Lunar IceCube: Enabling Technologies and Challenges to Interplanetary SmallSat Exploration

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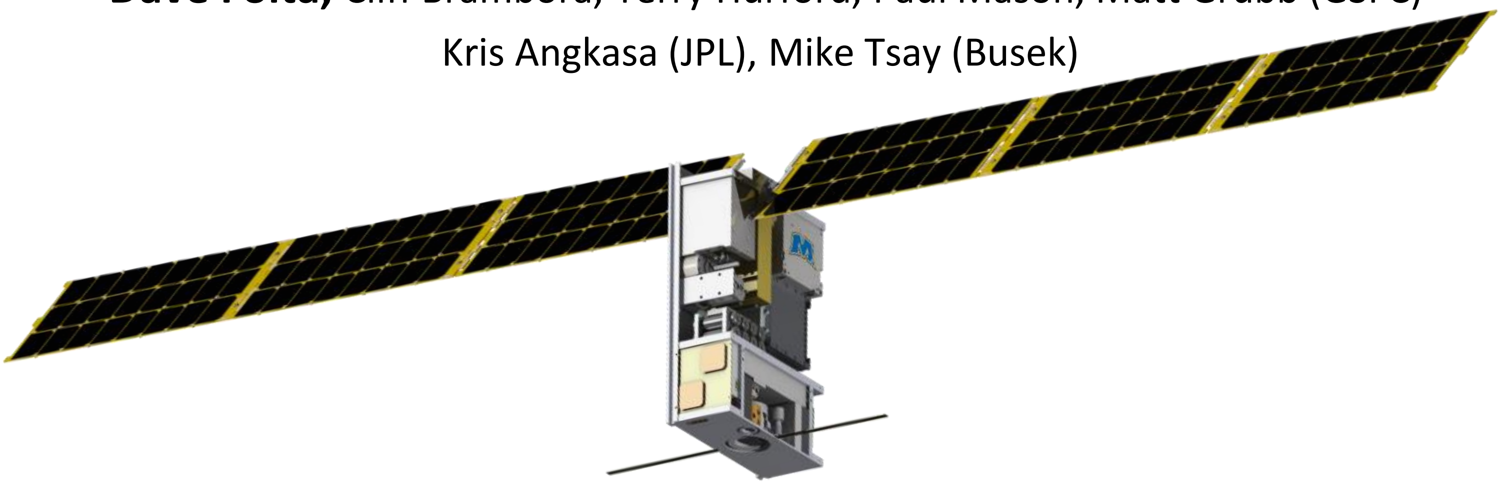

NASA GSFC SmallSat Symposium

June 26, 2019

Lunar IceCube Status

- **Lunar IceCube was awarded by Next Space Technologies for Exploration Partnerships (NextSTEP)**
- **Mission Description and Objectives**
  - Lunar IceCube is a 14kg, 6U small satellite whose mission is to prospect for water in ice, liquid, and vapor forms and other lunar volatiles from a low-perigee, inclined lunar orbit using a compact IR spectrometer.
  - Lunar IceCube will be deployed by the SLS on EM-1 (2020 launch)
  - Use an innovative RF Ion engine combined with a low energy trajectory to achieve lunar capture and a science orbit of 100 km perilune.
- **Strategic Knowledge Gaps**
  - **Polar Resources**: Temporal Variability and Movement Dynamics of Surface-Correlated OH and H2O deposits toward PSR retention
  - **Polar Resources**: Composition, Form and Distribution of Polar Volatiles
  - **Regolith**: Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith (depending on the final inclination of the Lunar IceCube orbit)

Critical Milestones

PDR	Phase 1	CDR/ΔCDR	Phase 2	Phase 3	FRR/ORR	Launch	Mission Ops	Mission Duration
05/19/2016	06/20/2016	05/16/17 3/14/18	04/26/2018	2/14/2019	10/15/2019	2020	2020-2022	2 years incl. ext.

Lunar IceCube Status

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Technology Demonstrations

- **NASA GSFC -** Broadband InfraRed Compact High Resolution Exploration Spectrometer (**BIRCHES**)
  - Miniaturized IR Spectrometer - characterize water and other volatiles with high spectral resolution (5 nm) and wavelength range (1 to 4 μm)
- **Busek BIT 3** - High Isp RF Ion Engine
- **Space Micro C&DH-** Inexpensive Radiation-tolerant Subsystem
- **JPL Iris v. 2.1** Ranging Transceiver
- **BCT- XACT** ADCS w/ Star Tracker and Reaction Wheels
- **Custom Pumpkin**- High Power (120W) CubeSat Solar Array

Current Status

- Team is preparing for acceptance and integration of Flight Hardware
- FlatSat with non rad-hard subsystems and emulators is in development
- Trajectory, navigation, and thermal models along with communications links, mass, volume and power budgets evolving

Design and Development Challenges

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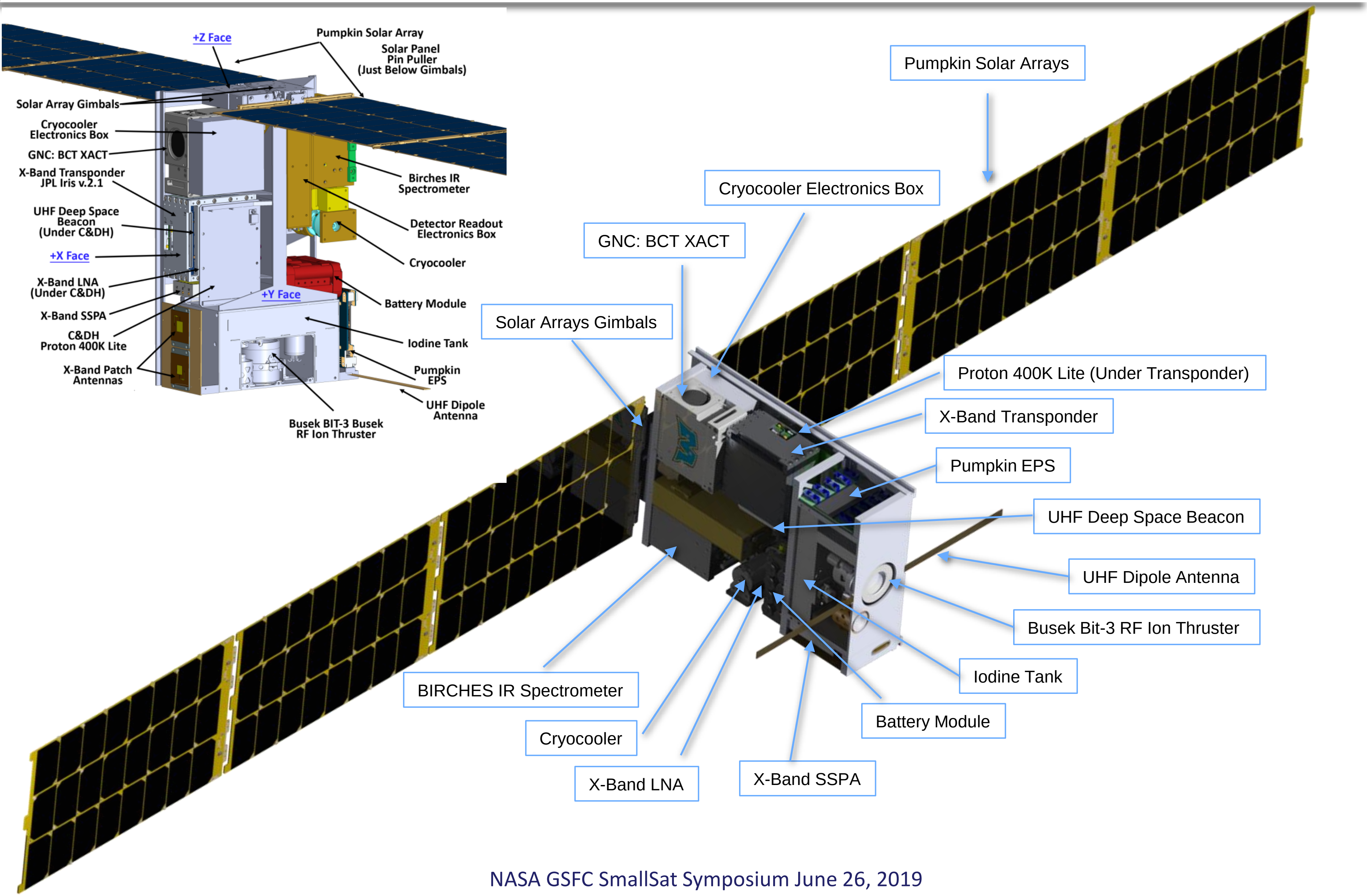
Many Aspects of CubeSat Missions Do Not Scale

- Require Complex Subsystems, Complex Ops and FSW
- Low Thrust Dictates Complex Low Energy Trajectory Design
- Mass and Volume Constrained
- Few COTS Radiation-Tolerant Components/Subsystems Exist for CubeSats
- COTS Systems at Low TRL and without Flight Heritage
- Thermal Management is a Challenge- BIRCHES requires cooling to cryogenic temperatures, spacecraft has limited Radiating Surfaces
- Complex Attitude Control Requirements
- Power Budget Requires ~ 120 W prime power
- Ground Data Systems Required to Communicate with DSN and Process Science Data
- Constrained Resources
- Highly Compressed Development Timeline

Lunar IceCube- Requires Complex Subsystems



Lunar IceCube BIRCHES Instrument

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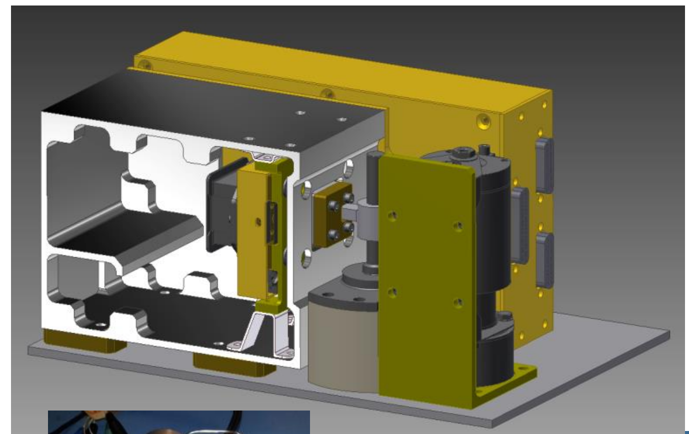
Description and Objectives

- Broadband InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES)
- Point Spectrometer will determine distribution of volatiles, including forms and components of water, and other volatiles such as NH3, H2S, CO2, CH4, to the extent possible, in lunar regolith as a function of time of day and latitude
- IR measurements associated with volatiles in the 3 micron region at </= 10 nm spectral resolution

Technology Demonstrations

- Meeting mass, volume, power constraints, 1.5U in volume and 3.2 kg, 10-15W
- High spectral resolution (5 nm) and wavelength range (1 to 4 μm)
- Innovative Smallsat thermal design will maintain detector <115K +/- 1K, optics box <230K +/- 5K, avionics in nominal range
- Cryocooler electronics create significant voltage ripple

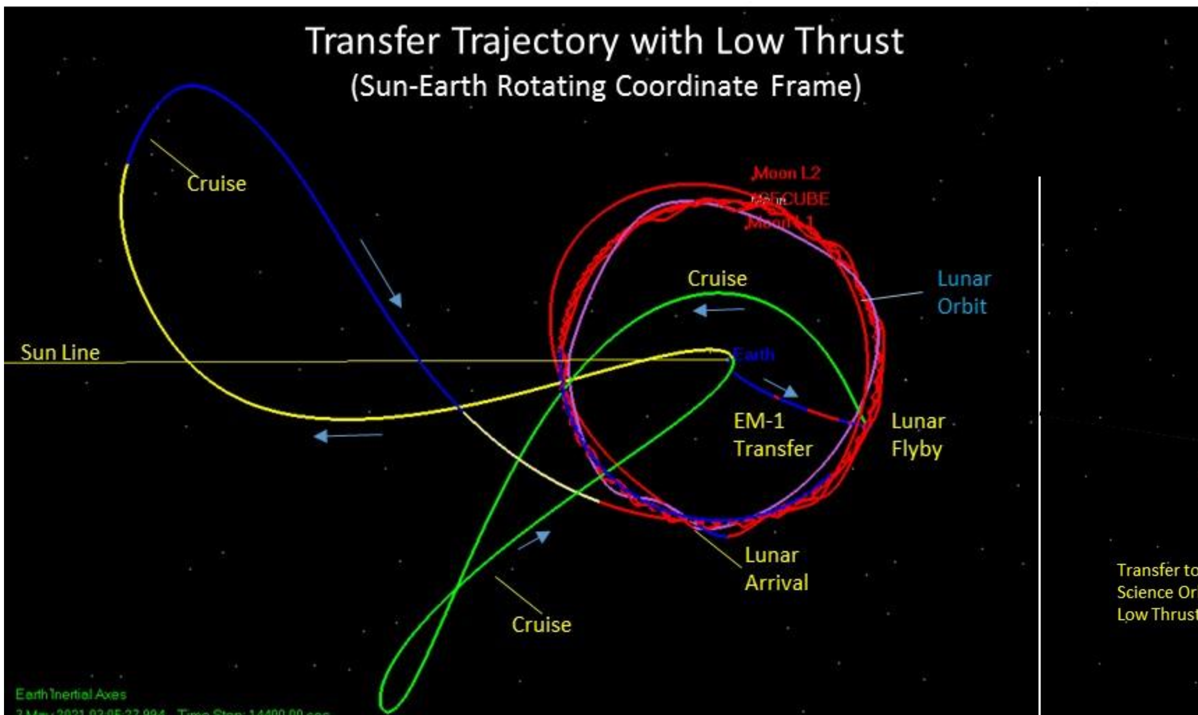


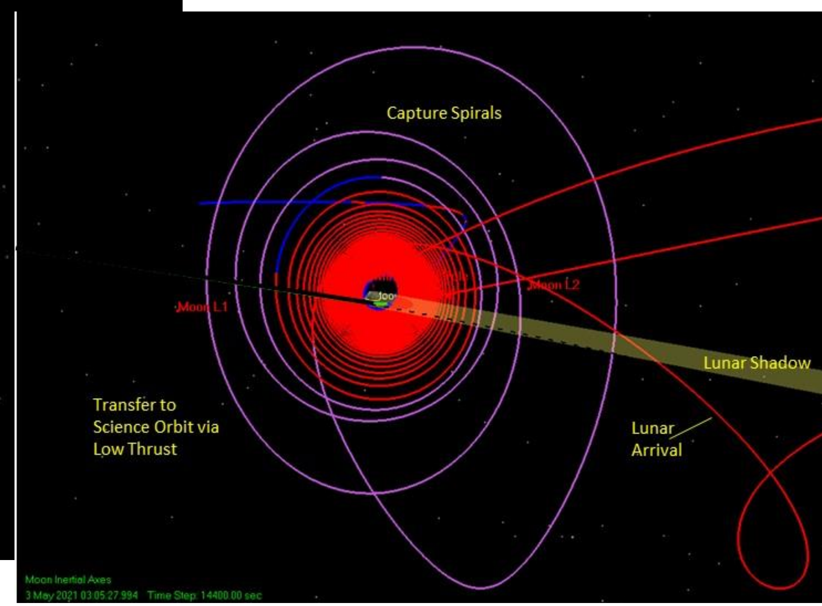
Current Status

- All Critical/Long lead Flight hardware ordered
- DRE Board Populated and in Testing
- Flight OBOX ordered in April
- H1RG Detector Package Design
- mLCCE and Cryo-Cooler HW procured and in testing

Transfer Trajectory and Science Orbit

- Capture into a long-term weakly-stable lunar orbit (based on energy and dynamics)
- Capture with Periapsis/Apoapsis reduction to achieve inclined polar science orbit with equatorial periapsis
- Spiral transfer orbit shown with ~6 month decreasing periapsis altitude over 120 days – dependent on thrust / mass ratio, on-time, shadows, tracking gaps, and efficiency
- Orbit design goal to minimize shadows, achieve stable orbit, minimize fuel





Iodine BIT-3 System

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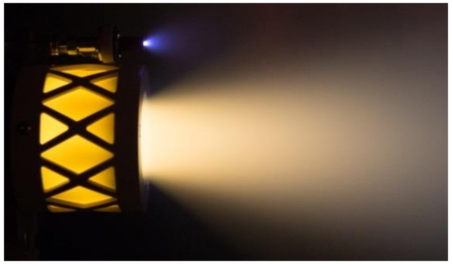
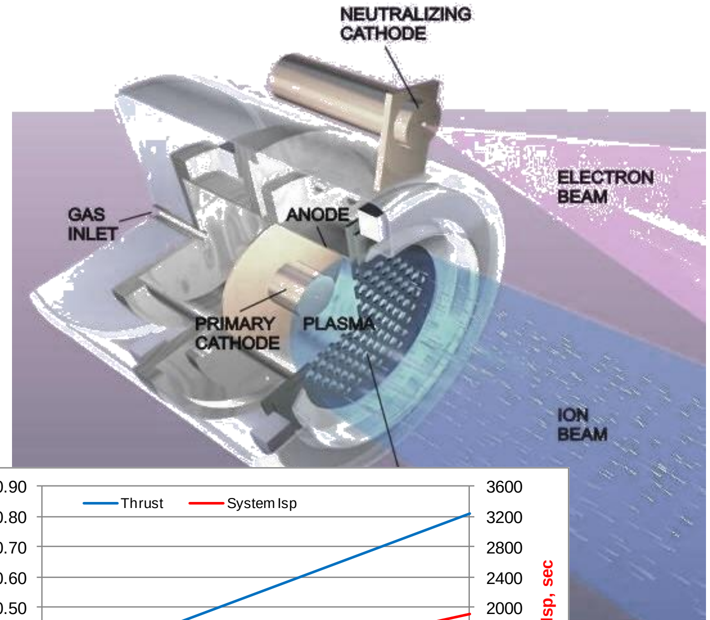
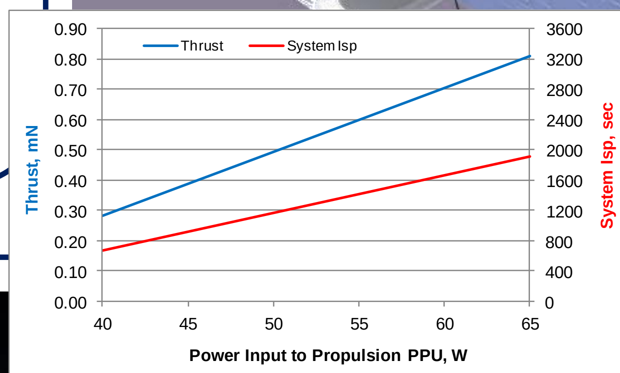


Busek 3cm RF Ion Thruster BIT-3; 50W Nominal at Thruster Head

Thruster

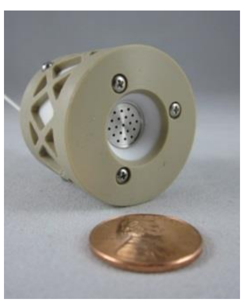


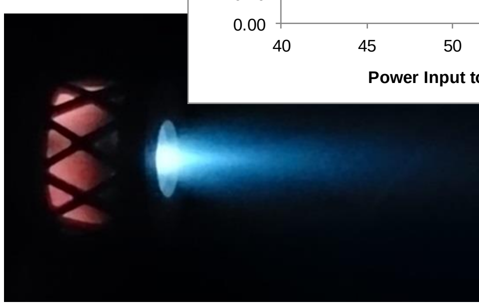


320cc/1.5kg Iodine Propellant Stored as Solid Crystals

Zero-Pressure Iodine Tank

Tank and Propellant



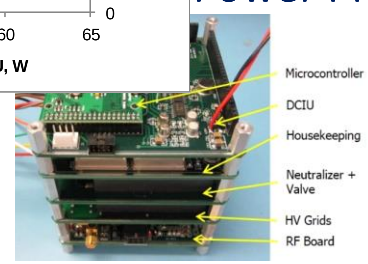


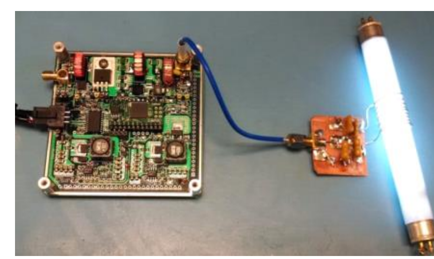
I_2-Compatible Mini RF Cathode, 16mA Output at 11W Nominal

Neutralizer

Power Processor

RF Board Demo





CubeSat Compatible Ion Propulsion PPU that includes DCIU, Housekeeping, Cathode/Valve, Grid HV, RF Generator & Power Amplifier

SubSystems

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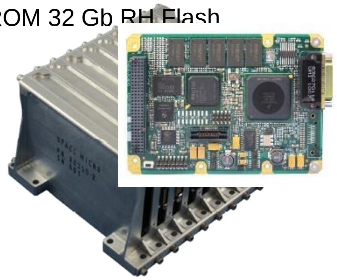
Space Micro Proton400k Single Board Computer

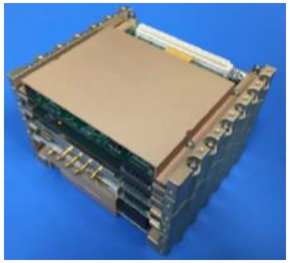
- 1 Ghz, 32-bit (per core) dual core processor
- 128 to 512 DDR 3/2 with EDAC 1 Mbyte EEPROM 32 Gb RH Flash
- Power: 8 to 12 Watts
- OS: Linux Board Support Package (BSP)
  - VxWorks Board Support Package
- Radiation Tolerance:
- **SEL:** >63 (MeV-cm2/mg)
- **SEU:** < 1 per 1,000 days (1.0 E-4, 90%
  - 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



Custom Pumpkin High Power Array

- 2 x 3 x 16S, for a total of 48 XTJ cells per side (three individual strings of 16 cells, per side)
- System Power (BOL) = 120W
  - Stowed thickness ≈ .393" (10.0 mm)
- Custom Gimbals
- Robust Pin Puller-Sear Constraint/Deployment
- MSU EPS w/ components vetted via NEPP database

JPL Iris 2.0 + Patch Antennas



- X-Band Uplink: 7.145 GHZ
- X-Band Downlink: 8.450 GHz
- Doppler, Ranging
- 0.5 U Volume
- Radiation Tolerant Parts for Extended Deep Space Missions
  - LET >37 MeV–cm2/mg (Virtex 6), 20 krad (ELDRS to 5 krad)
- Full Transponder
- 4W Output
- DSN Compatible

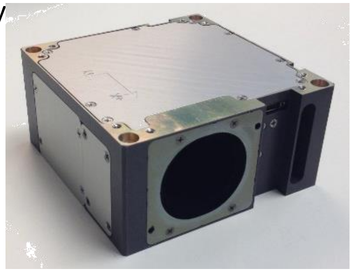
Blue Canyon Technologies Modified XACT + RWAs

- 3-axis Stellar Attitude Determination with light baffle
- 0.5U Micro-package
- Low jitter 3-axis reaction wheel control
- Spacecraft Pointing Accuracy

$\pm$0.003 deg(1-sigma) for 2 axes

$\pm$0.007 deg(1-sigma) for 3rd axis

- Slew Rate: 10 deg/sec
- Flight Heritage on:
  - ASTERIA
  - MinXSS

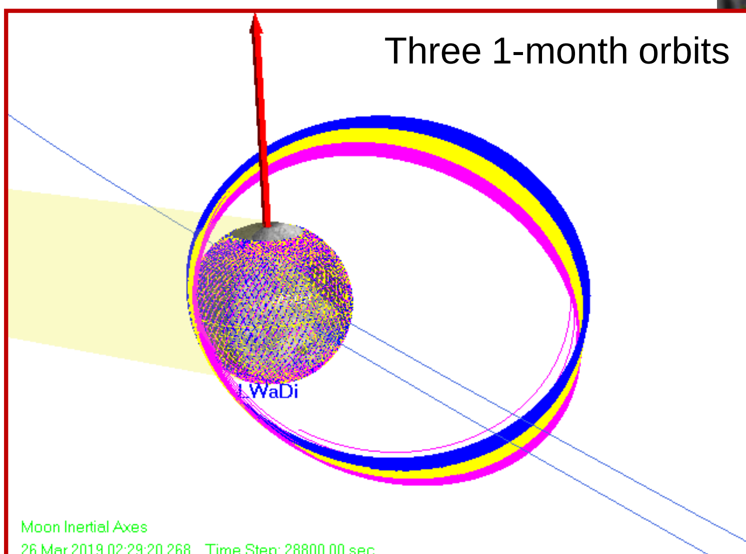


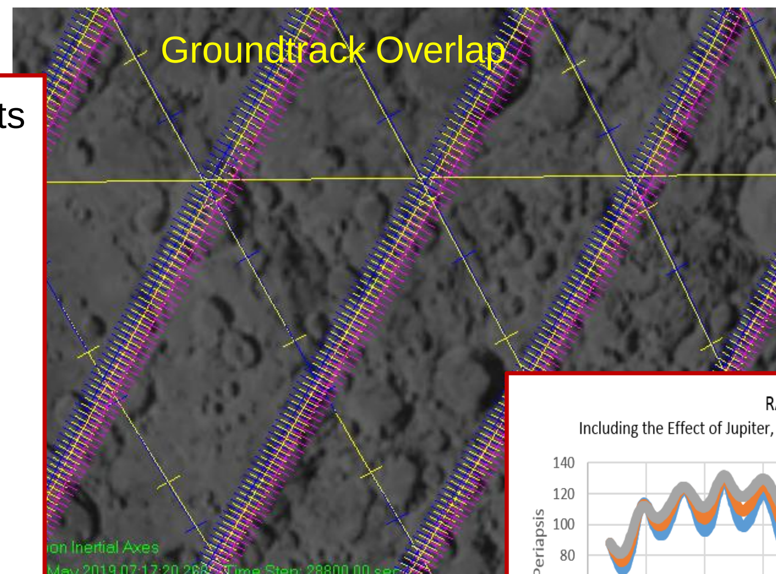
Mission profile

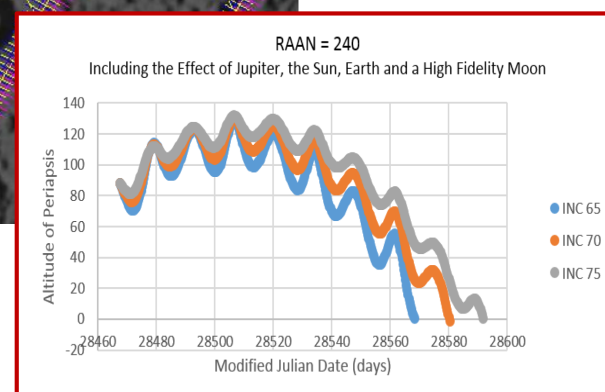
- The timespan ~ 15-21 months (6 months cruise to the Moon, 3 months to achieve science orbit, > 6 months of science operations)
- Utilizes DSN 34-m BWG and Morehead State 21-m
- Bulk of antenna coverage provided by Morehead State 21-m with DSN used for Southern Hemisphere coverage and Mission-Critical Events
- Mission Phases
  - **LEOP**
  - **Cruise**- Real-time Tracking for Navigation Solutions
  - **Lunar Orbit Capture/ Transfer Orbit**
  - **Science Orbit**: Download TBD (Target >2 MB) of science data per day

Science orbit

- 100 km Periapsis Altitude at Equatorial Crossing
  - Drives Argument of Periapsis at Ascending Node
- High Inclination wrt the lunar equator (~ 90 deg)
- Overlap of groundtracks for calibration
  - Drives semimajor axis (period of 7 hrs)
  - Yields a candidate orbit with a 100 km periapsis and 5000 km apoapsis altitude
- Maximize Lifetime with no stationkeeping maneuvers
  - Dependent on inclination, placement of ascending node wrt Earth, Initial periapsis altitude, and eccentricity



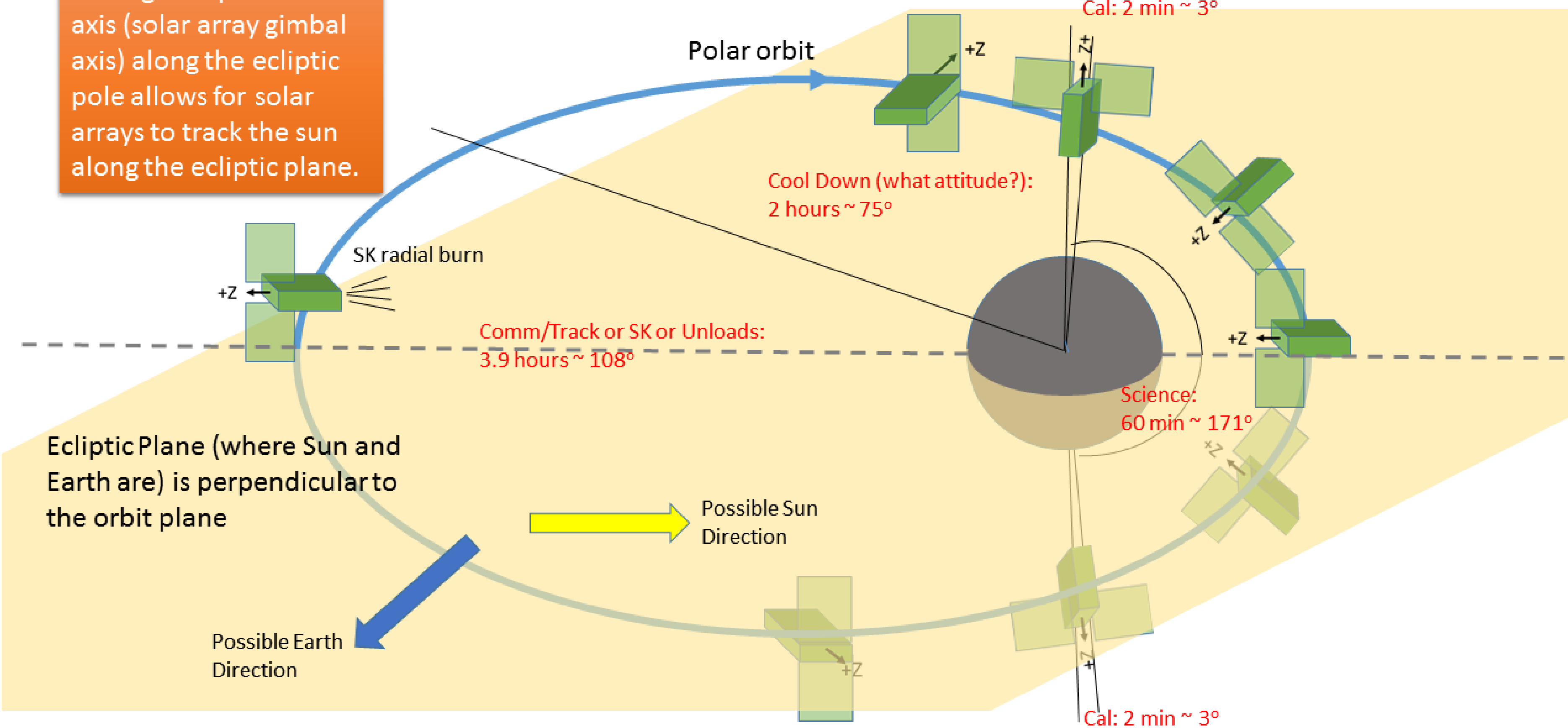




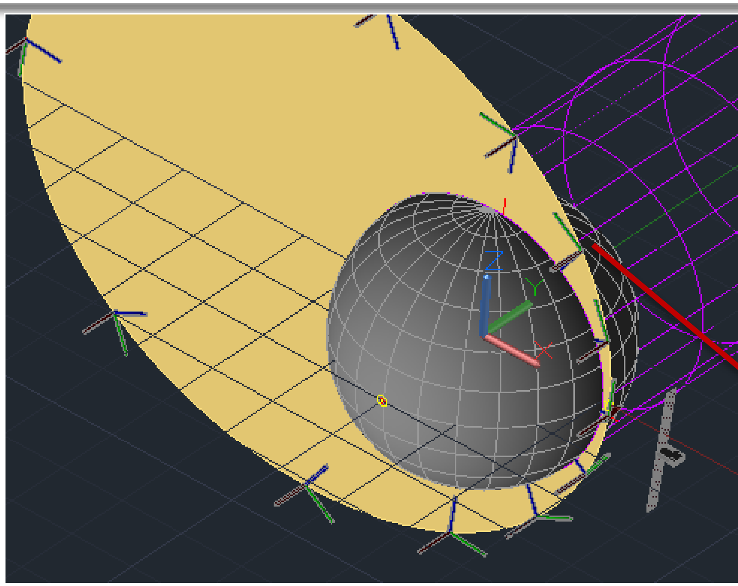
Science Orbit Dictates Complex ACS

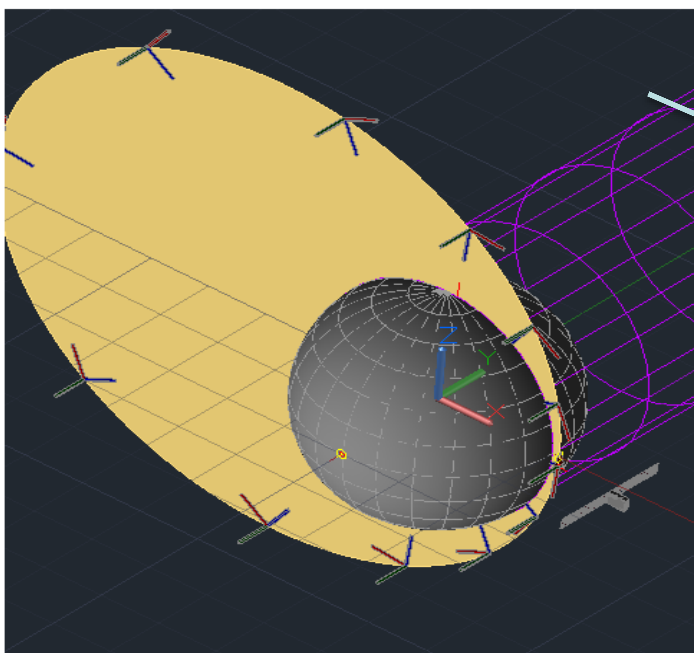
+Z must never point toward the sun

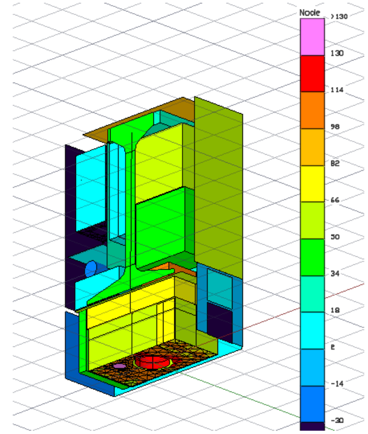
Having the spacecraft Y-axis (solar array gimbal axis) along the ecliptic pole allows for solar arrays to track the sun along the ecliptic plane.

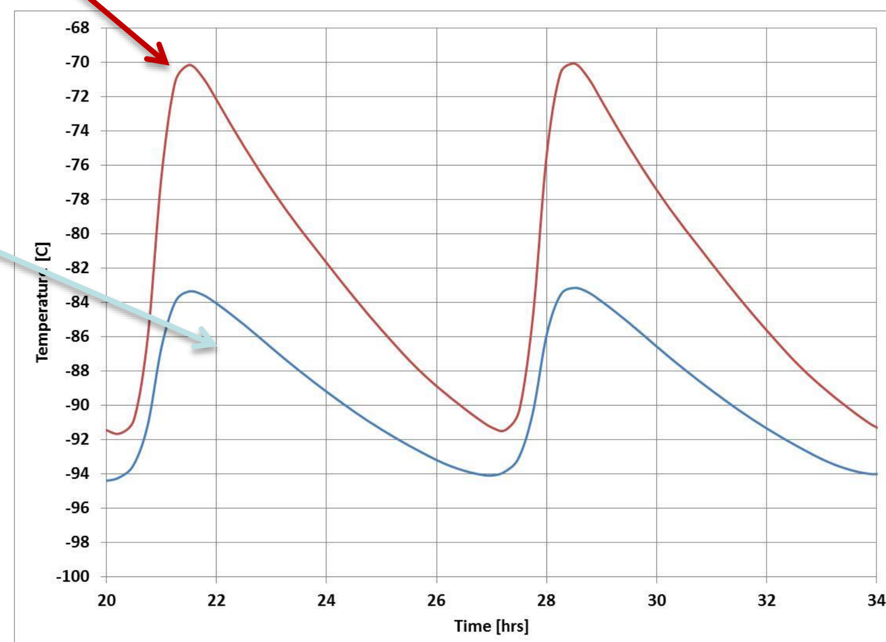


Thermal Management Through ACS Ops and Thermal Design





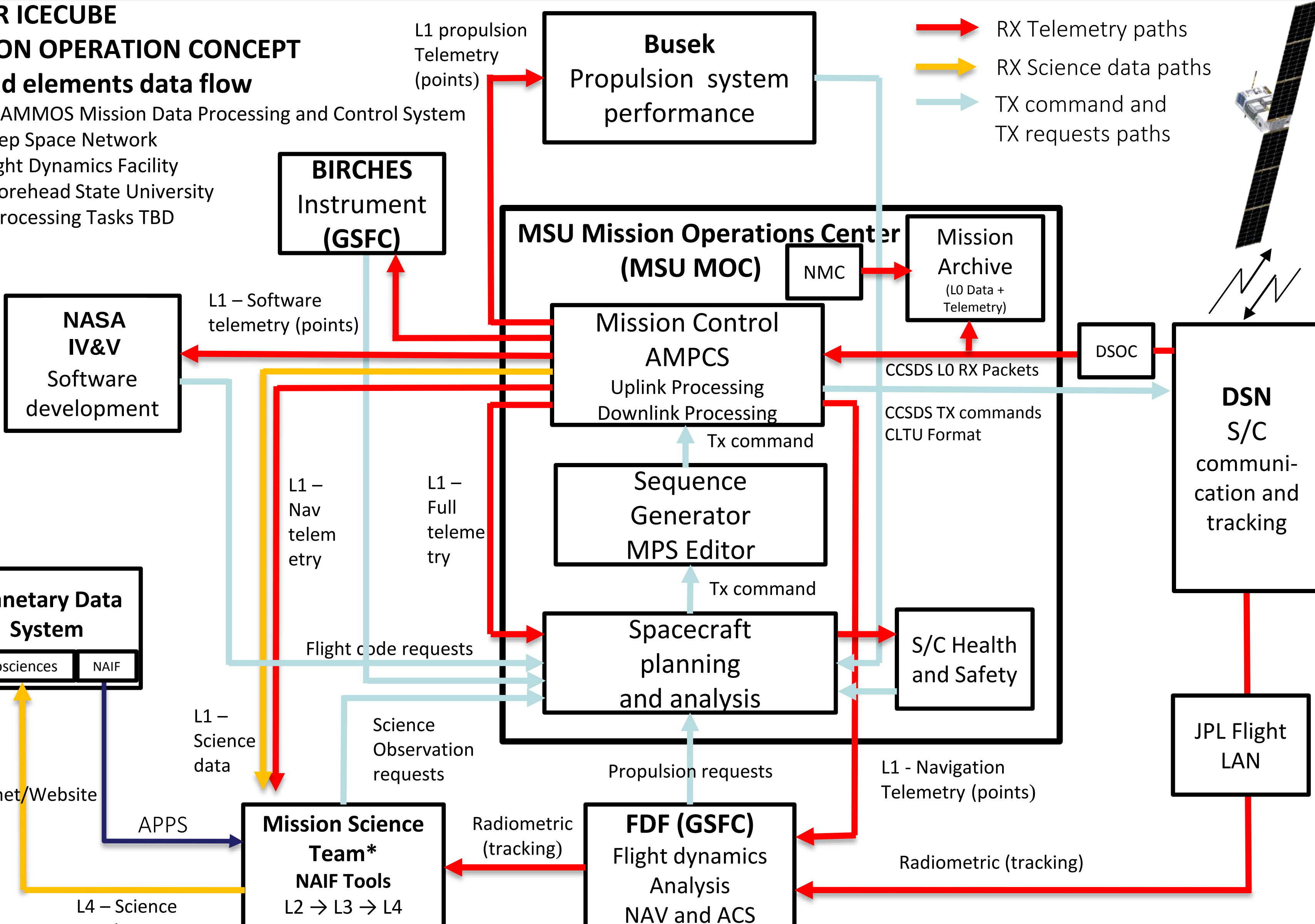




Communications

LUNAR ICECUBE
MISSION OPERATION CONCEPT
Ground elements data flow

AMPCS: AMMOS Mission Data Processing and Control System
DSN: Deep Space Network
FDF: Flight Dynamics Facility
MSU: Morehead State University
* NAIF Processing Tasks TBD



Summary and Lessons Learned

- Expecting the first prototypes of deep space Cubesats - that require active control systems and are not exclusively tech demos - to be low-cost AND meet user requirements and thus are performance driven, is challenging.
  - Many aspects of a mission do not scale. Navigation and tracking, attitude modeling and control, flight software, ground data systems, and especially telecommunications systems complexity do not scale.
  - Thermal management and thermal systems design represent a significant challenge.
  - Compressing all the technology of BIRCHES into a 1.5U volume and 3.2 kg of mass represented a challenge

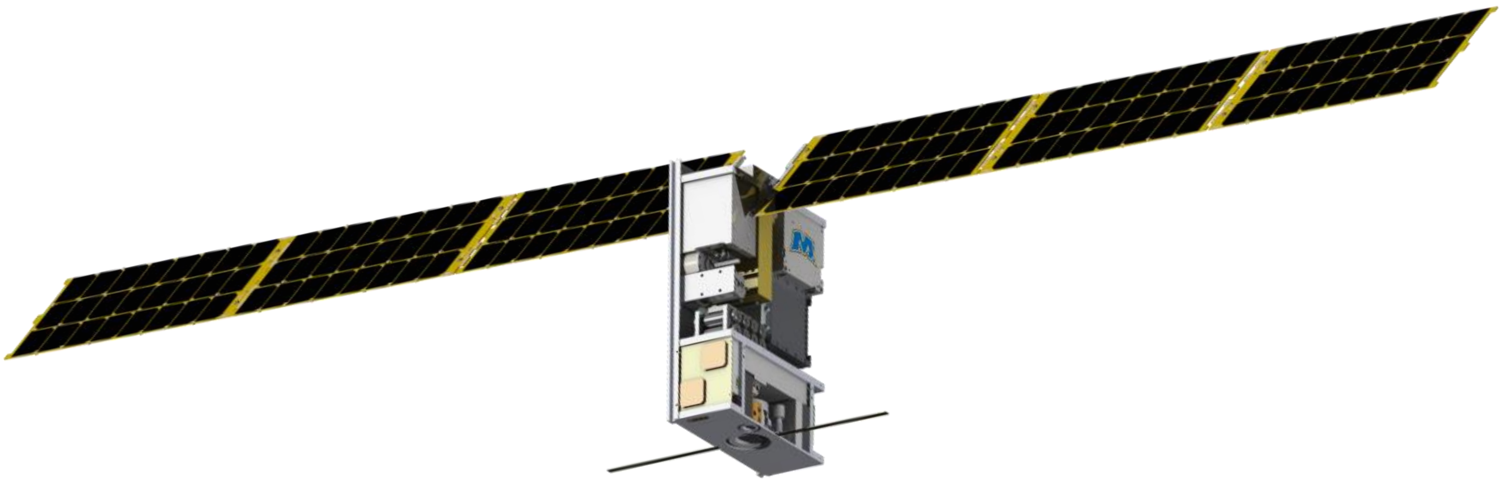
- The cubesat paradigm is largely about rapid, low-cost development and low-cost operation with minimum (automated electronically captured) documentation and data capture as well as compact, standardized packaging.

- Need to embrace the 'shared resources' part of the cubesat paradigm in terms of shared personnel resources, hardware and software tools, documentation templates

- An alternative track embracing this approach along with an alternative (test by flying) risk posture and capitalizing on emerging launch services would lead to enhanced flight qualification of new technologies and greater capability for conventional (e.g., NASA Classes A, B, C, D) missions.

- EM-1 Interplanetary CubeSats will certainly break new ground- ushering in an era of planetary exploration utilizing small satellite platforms

Lunar Ice Cube



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