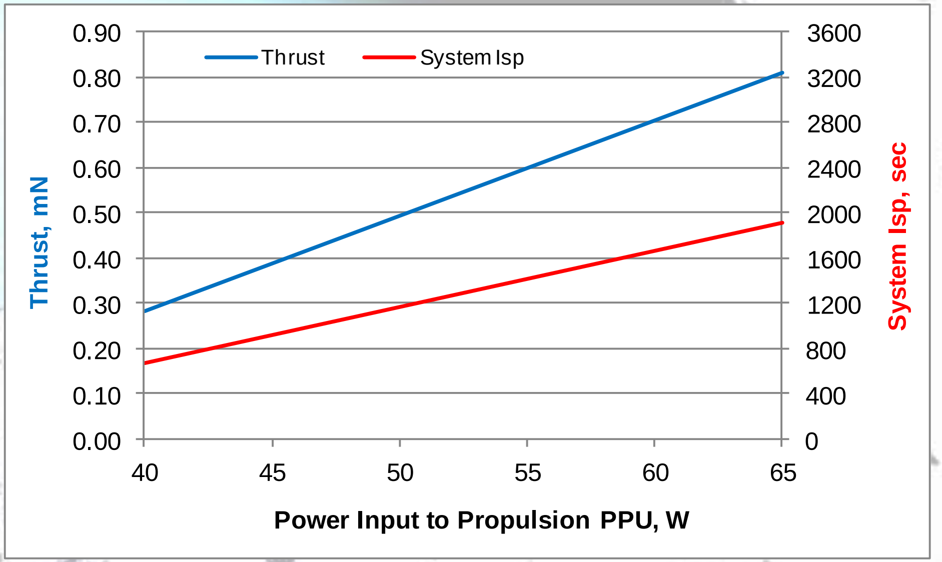
Engineering Model of Lunar IceCube BIT-3 Thruster

BIT-3 System: Thruster vs. Power

- IceCube can allocate maximum 65W to propulsion, so BIT-3 is de-scale to a 2.5cm thruster
  - –**Isp will be ~2,000sec** (including neutralizer flow)
  - –**Thrust will be ~0.8mN**, est.
  - –With 1.5kg iodine mass, the propulsion system can provide **>** **1.2 km/s** **deltaV** capability to a 14kg spacecraft

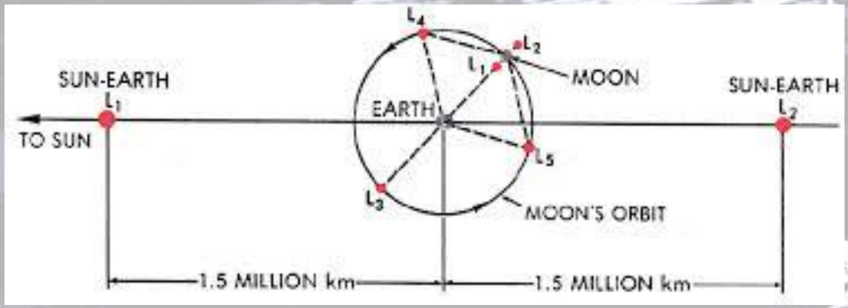


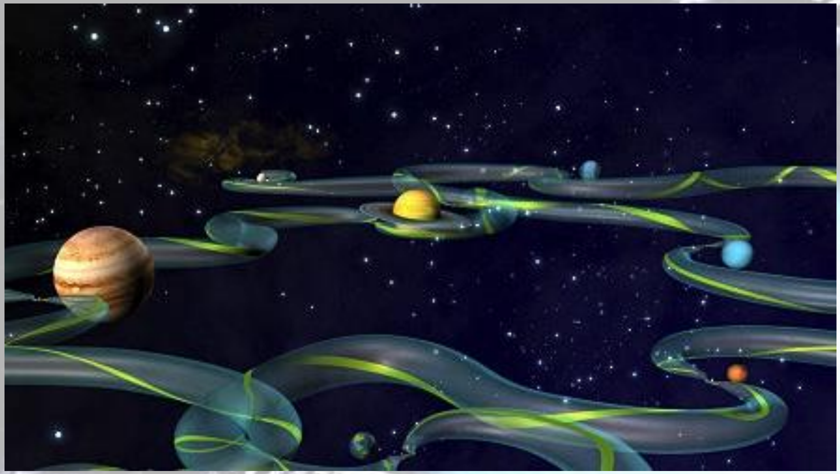
BIT-3 Thruster Firing at the Busek Facilities



Estimated Performance of a New, Scaled-Down Iodine BIT-3 Thruster; Isp Includes Neutralizer Flow

Interplanetary Superhighway (IPS)

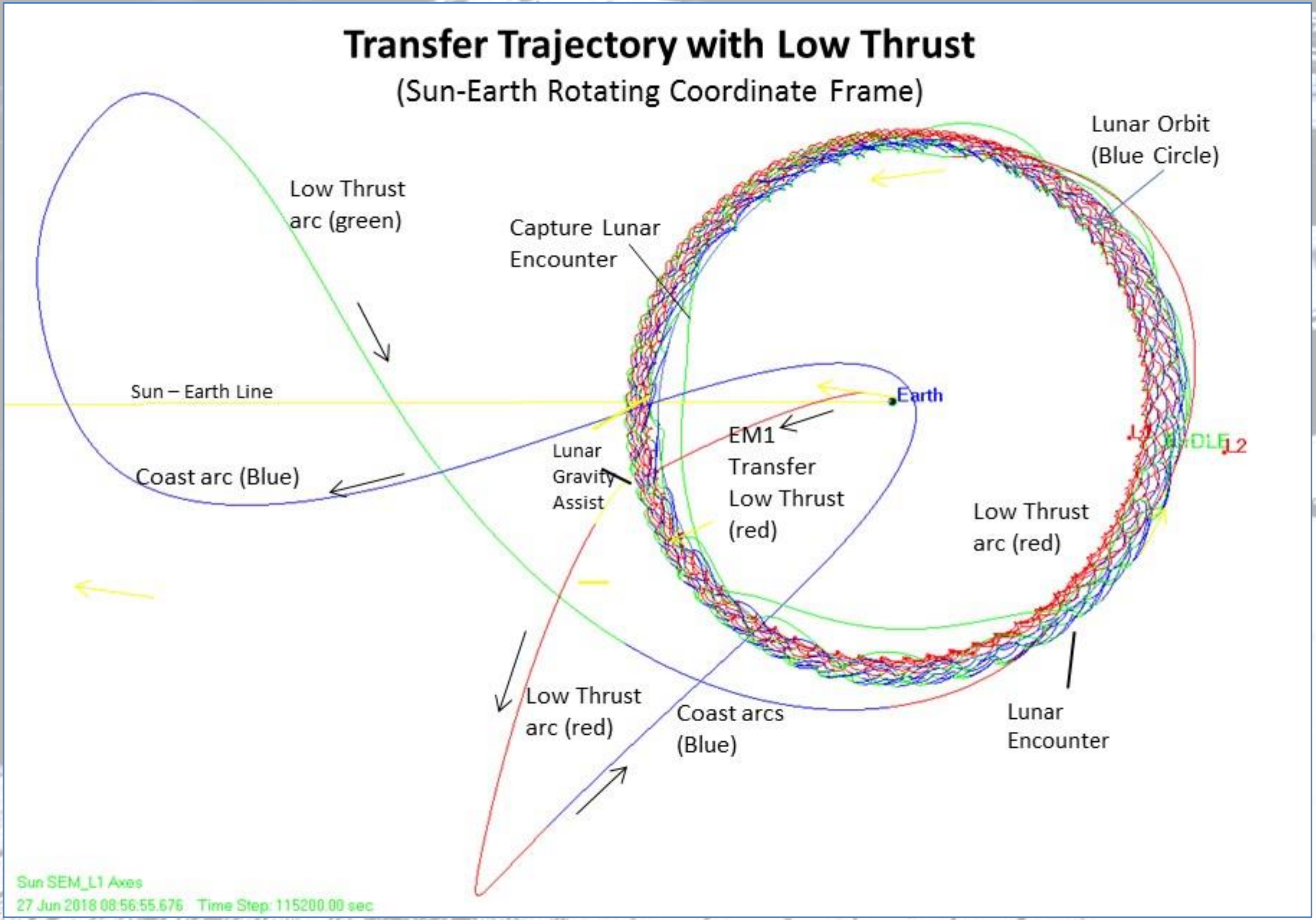




Developed by M. Lo and S. Ross at JPL, the IPS uses low energy manifold trajectories based on stable and unstable manifolds and ballistic capture. Manifolds are created by Lagrange points through n-body effects and can now be modeled for realistic interplanetary trajectories

Interplanetary Superhighway Makes Space Travel Simpler // NASA 07.17.02: "Lo conceived the theory of the Interplanetary Superhighway. Lo and his colleagues have turned the underlying mathematics of the Interplanetary Superhighway into a tool for mission design called "LTool," ... The new LTool was used by JPL engineers to redesign the flight path for the Genesis mission"

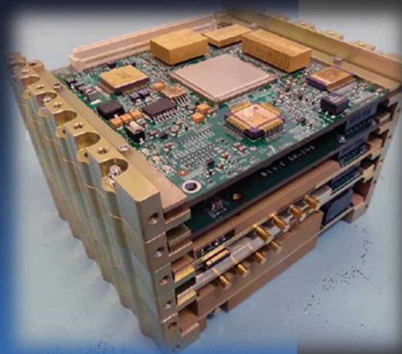
Lunar IceCube's Low Energy Trajectory

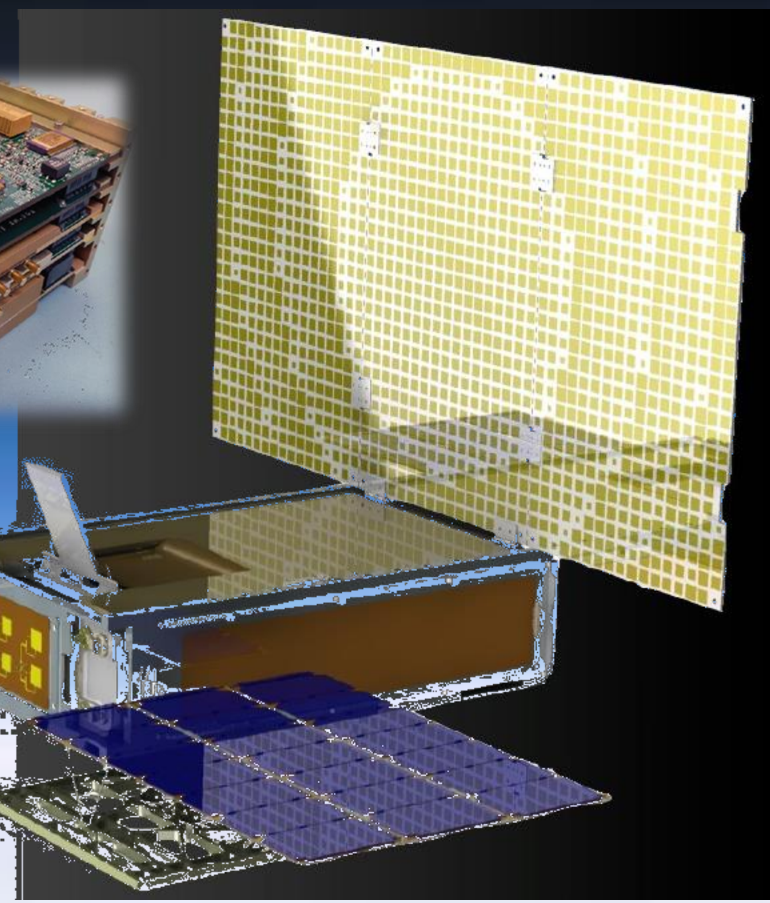


IceCube utilizes a minimal DV transfer trajectory harnessing expertise of GSFC flight dynamics.

Communications and Ranging Systems

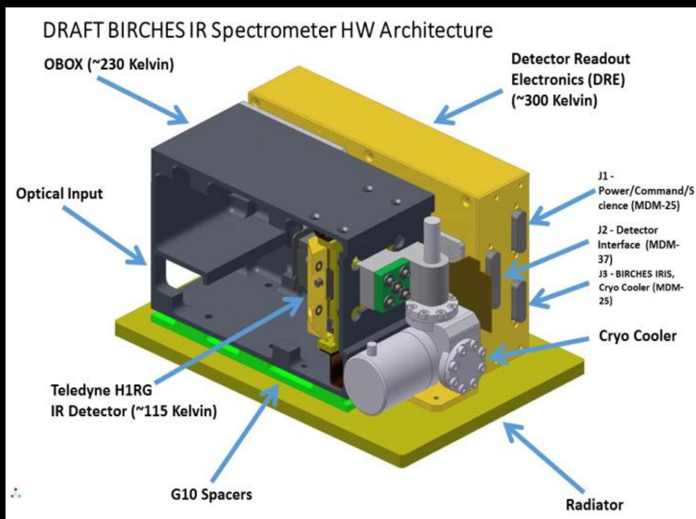
- JPL Iris X-Band Deep Space CubeSat Transponder- *Lunar IceCube uses Iris v 2.1*
- Increasingly Sophisticated SDRs
- ReflectArray Antennas
- Inflatable Antennas
- Deployable High Gain Reflectors





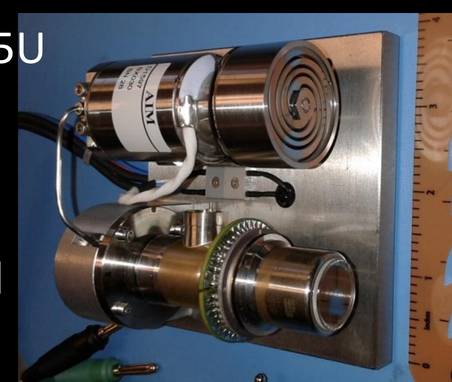
Miniaturized Science Instruments

- Neutron Spectrometer- LunaH Map
- JPL IR Imager- NEA Scout
- Miniaturized Cryocoolers



BIRCHES IR Spectrometer- Lunar IceCube

- High-resolution point spectrometer with microcryocooler, 1.5U in <2.5 kg, <5 W
- Detector Cooled to ≤ 120K to provide long wavelength coverage
- Mercury Cadmium Telluride (HgCdTe) two-dimensional focal point array (FPA)
- 1024 x 1024 pixels giving Resolution (10 nm@ 3 microns)



Radiation Hardened/Tolerant Systems

TID and SEUs (from Solar Events and Cosmic Rays) occur at significantly higher levels beyond the Earth's Magnetic Field

Lunar IceCube Requirements:
Parts shall meet Linear Energy Transfer Threshold (LETth) of > 37 MeV-cm2/mg for soft errors from single events (SEU, Single Event Transients, etc).

Parts shall meet 10 krads (Si) Total Ionizing Dose (TID) assuming 50 mil Al shielding.

Amelioration Methods Include:

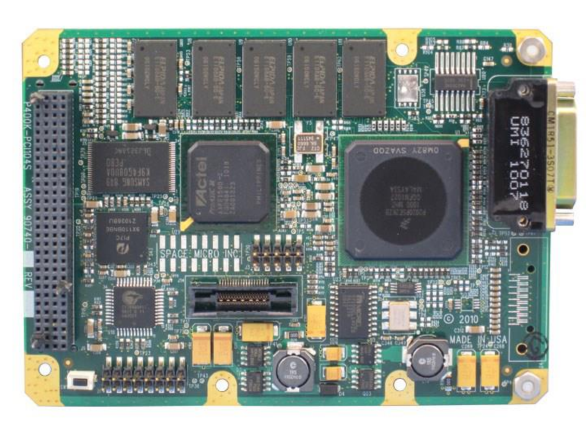
- Triple Mode Redundancy
- Radiation Tolerant FPGA-Based Processors
- Multiple Processors
- FSW Healing
- NASA MAPTIS Database

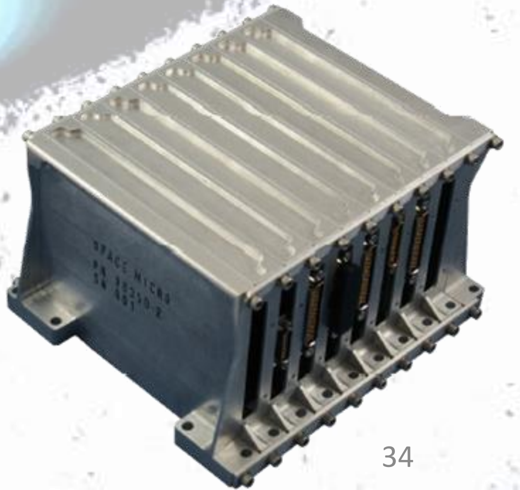
Lunar IceCube and Tranponer are Rad Hard, other systems are Rad Tolerant

C&DH

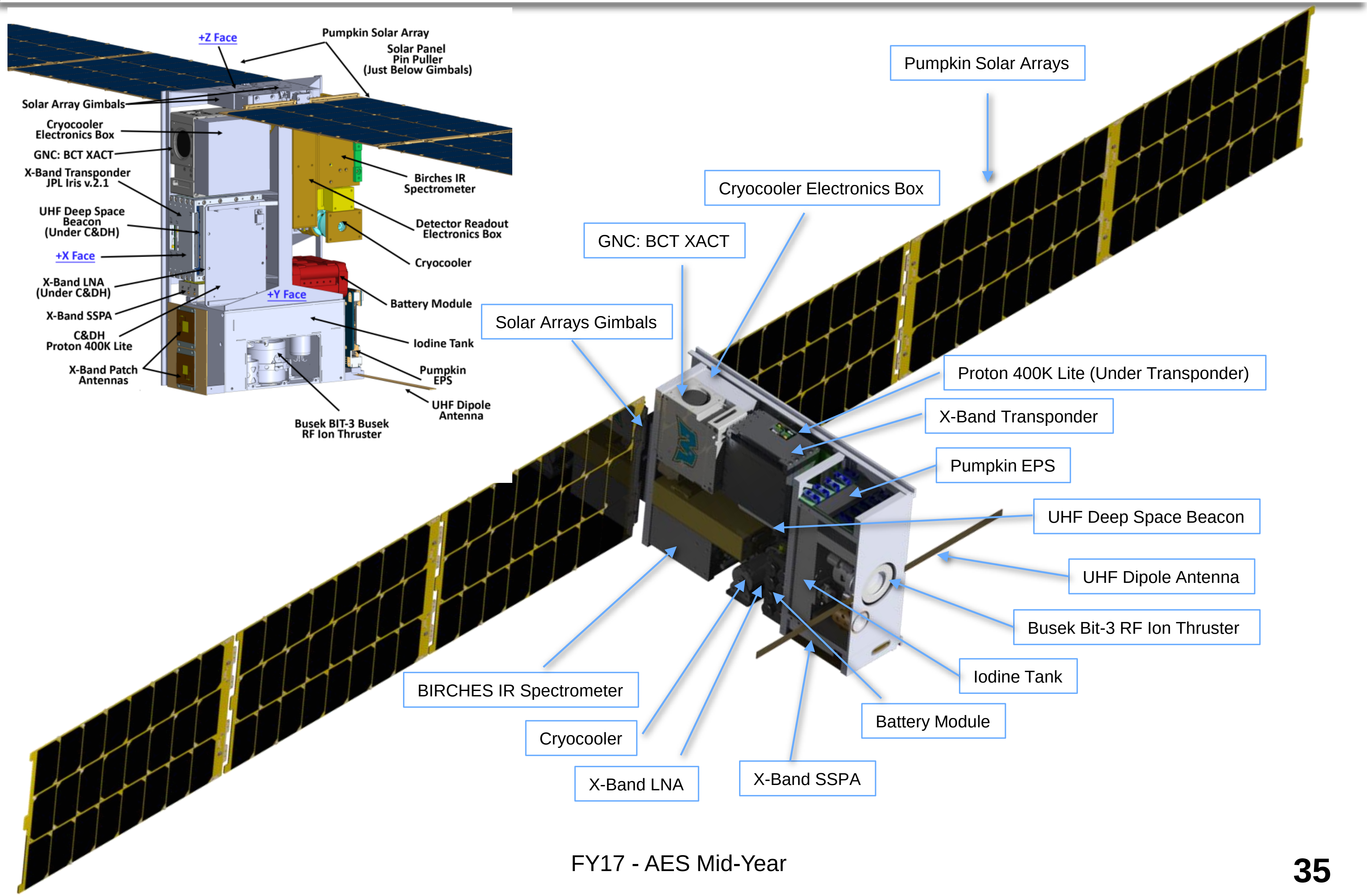
Space Micro Proton400k Single Board Computer

- 1 Ghz, 32-bit (per core) dual core processor
- 128 to 512 DDR 3/2 with EDAC 1 Mbyte EEPROM 32 Gb RH Flash
- Power: 8 to 12 Watts
- OS: Linux Board Support Package (BSP)
  - VxWorks Board Support Package
- Radiation Tolerence:
- **SEL:** >63 (MeV-cm2/mg)
- **SEU:** < 1 per 1,000 days (1.0 E-4, 90%
  - W.C. GEO, Orbit dependent)
  - TTMR™ technology for SEU detection/mitigation
- **TID** 100krad (Si), Orbit dependent
- **SEFI** 100% recoverable
  - H-Core™ technology for SEFI detection/mitigation





Lunar IceCube- Pushing the 6U Envelope

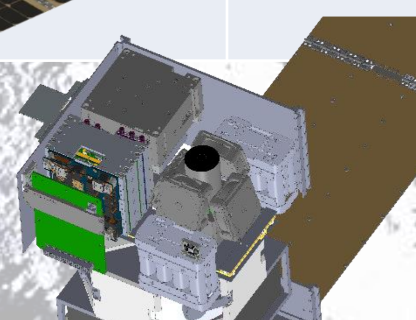


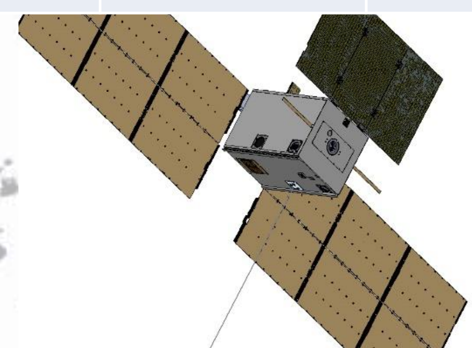
Future Interplanetary CubeSat Missions (A Subset)

Mission	Objective	Destination	Org	Date
AIDA	Asteroid Impact and Deflection Assessment	Didymos and Didymoon	ESA/NASA	2020
DARCSIDE	3U CubeSat with Europa Clipper spacecraft to study Europa's atmosphere with high energy particle detector	Europa	NM State	Concept for mid-2020s
PrOVE	"Primitive Object Volatile Explorer (PrOVE)	Targeted Approaching Comet	NASA GSFC	>2020
CUVE	Venus UV Experiment	Venus Atmosphere	JPL	>2020

Planetary Science Deep Space SmallSat (PSDS3) Missions Studies- 13 Selected

Mission	Description	Destination	Org	Date
BOLAS	Bi-sat Observations of the Lunar Atmosphere above Swirls	Moon	NASA GSFC	>2022
PRISM	Phobos Regolith Ion Sample Mission	Phobos	NM State	>2022
PrOVE	"Primitive Object Volatile Explorer (PrOVE)	Targeted Approaching Comet	NASA GSFC	>2022
10 Others	Various	Asteroids, Venus, Jupiter	JPL, GSFC, SAO, JHU-APL, UMd…	>2022





Design and Development Challenges

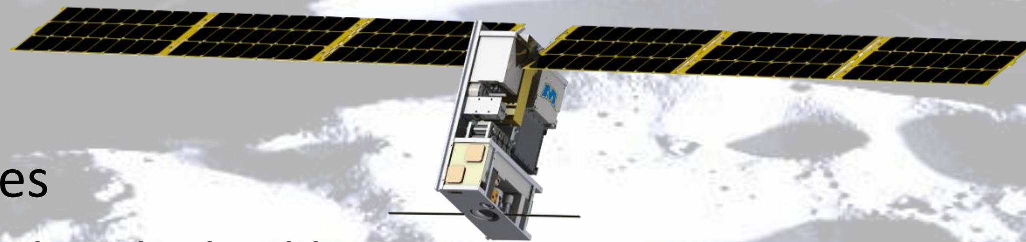
- Power Budgets Require 100 W or more of prime power
- Significant ΔV Requirement Dictates Complex Low Energy Manifold Trajectory
- Volume of Subsystems Pushing the 6U Envelope
- Few COTS Radiation-Tolerant Components/Subsystems Exist for CubeSats
- Thermal Management is a Challenge with Limited Space Frame and Radiating Surface
- Constrained Resources
- Many Aspects Do Not Scale
- But… iCubes are Designed by Outstanding Teams, Using Innovative Technologies and a New Paradigm for Solar System Exploration

Interplanetary CubeSat Conferences Emerge in Europe and the US

COSPAR Scientific Commission B0.2 Planetary Science Enabled by CubeSats and Microprobes

In Conclusion

- We have are entering a New Era of Space Exploration with Small Satellite Platforms



- Ushered in by :
  - New Enabling Technologies
  - New Highly Capable Launch Vehicles like SLS
  - Access to Soyuz through GK
  - New Paradigm of SmallSats as secondary payload “probes”
- MarCO will likely be the First Interplanetary CubeSat
- EM-1 CubeSats are Imminent: 13 SmallSats to beyond-LEO
- PSDS3s and Many Others are Planned
- Many Opportunities for Future Lunar and Planetary Exploration and for Training Future Generations of Aerospace Engineers

Questions Before Scottie Beams Me Up?