Interplanetary CubeSats and Smallsats for Lunar Exploraton

Keck Institute for Space Studies (KISS)

Workshop on New Approaches to Lunar Ice Detection and Mapping

2013 July 22

California Institute of of Technology, Pasadena, California

Presented by Robert L. Staehle

Jet Propulsion Laboratory, California Institute of Technology

Authors listed in slides 3 through 8 from previously presented material.

Explorer 1 - JPL's Origins in Small Spacecraft

Explorer 1 – First US Satellite - Launched on January 31, 1958 – Cape Canaveral, FL

Courtesy: JPL Photo Archives

Interplanetary CubeSat Architecture and Missions

Space 2012
American Institute of Aeronautics & Astronautics (AIAA)
2012 September 12
Pasadena, CA

Robert L. Staehle, Diana Blaney, Hamid Hemmati, Dayton Jones, Andrew Klesh, Joseph Lazio, Paulett Liewer, Martin Wen-Yu Lo, Pantazis Mouroulis, Neil Murphy, Paula J. Pingree, Thor Wilson, Chen-Wan Yen
Jet Propulsion Laboratory, California Institute of Technology

Jordi Puig-Suari, Austin Williams
California Polytechnic University, San Luis Obispo

Tomas Svitek
Stellar Exploration

Bruce Betts, Louis Friedman
The Planetary Society

Brian Anderson, Channing Chow
University of Southern California

Report on Phase 1 of a NASA Innovative Advanced Concepts (NIAC) task.
No mission described herein has been approved or funded.

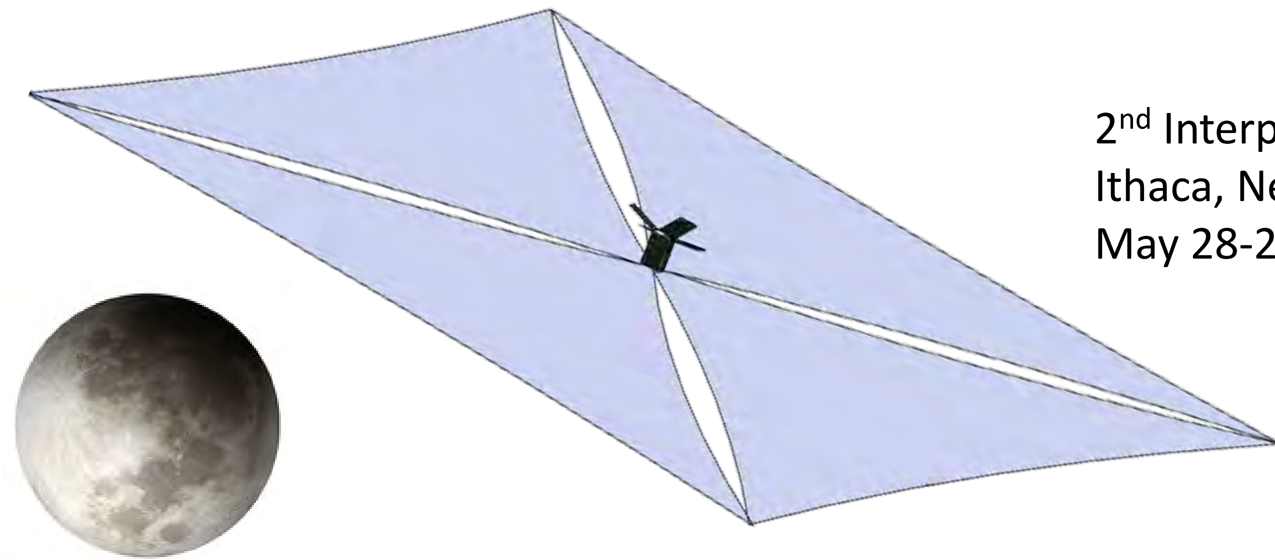
JPL Does Cubesats

Tony Freeman*
Manager, Innovation Foundry

April 2013

- With a lot of help from the Cubesat Kitchen Cabinet:
  C. Norton (3X/8X), J. Baker (4X/6X), A. Gray (7X), L. Deutsch (9X)

Utilization of a Solar Sail to Perform a Lunar CubeSat Science Mission



2nd Interplanetary CubeSat Workshop
Ithaca, New York
May 28-29, 2013

The University of Texas at Austin (UT): Texas Spacecraft Laboratory (TSL)
Peter Z. Schulte Undergraduate Research Assistant
E. Glenn Lightsey Professor
Katharine M. Brumbaugh Graduate Research Assistant

Jet Propulsion Laboratory, California Institute of Technology (JPL)
Robert L. Staehle Assistant Manager for Advanced Concepts, Instruments Division

INSPIRE

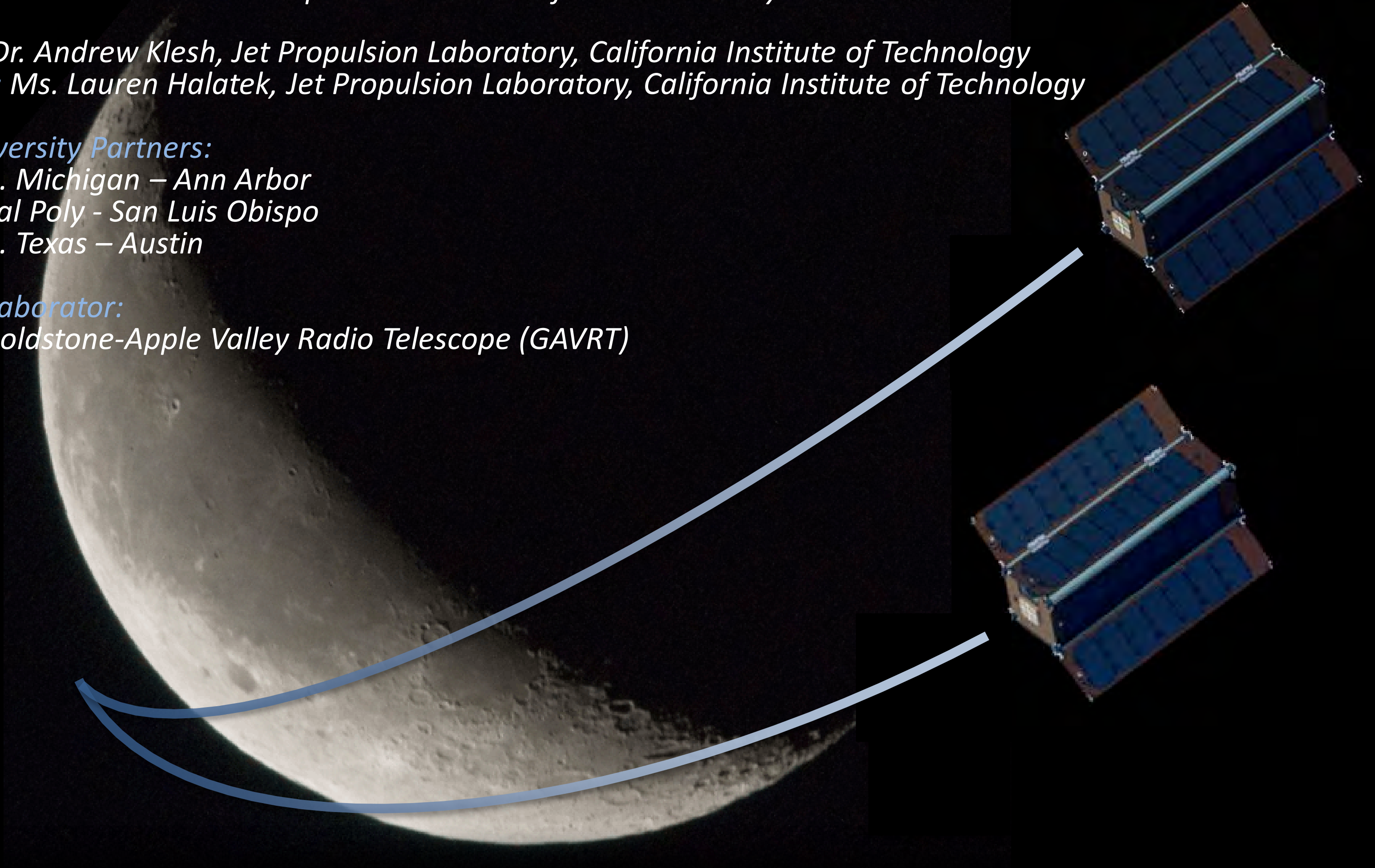
***I**nterplanetary **N**ano**S**pacecraft **P**athfinder **I**n a **R**elevant **E**nvironment*

Low-cost mission leadership with the world's first CubeSat beyond Earth-orbit

PI: Dr. Andrew Klesh, Jet Propulsion Laboratory, California Institute of Technology
PM: Ms. Lauren Halatek, Jet Propulsion Laboratory, California Institute of Technology

University Partners:
- *U. Michigan – Ann Arbor*
- *Cal Poly - San Luis Obispo*
- *U. Texas – Austin*

Collaborator:
- *Goldstone-Apple Valley Radio Telescope (GAVRT)*



Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology

A Low-Cost NEO Micro Hunter-Seeker Mission Concept

A $100M micro-mission to discover and visit multiple near-Earth objects

Joseph E. Riedel, Colleen Marrese-Reading, & Young H. Lee
Jet Propulsion Laboratory, California Institute of Technology,
joseph.e.riedel@jpl.nasa.gov

*With critical contributions from
David Eisenman, Dan Grebow,
Tim McElrath and Juergen Mueller*

Low Cost Planetary Missions – 10 Conference, June 19 2013

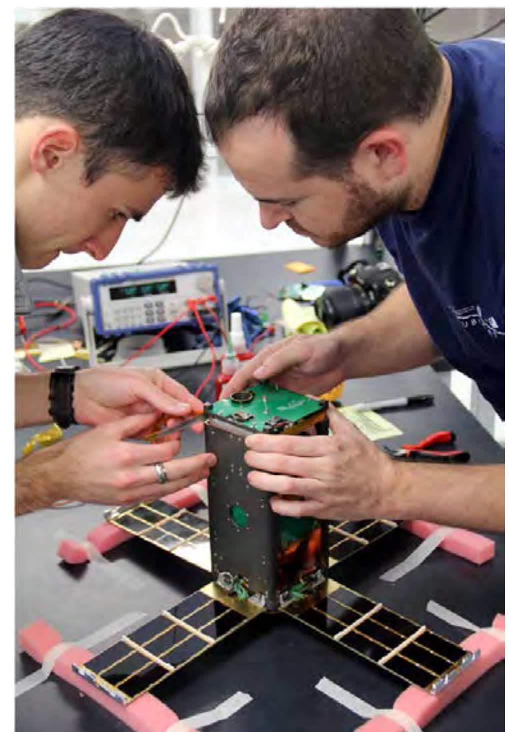
MOREHEAD STATE UNIVERSITY

Morehead State University SmallSat Program

Benjamin Malphrus

Space Science Center

Morehead KY



Benjamin Malphrus/Morehead State Univ

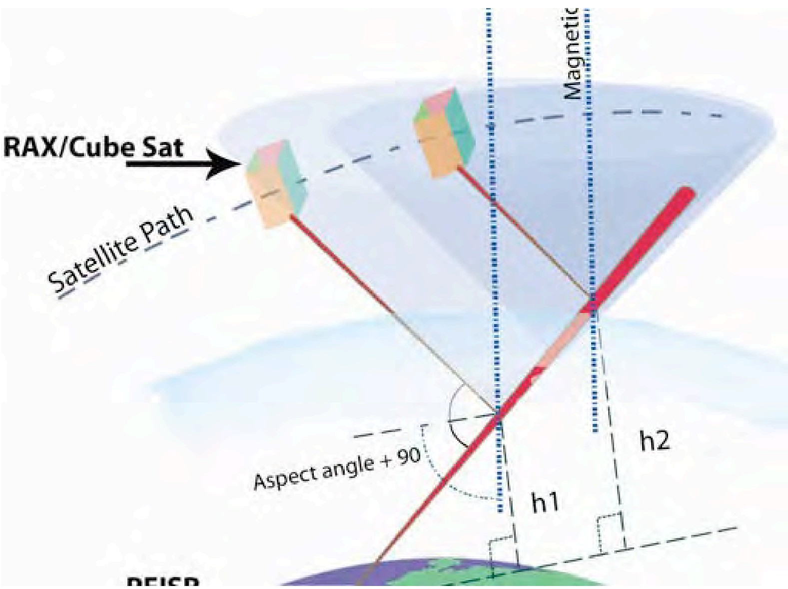
What is a CubeSat?

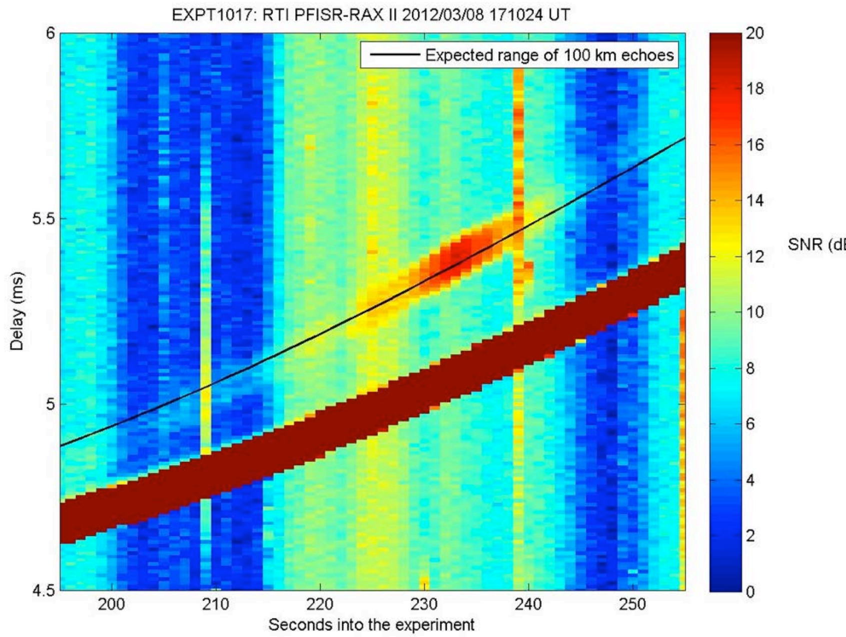
- A CubeSat is an accepted standard to enable low-cost launch access at the price of higher risk – but not to the primary **(encapsulation of risk)**
- **A CubeSat is a flexible platform** without defined "innards"
- **A CubeSat is an instrument** – with a few spacecraft parts tacked on.
- **A CubeSat allows for low-cost** if the project accepts higher risk

A CubeSat is a focused tool, trading capability for size, and maximizing utility through acceptance of risk.

CubeSats – Inside the Box

- 10 years orbiting in LEO
- Currently >50 launches per year
- Have developed significant capability for science return





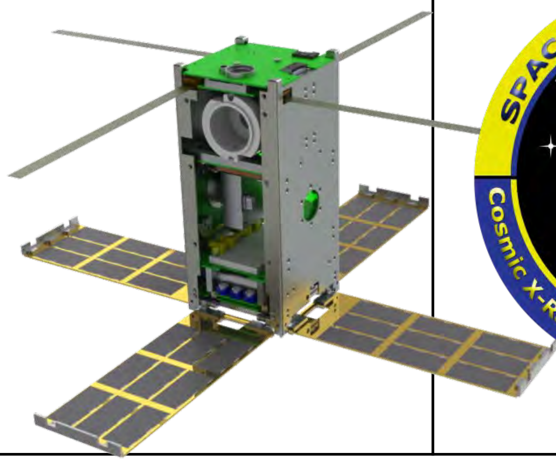
The RAX radar echo discovery has convincingly proved that miniature satellites, beyond their role as teaching tools, can provide high caliber measurements for fundamental space weather research.

- ***Dr. Therese Moretto Jorgensen, Geospace program director, Division of Atmospheric and Geospace Sciences, NSF***

Cosmic X-Ray Background Nanosatellite-2

Morehead State University and Kentucky Space

CXBN-2



Mission Description/Goal

•Increase the precision of measurements of the Cosmic X-Ray Background in the 30-50 keV range
•Constrain models that explain the relative contribution of cosmic X-Ray sources to the CXRB
•Produce data that will lend insight into the underlying physics of the Diffuse X-Ray Background
•Provide flight heritage for innovative CubeSat technologies
•Provide flight heritage for CZT-based X-Ray-Gamma Ray Detector

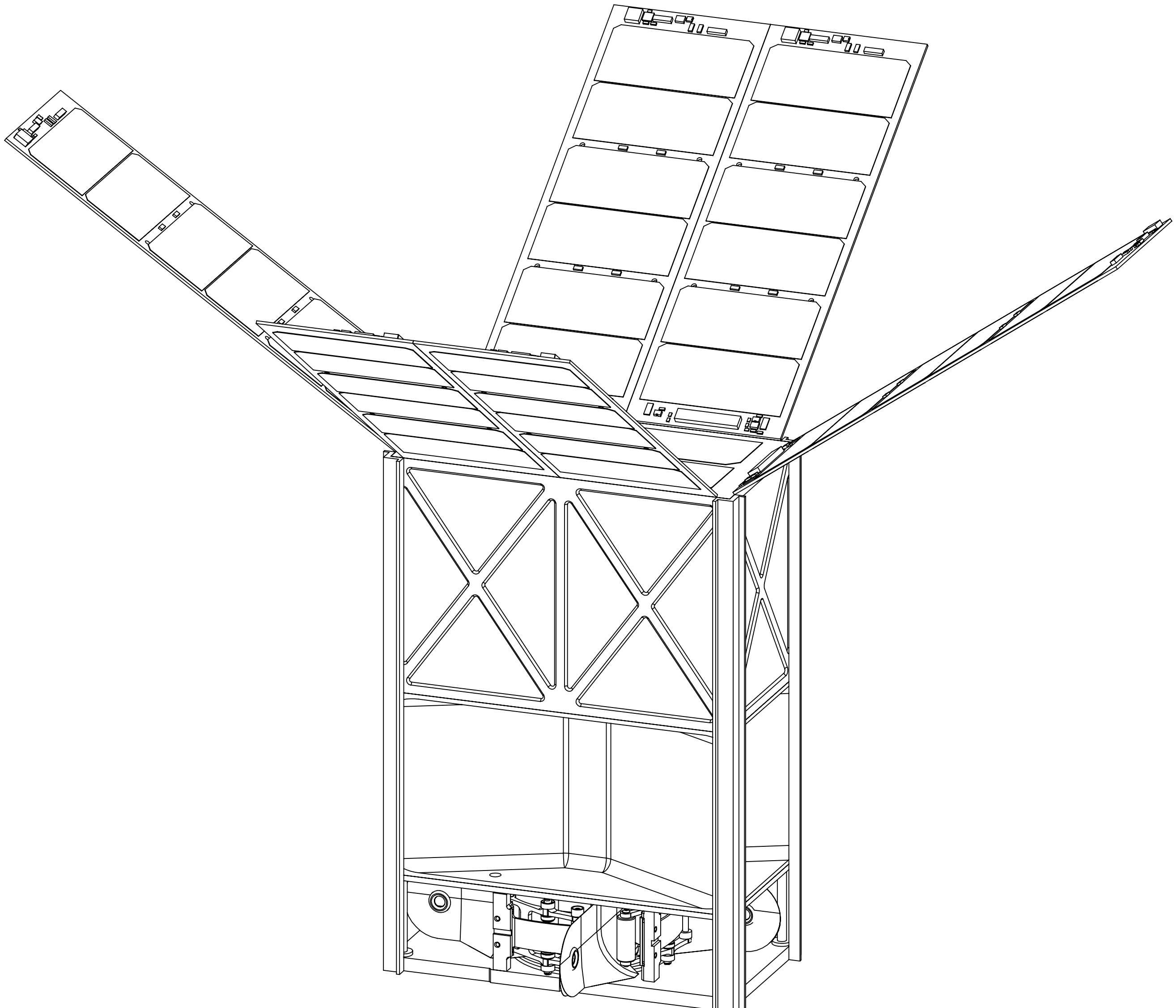
Major Milestones

- Completion of requirements, design, and mission/flight readiness reviews
- Completion of fabrication benchmarks
- Completion of pre-flight testing
- Integration, Launch, and LEOP—contact established and subsystems operating nominally
- Science objectives:
    - 3 million seconds of data
    - ~1 year of operation
    - broadband S/N ~250
- End of mission de-orbit in 15 years

Spacecraft Specifications

- Spacecraft Developers: Morehead State University Space Science Center, Kentucky Space, Univ. of California Berkeley
- Integration & Test Location: Morehead State University Space Science Center (Kentucky USA)
- Mass: 2.6 kg
- Power: 15 W max generated; Regulated Power to Subsystems at 3.3VDC, 5VDC, 12VDC
- Size: 2U = 10 cm x 10 cm x 20 cm
- Dynamics: Sun Pointing, Rotation Rate = 1/6 Hz

One Preliminary Configuration



Tomas Svitek, 2012/3/17

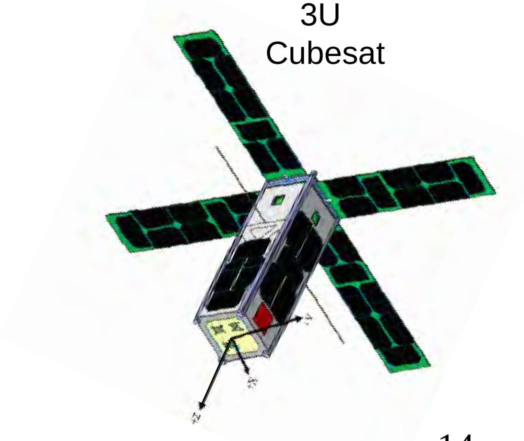
Why Cubesats? Why Now?

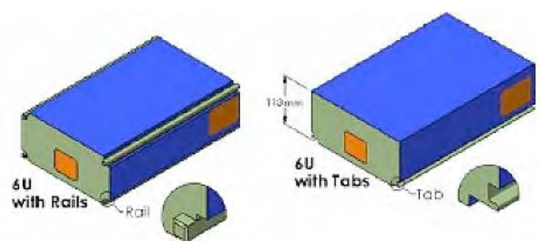
- Cubesats have been around since 1999
- They have been through a lengthy ‘Sputnik’ period
- Cubesat spacecraft capabilities have advanced…
- And they are now at their ’Explorer-1’ moment:
  - 2009 JPL begins technology validation payloads (Earth Science)
  - 2010 U. Mich Radio Aurora Explorer (Heliophysics)
  - 2011 Rob Staehle (JPL) Interplanetary cubesat NIAC study funded
  - 2014 MIT/Draper Labs Exoplanetsat cubesat (Astrophysics)
  - 2014 MIT/LL MicroMAS cubesat radiometer (Earth Science)
  - 2014 JPL RACE/CHARM μwave radiometer (Earth Science)
  - 2 interplanetary cubesat conferences
  - Cubesat ideas proposed to Mars program at recent LPI event
  - CubeSat ideas explored for Outer Planet missions (Europa)
  - 2014 JPL’s proposed INSPIRE could be the first cubesat to fly beyond Earth orbit (we think)
- Cubesats beyond Earth orbit would be an obvious next step for JPL

Cubesat Capabilities have advanced

- Position and Attitude Determination and Control
  - Active systems using reaction wheels, torquers, and sun sensors have provided <0.2 deg RMS
  - 3-sigma 2.3 arcsecond pointing has been demonstrated in lab
  - Position knowledge typically obtained by NORAD TLEs, or occasionally GPS
- Propulsion
  - 20 m/s cold gas systems have flown
  - JPL is developing a small (0.5-1U) propulsive stage (MEP) that could provide ~1 km/sec
- Command, Communications and Control
  - Microcontrollers (especially the MSP430, PIC and Atmel chips) have primarily been flown, Linux-based computers, ARM chips, and now FPGAs have all been demonstrated.
  - UHF L3 transceiver or Software Defined Radio >1.5 Mbps
- Power
  - Several deployable solar array configurations, capable of providing up to 50 W average
- Structure
  - CubeSat structure is driven by the dispenser design
  - Currently only 3U dispensers exist; expect 6U flight demo in 2013 or later

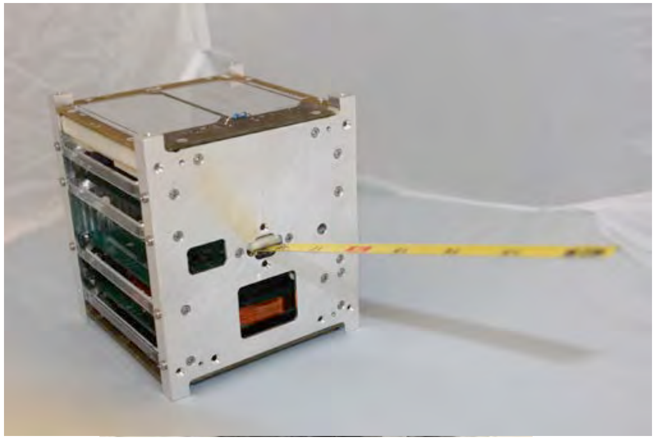
3U Cubesat



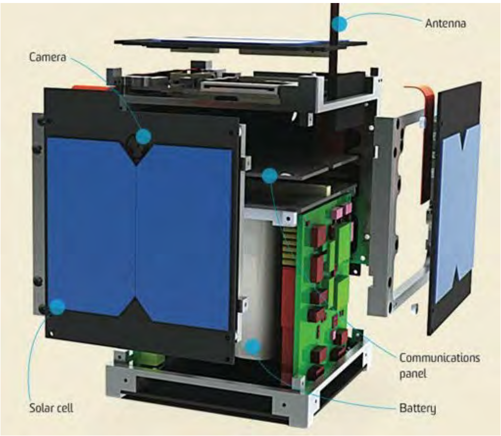


6U Cubesat

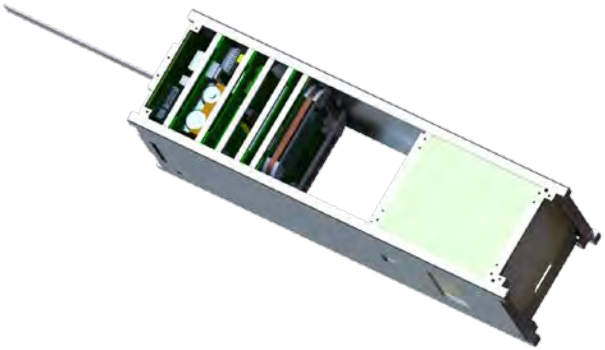
JPL is Already in the CubeSat Business



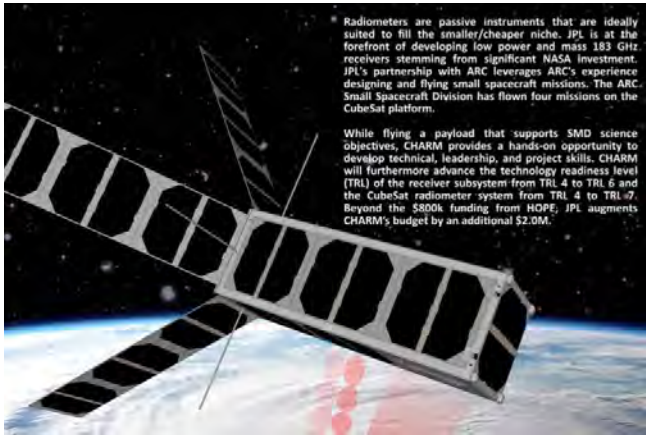
M-Cubed/COVE
High data-rate on-board processing
P. Pingree: JPL, U. Michigan



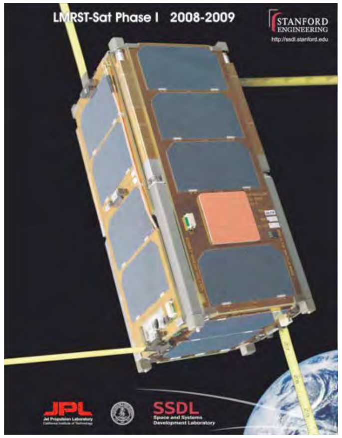
IPEX
Autonomous low-latency product generation
S. Chien: JPL, GSFC, Cal Poly SLO



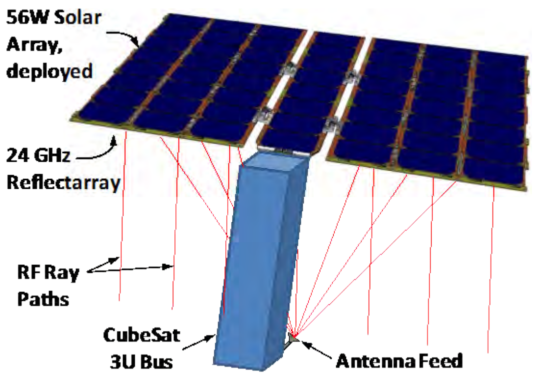
GRIFEX
Unprecedented frame-rate ROIC/FPA
D: Rider JPL, U. Michigan



RACE
183 GHz radiometer for precipitation science
B. Lim: JPL, UT Austin



LMRST*
Deep Space Radio Transponder
C. Duncan: JPL, Stanford



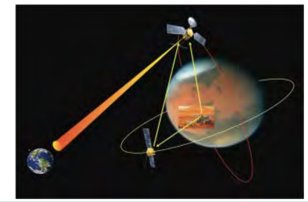
ISARA*
Integrated Solar Array & Reflectarray Antenna
R. Hodges: JPL, Pumpkin Inc.

*Proposed Mission - Pre-Decisional – for Planning and Discussion Purposes Only

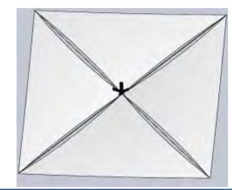
Getting to Interplanetary CubeSats

Six Technology Challenges

1. Interplanetary environment



2. Telecommunications



3. Propulsion (where needed)

4. Navigation

5.Instruments

6. Maximizing downlink info content

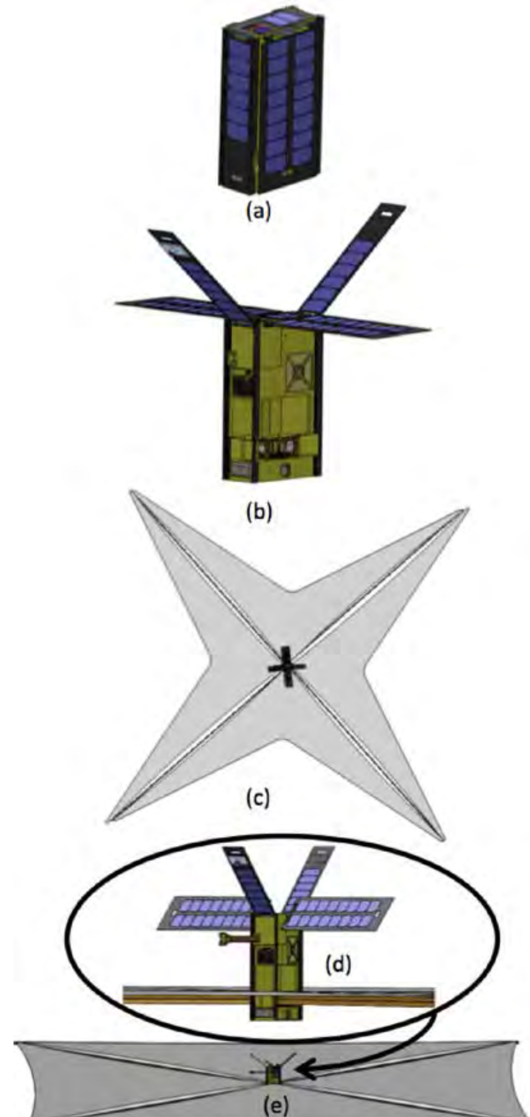
Taxonomy

- Launch off $C_3>0$ ~ballistic traj
  - Cruiser
- Depart from "Mothership", 10s to 100s m/sec
  - Companion
  - Orbiter
  - Lander
  - Impactor
- Self-propelled

  1 – 10 km/sec/yr
  - *Electric*
  - *Solar Sail*

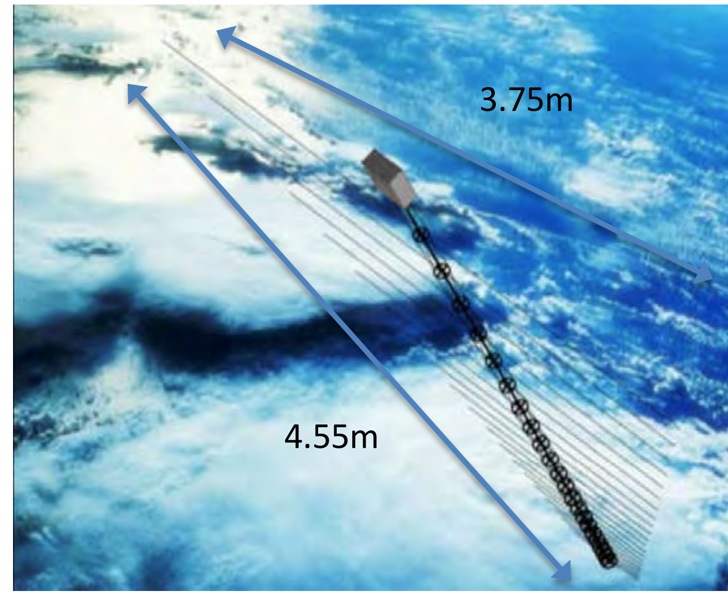
A Workable Interplanetary CubeSat System Architecture emerges from the maturation of six key technologies

LightSail 1tm: Planetary Society, Stellar Exploration, CalPoly-SLO
RAX-2: University of Michigan



JPL is Already in the CubeSat Business

INSPIRE*
Interplanetary Nano-Spacecraft Pathfinder in Relevant Environment
A. Klesh: JPL, U. Michigan, UT Austin, Cal Poly SLO



CHIRP*
CubeSat very high frequency transmitter to study Ionospheric transmission of Radio Pulses
A. Romero-Wolf: JPL

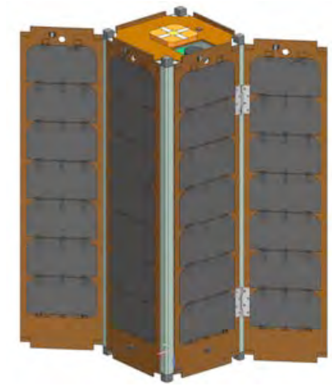
AAReST*
Autonomous Assembly and Reconfiguration Experiment for a Space Telescope (Tech Demo)
S. Pellegrino: Caltech

*Proposed Mission - Pre-Decisional – for Planning and Discussion Purposes Only

INSPIRE

INSPIRE would enable a new class of interplanetary explorer, while providing components to reduce the size and cost of traditional missions

Mission Objectives

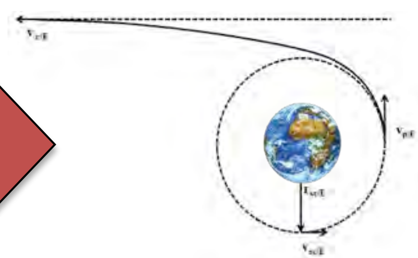


- Demonstrate and characterize key nano-spacecraft telecommunications, navigation, command & data handling, and relay communications for mother-daughter
- Demonstrate science utility with compact science payload (1/2U Helium Vector Magnetometer and Imager)
- Demonstrate ability to monitor and power cycle COTS/university processing systems

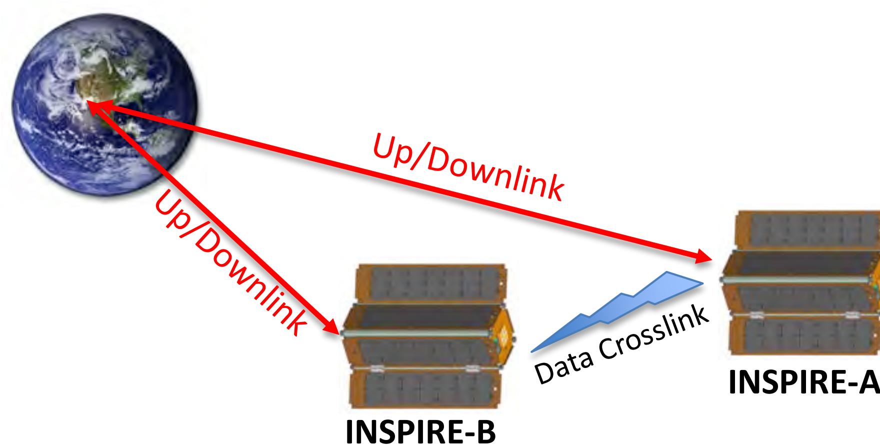
Mission Concept

- JPL-built spacecraft; collaborative partnerships with Michigan, Texas, and CalPoly/Tyvak for COTS processing systems. Ground stations at U. Michigan and Goldstone with DSN compatibility

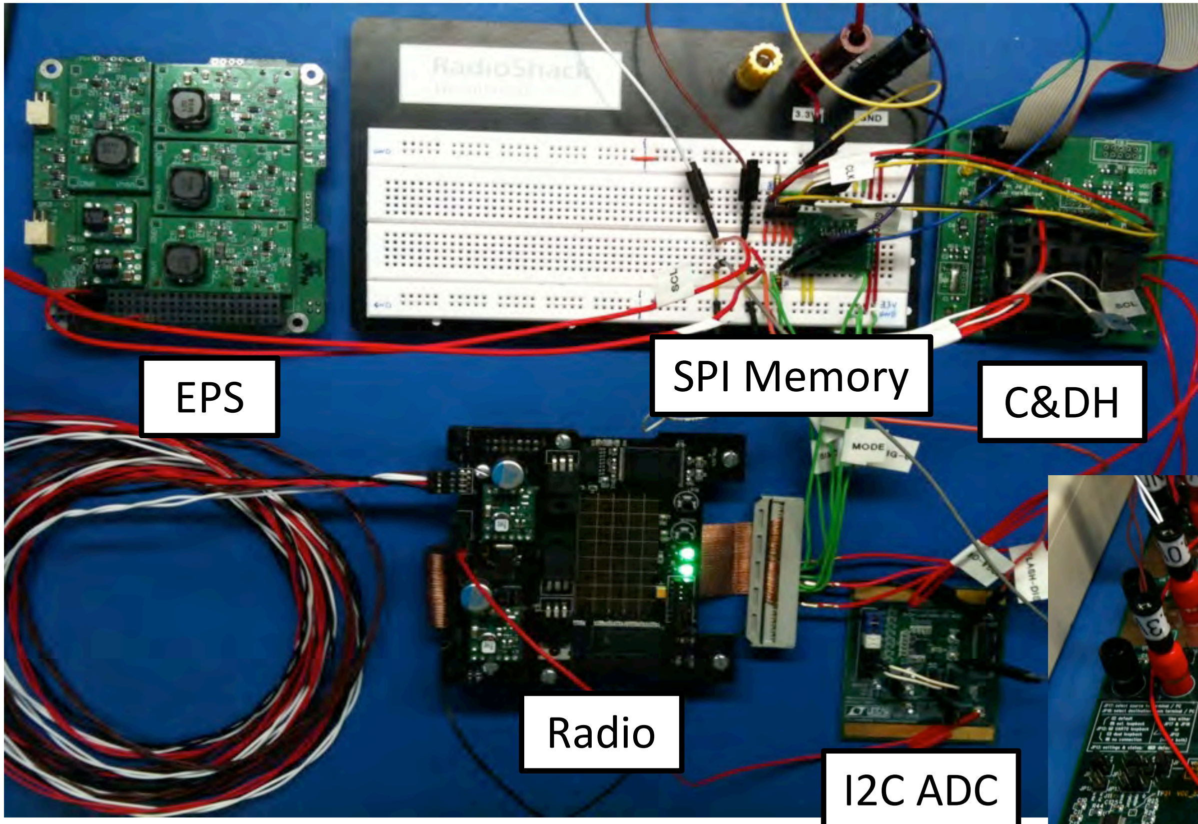
Nominal:
NASA CLI Launch:
Ready by Summer 2014



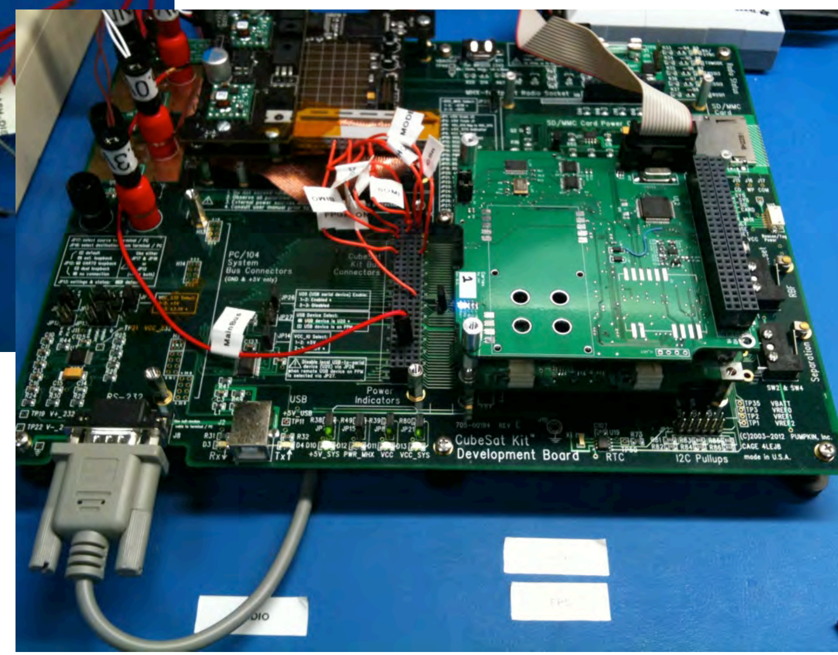
Nominal:
Deploy to Escape



Current INSPIRE Development



FlatSat in initial stack on development board



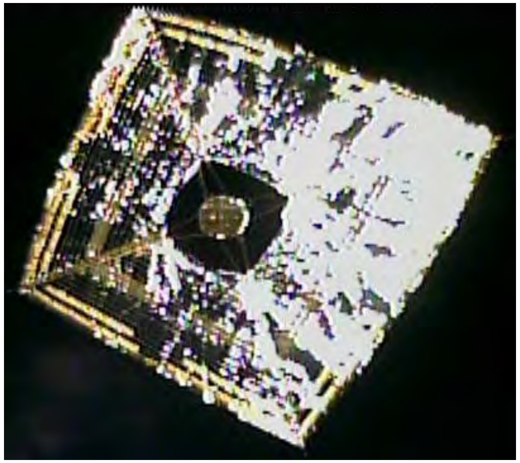
Current Status:

- Selected by the CubeSat Launch Initiative – awaiting manifest
- Prototype units are arriving at JPL (with interns). Characterization and integration is ongoing.
- 3 operating "Flat-Sats" for development and testing
- Approximately 10 months until launch ready

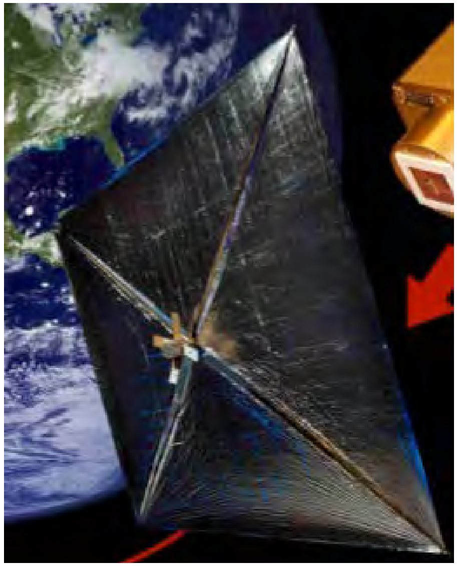
Solar Sail Technology

- Constant low-thrust propulsion with reduced mass and limited propellant use
- Several 400 m^2 sails have been deployed on the ground in demonstrations by NASA and DLR[1]
- Recent and upcoming Earth-orbiting solar sail technology demonstration flights[2-4]:

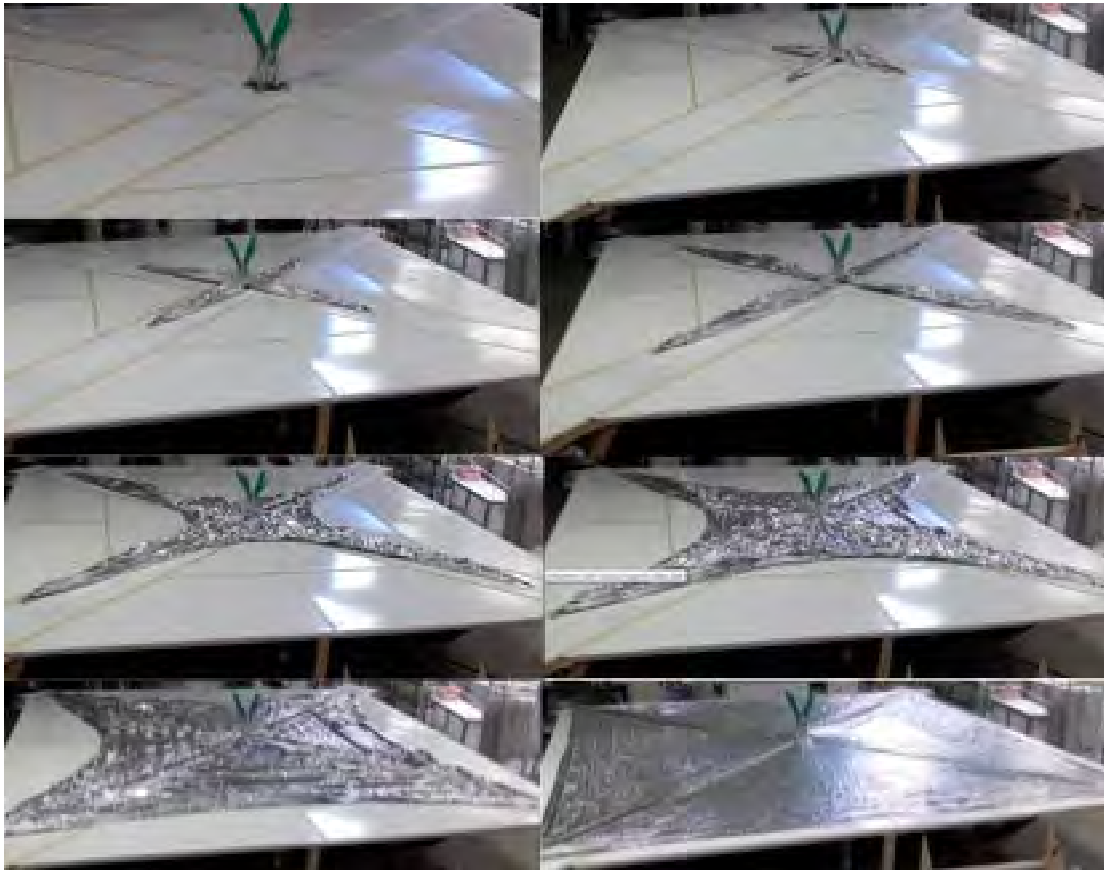
Name	Organization	Sail Size	Date	Spacecraft
IKAROS	JAXA	200 m^2	June 2010	Custom
NanoSail-D2	NASA/AFRL	10 m^2	January 2011	3U CubeSat
CubeSail	NASA/CU Aerospace/ Univ. of Illinois	25 m^2	Planned 2013	3U CubeSat
DeOrbitSail	Univ. of Surrey	25 m^2	Planned 2014	3U CubeSat
LightSail™-1	Planetary Society	32 m^2	Planned 2015	3U CubeSat

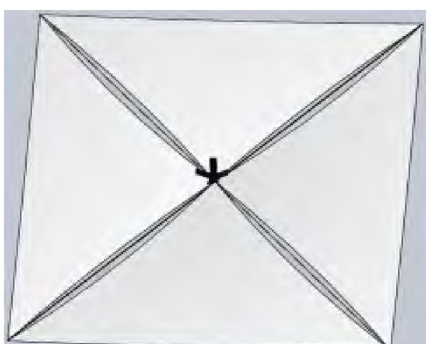


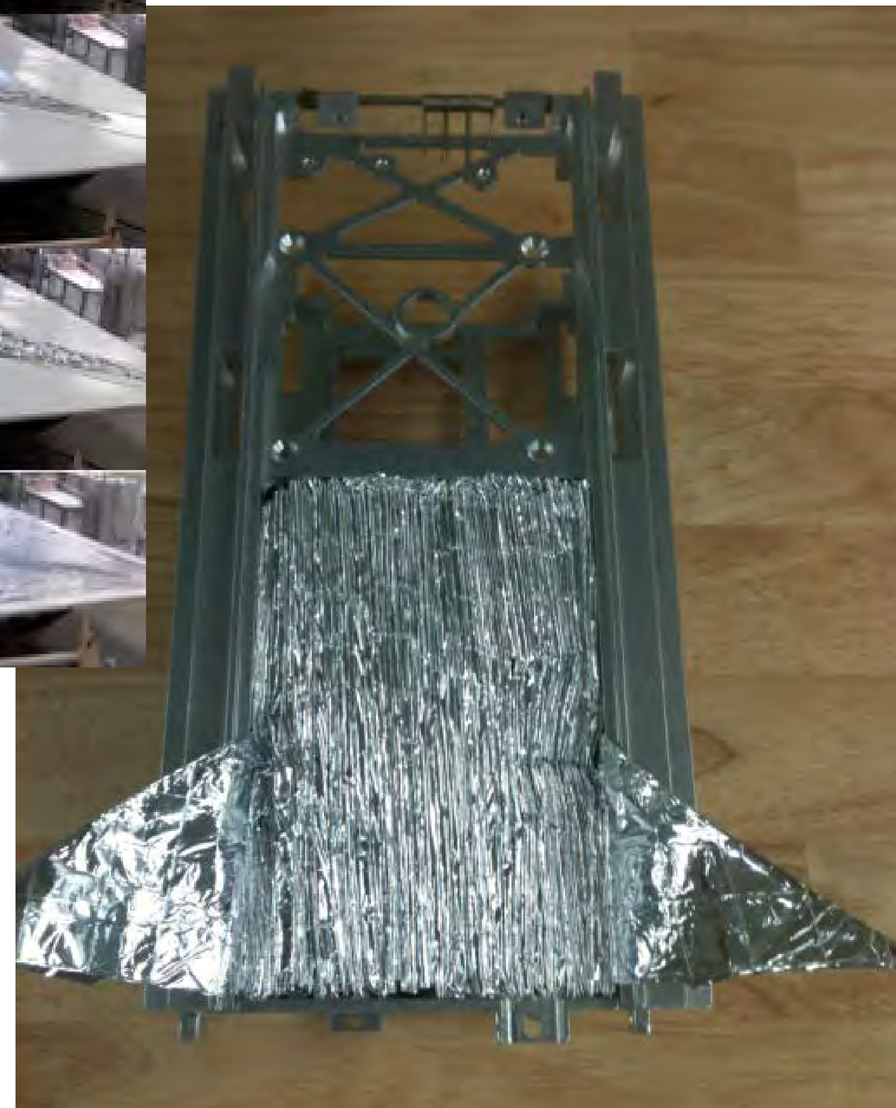
IKAROS Spacecraft (JAXA)[2]



NanoSail-D2 Spacecraft (NASA)[3]







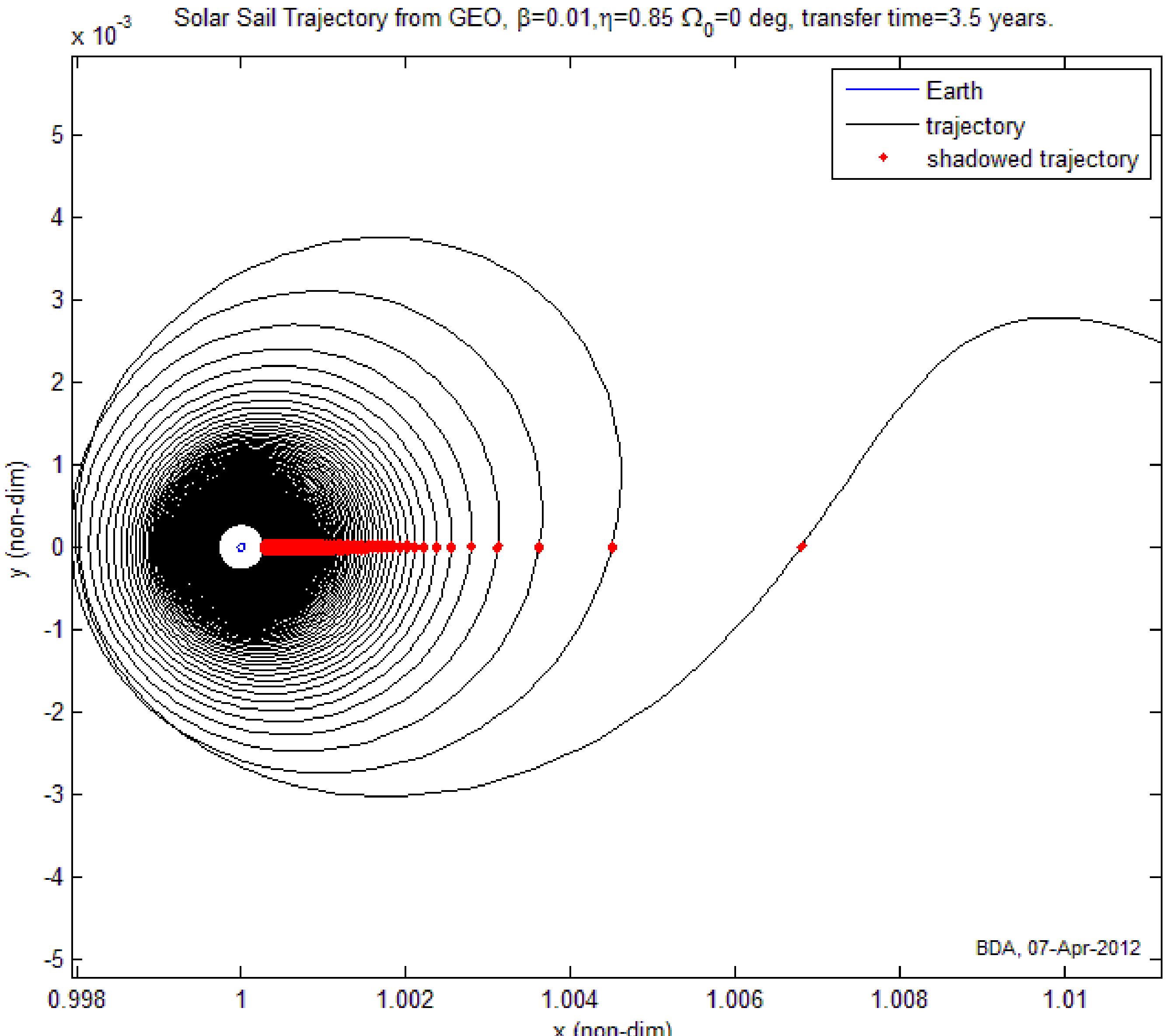
3. Propulsion

Solar Sail Earth Escape Trajectories from GEO

- Sail at 85% Efficiency
- 5.6m sail at 4.6 kg
- 10m & 20m sail at 10 kg
- Benefits of lunar gravity assist not accounted

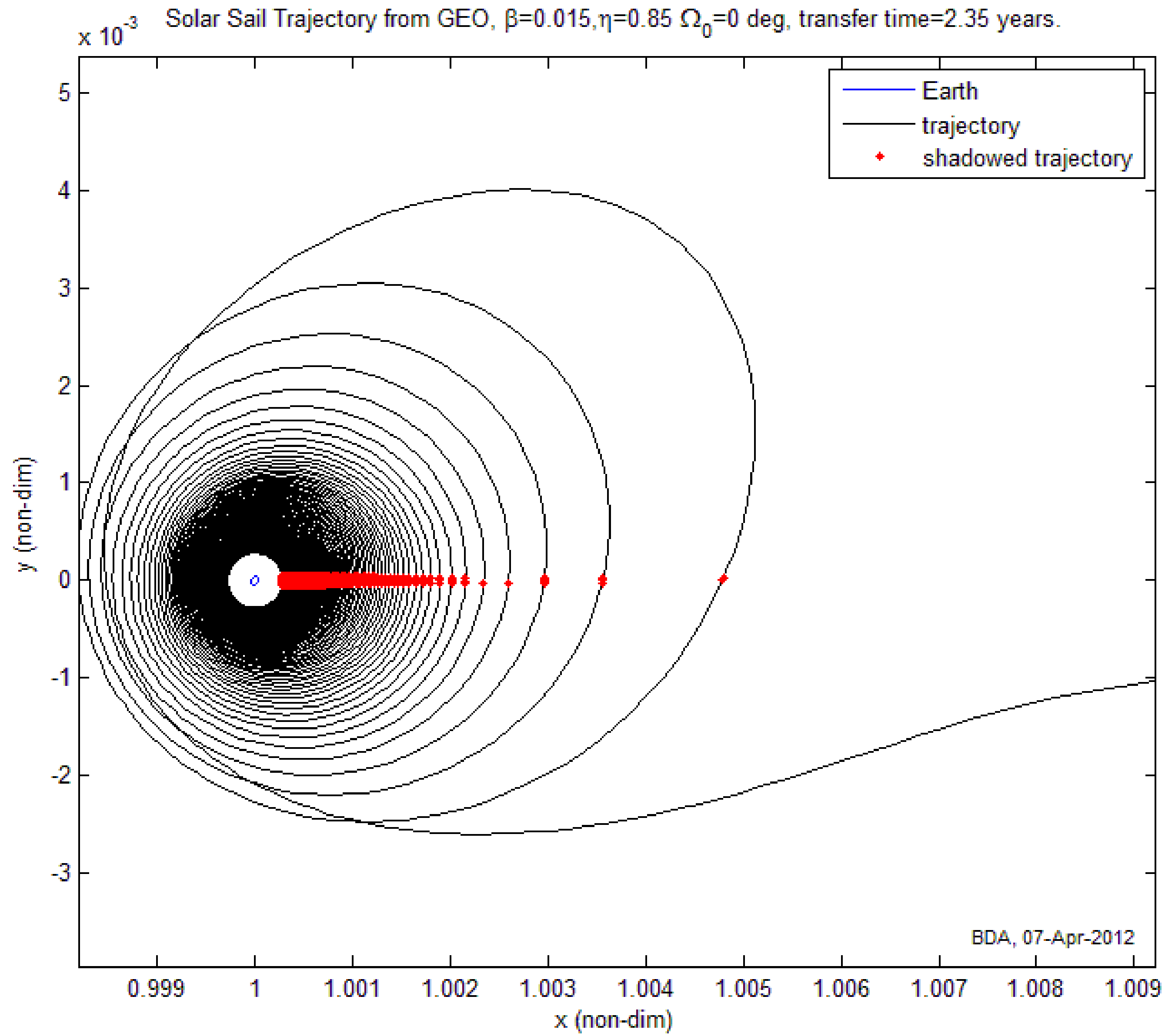
…if you can’t find a ride
to Earth escape or better

Earth Escape 5.6m Solar Sail, 3.5 Yrs.



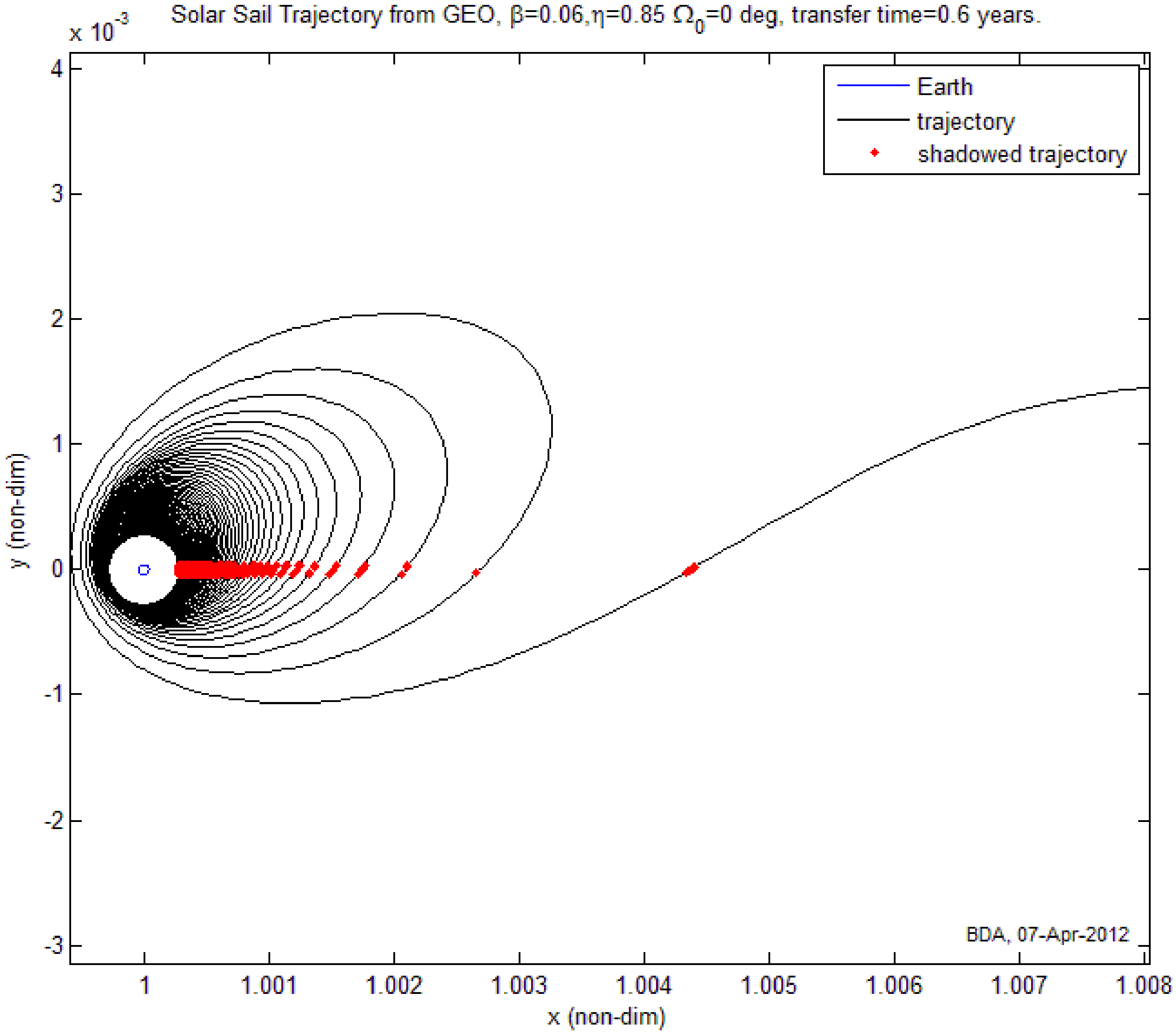
Brian Anderson (USC) and Martin Lo

Earth Escape 10m Solar Sail, 2.35 Yrs



Brian Anderson (USC) and Martin Lo

Earth Escape 20m Solar Sail, 0.6 Yrs.



Brian Anderson (USC) and Martin Lo

Concept of Operations

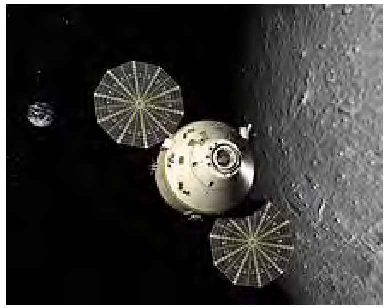
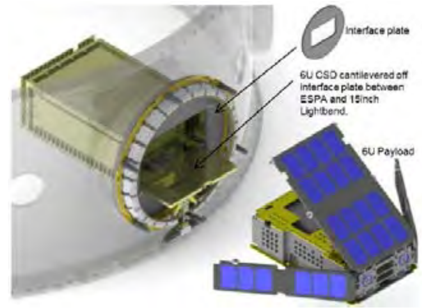
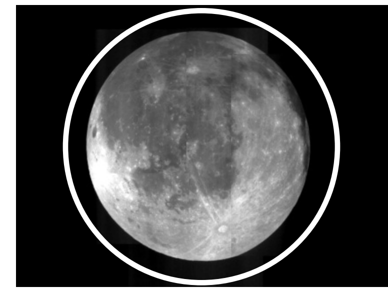
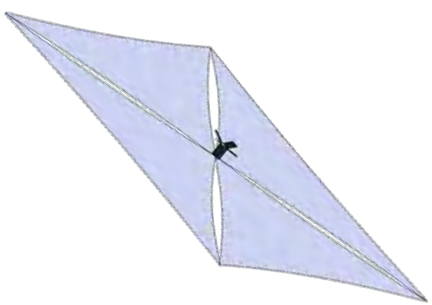
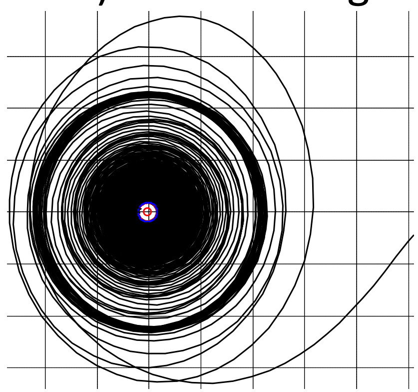
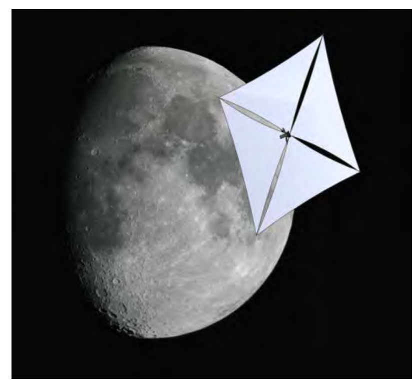
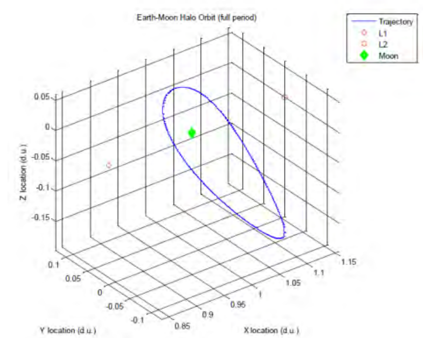
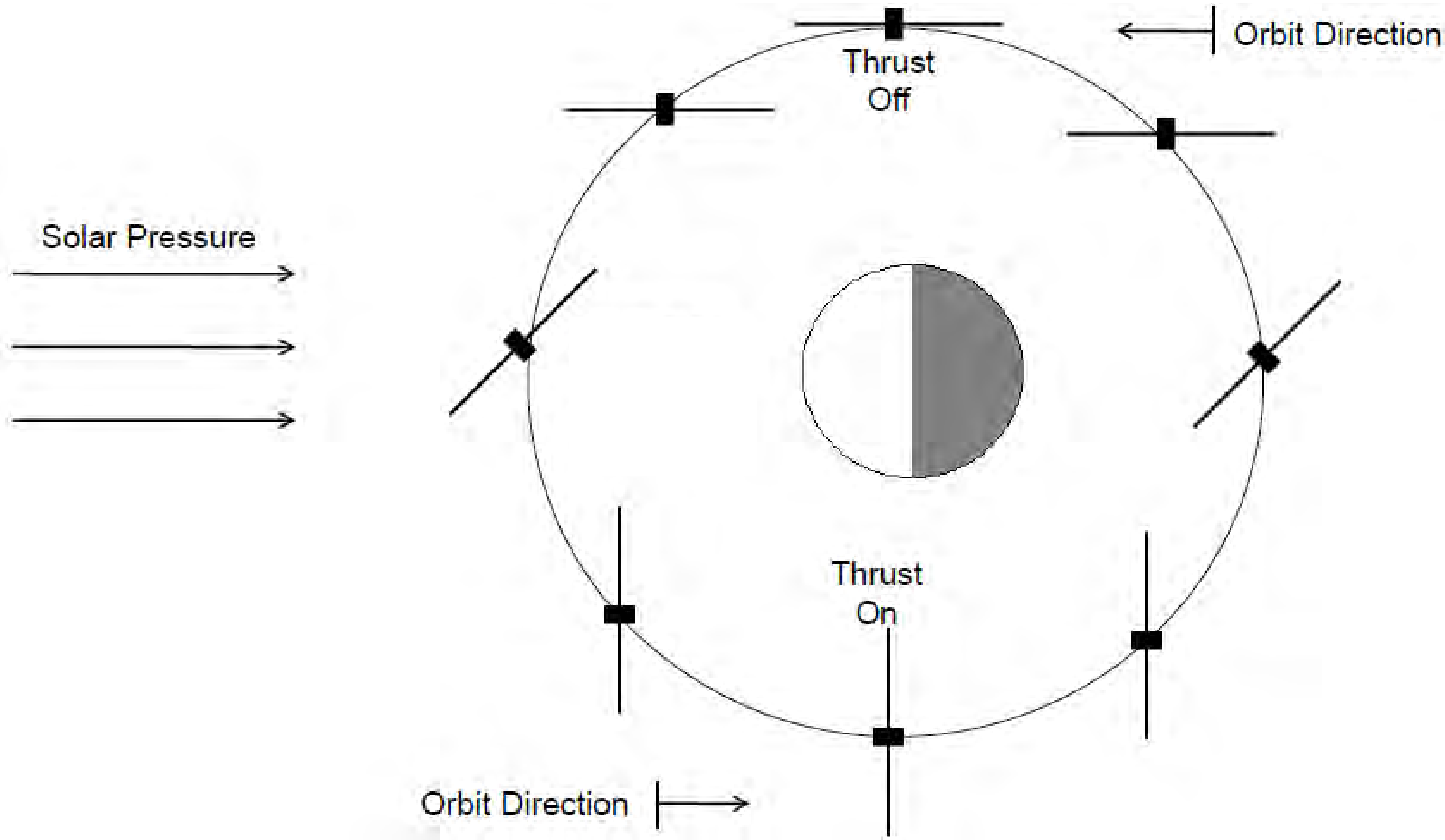
1.) Launch 	2.) Deliver to Moon on MPCV 	3.) Deploy 6U CubeSat from MPCV 	4.) Cruise Phase in Lunar Circular Orbit 
5.) Deploy Solar Sail 	6.) Orbit Raising 	7.) Transfer to L2 	8.) Halo Orbit at L2 

Image Sources: Panels 1,2, and 4 - various public NASA websites. Panel 3 - Canisterized Satellite Dispenser Data Sheet, p. 15, Planetary Systems Corporation website, http://www.planetarysystemscorp.com/#!   downloads

Solar Sail Thrust Control

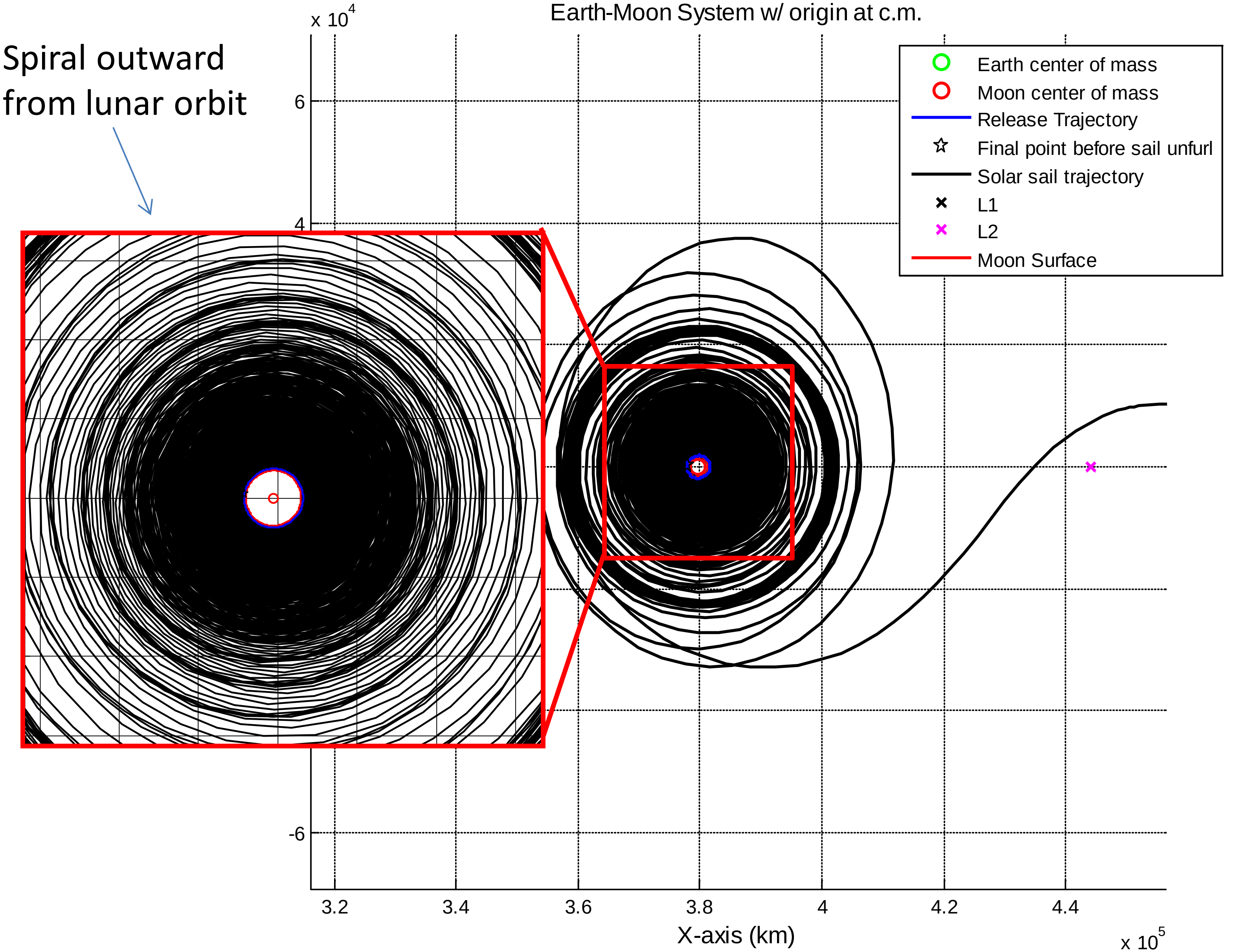
- Thrust off when moving toward Sun
- Thrust on when moving away from Sun



LightSail-1 Attitude Control System Orbit Raising Mode[7]

Orbit Raising Maneuver

Spiral outward from lunar orbit



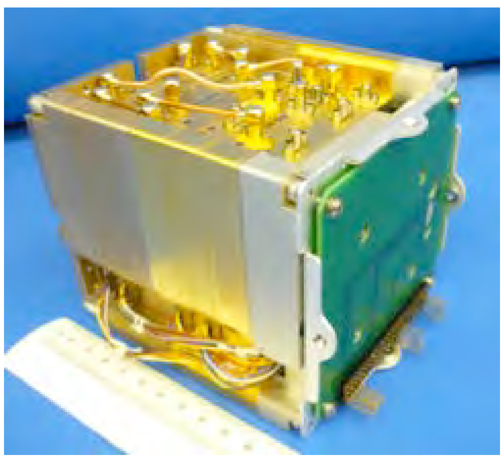
Candidate Science Mission Applications Enabled

- Significant orbital maneuvering capability of an inexpensive s/c in lunar orbits could be used for:
  - Radio survey and mapping of Moon's radio shadow[9]
  - Observations into polar craters[10]
  - Constellations to measure fields and particles with simultaneous spatial and temporal resolutions[9]
  - Telecom relay from small science packages emplaced out of Earth view on lunar farside and in some polar craters[10]

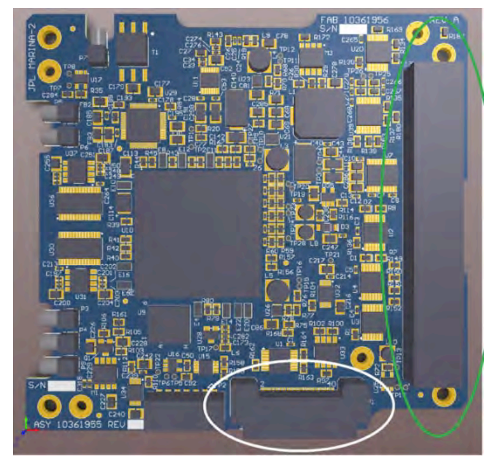
- If you can raise from 110 km circular orbit to escape, the same propulsion technique can be used to go from incoming V-infinity to any orbit

Iris X-Band Communication / Navigation Radio

- **Heritage:** Derived from extensive radio heritage from Electra, SDST and the Low Mass Radio Science Transponder (LMRST)
- **Technical:** ~8 GHz radio with a 5 W amplifier, supporting 2 x Rx and 2 x Tx patch antennas – 4x10x10cm at less than 0.5kg.
  - 62.5 bps to 256kpbs and 1kbps from 1.5m km
- **Navigation:** Coherent uplink / downlink allowing for accurate ranging and Doppler measurements.



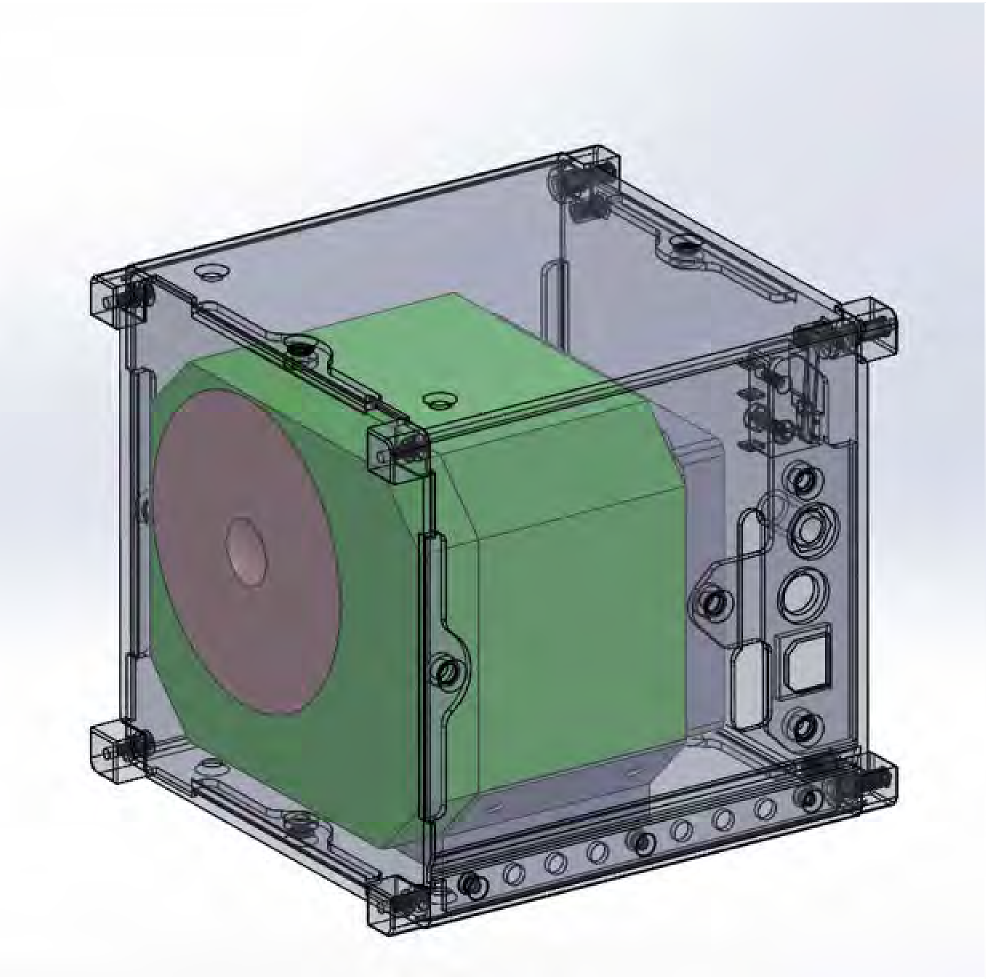
LMRST Prototype

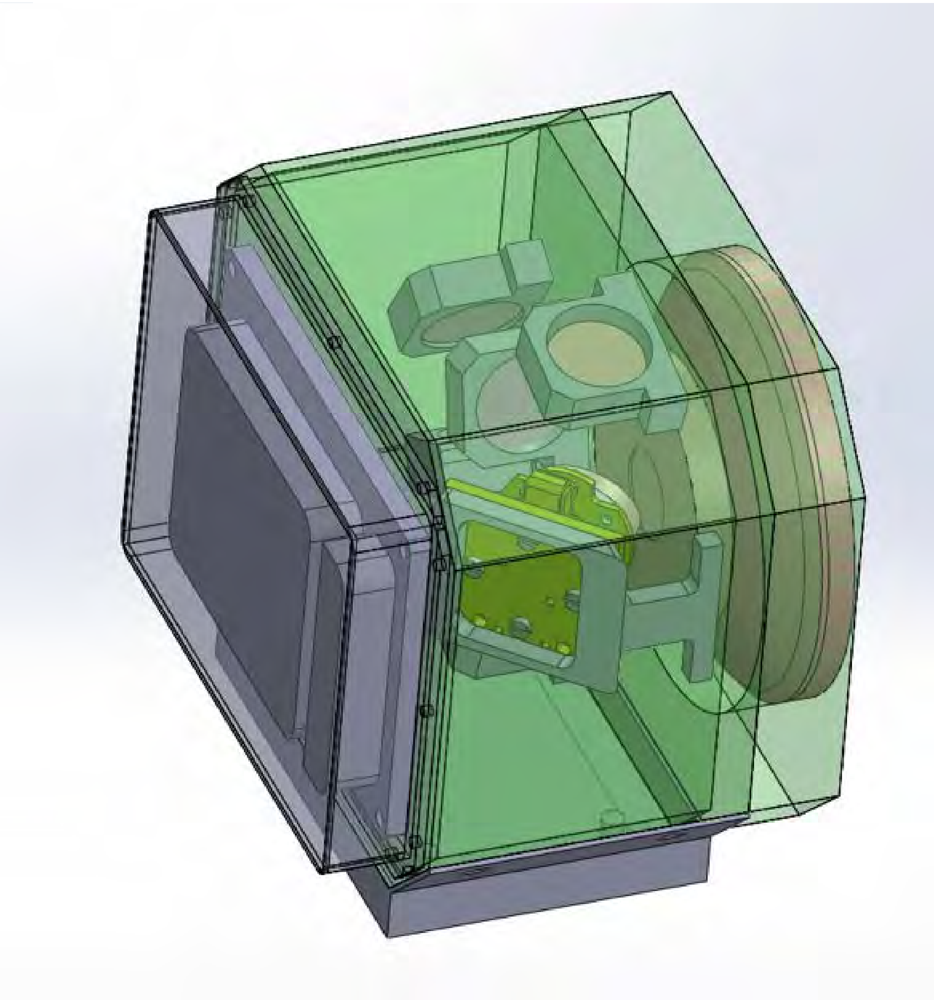


CubeSat Kit Compliant Iris Digital Board
(Arrives next week)

- **Operations:** DSN / CCSDS Compliant – libraries built for NASA AMMOS mission operations / ground data systems software, but are flexible

Monolithic optical transceiver for CubeSat 1U form factor





Hamid Hemmati, 2012 March

Laser Telecom
Uplink and Downlink Options

-------------Downlink-------------   ---Uplink---

A

5 m
Hale

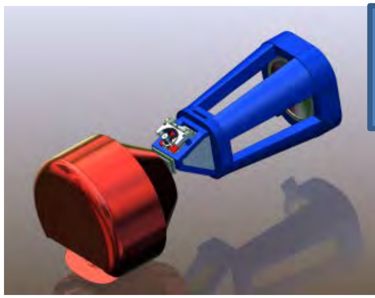
B

11.8 m
Large Binocular
Telescope (LBT)

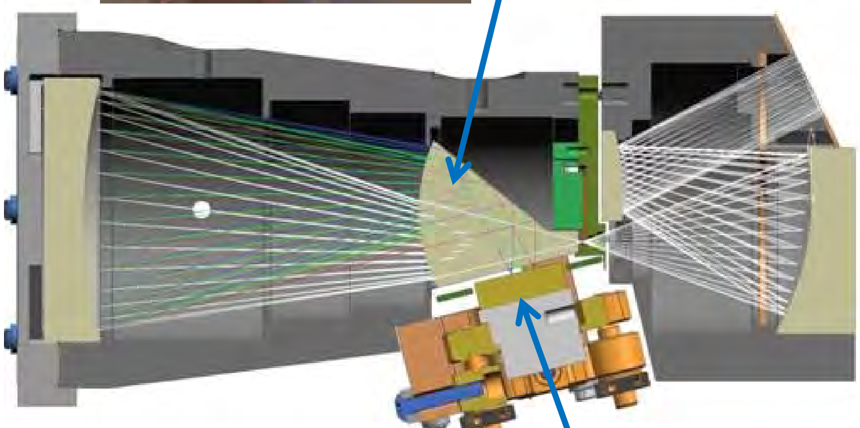
C

1 m
Optical Communications
Telescope Laboratory
(OCTL)

Hamid Hemmati, 2012 March



5.Instruments



Overview

The spectrometer is a miniaturized version of the compact Dyson design form that is currently under development at JPL and elsewhere. Our work will extend our concept from the PRISM airborne spectrometer, tested in early 2012, and a fast, wide-field imaging spectrometer demonstrated as a laboratory breadboard through NASA's PIDDP program.

Instrument Electronics

- Detector similar to the one flown on PRISM (Portable Remote Imaging Spectrometer)
- Data processing based on a heritage design
- Consumes ~1W of average power
- Detector interface and data storage would be a new design feature

Parameter	Value
Wavelength Range	450-1650 nm
Wavelength Sampling	10 nm
Detector Type	Thinned InGaAs array
Pixel Pitch	25 µm typ.
Angular Resolution	0.5 mrad
Field of View	14°
Detector Operating Temp	270 K
Response Uniformity	'95%

6. Maximizing downlink information content

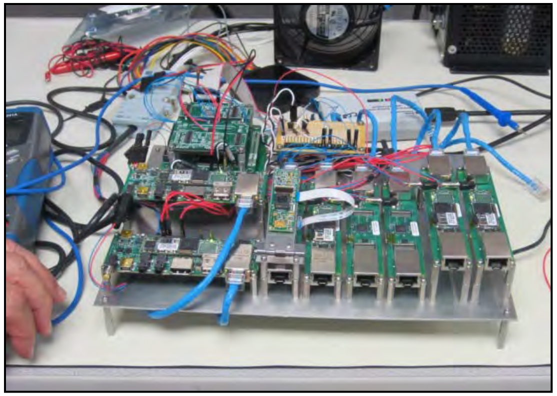
CubeSat Onboard processing Validation Experiment (COVE)*

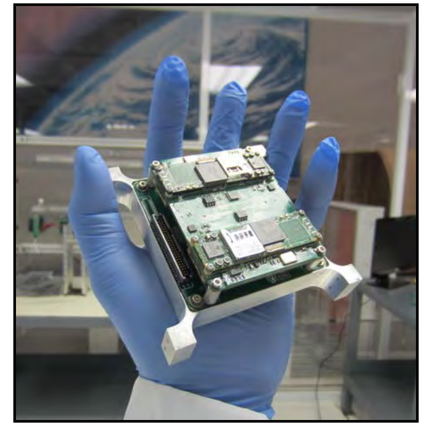
- Funded by NASA Earth Science Technology Office (ESTO)
- JPL payload aboard University of Michigan's M-Cubed CubeSat
- Launched 2011 Oct 28 with NPP

- Intended to demonstrate Xilinx V5QV FPGA with an algorithm to reduce output data rate from MSPI's 9 multi-angle cameras by more than 200x.
- ?Executed unintentional first autonomous docking with Montana State's E1P CubeSat?
- Funded for re-build/re-flight.

* Dmitriy L. Bekker, Paula J. Pingree, Thomas A. Werne, Thor O. Wilson, Brian R. Franklin, *The COVE Payload – A Reconfigurable FPGA-Based Processor for CubeSats*, USU SmallSat Conf, Logan, UT 2012 August.

DM Cube: Dependable Multiple Processor for Nanosat Applications



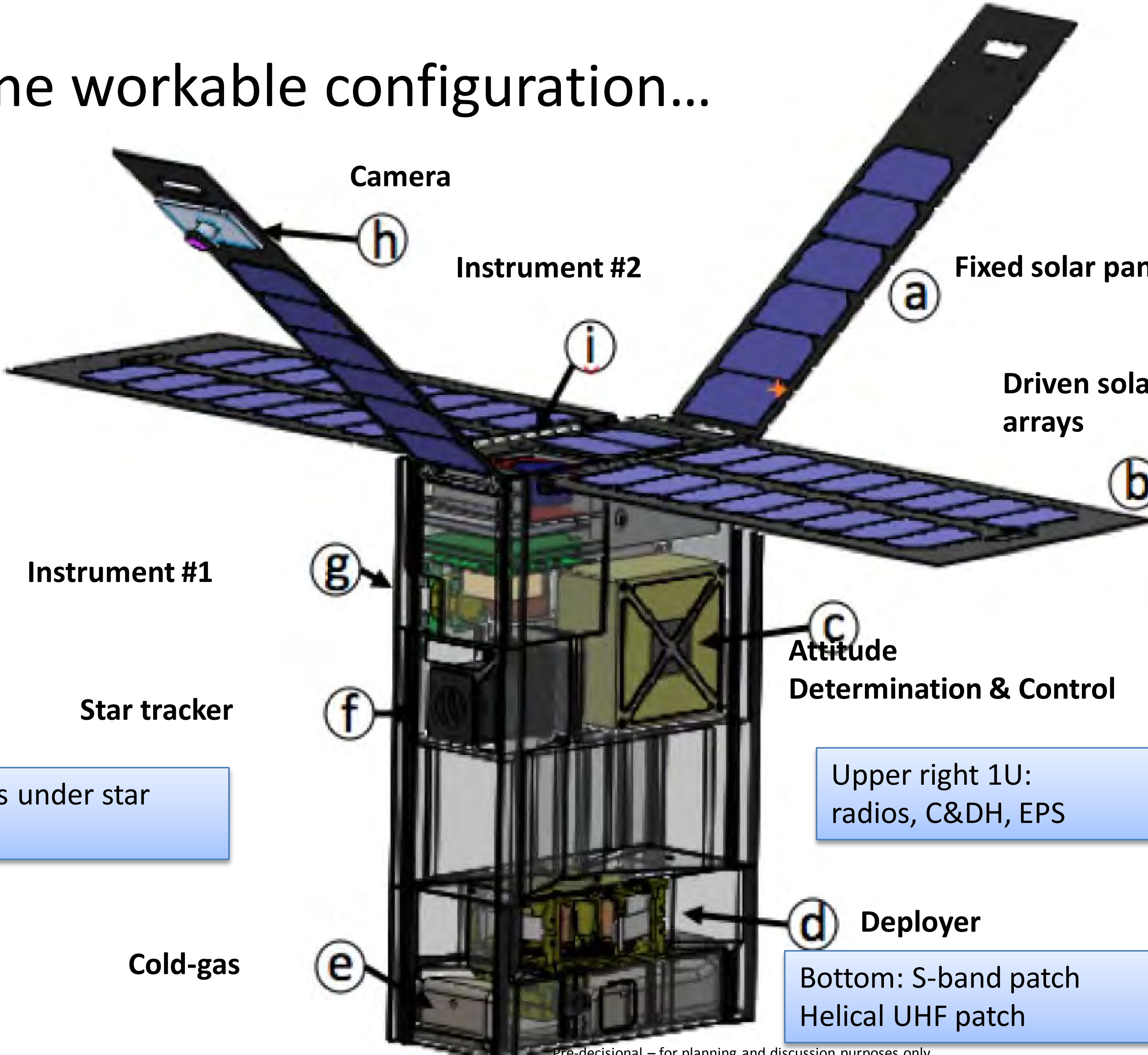


•Developed by Morehead and Honeywell Space and Defense for the US SMDC
•Based on small, light-weight, low-power, low-cost, Gumstix™ COM (Computer-On-Module)-based, for high-performance onboard payload processing
•Leverages $14M NASA NMP ST8 investment in the development of DM technology
• Scalable cluster of high (COTS) processors to >24
•Peak throughput density of 300 million (MOPS)/watt
•Fault tolerant DM Middleware (DMM) + 8 Processors mitigate high-current SEFIs and will be resilient to total radiation doses expected in the lunar environment
•8 Processor version: mass = 0.24 U and weight =350 g

Processor Architecture	Clock Rate	Memory	Max Power Usage	Digital Interface Types	Mode	Manufacturer
Cluster Nodes: ARM Cortex A8	600 MHz	512 MB RAM 512 MB Flash	1.5 Watt	UART, I2C, USB, SPI, CAN, PHY	Network Node	Gumstix™
Cluster Backbone	24 MHz	1 MB	2.0 Watts	PHY, UART, SPI	Network Backbone & Management Interface	MSU

Benjamin Malphrus/Morehead State Univ

One workable configuration…

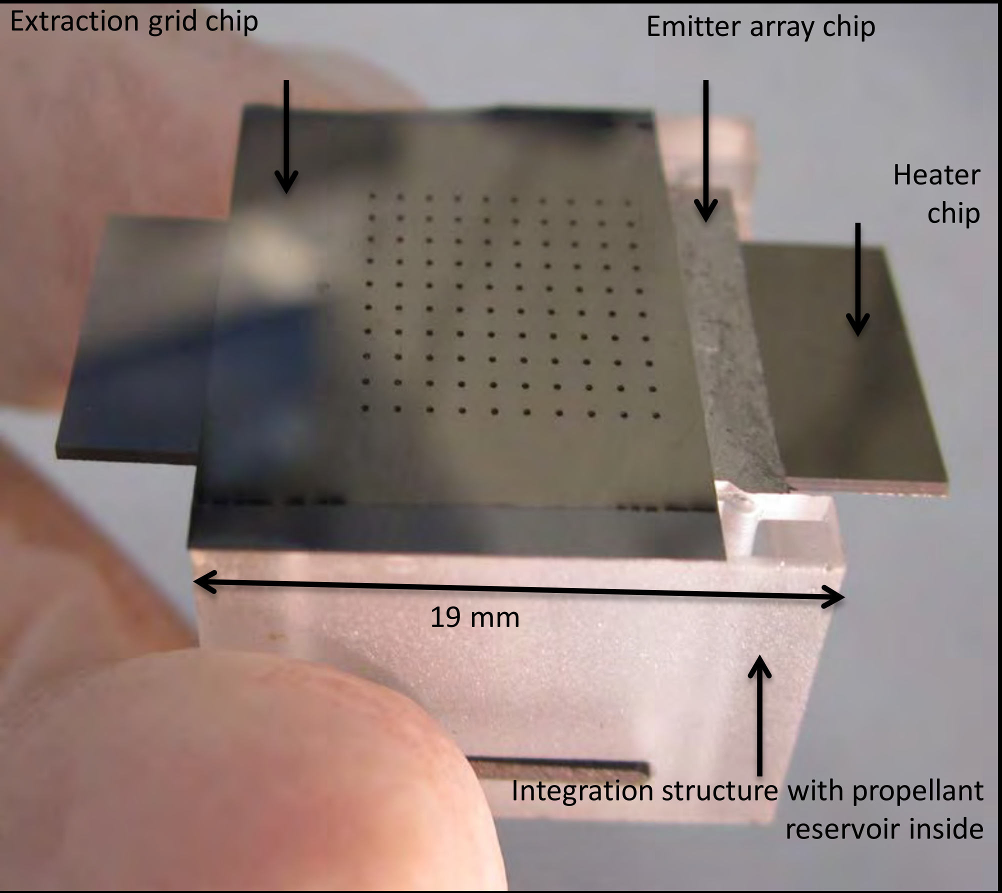


Batteries under star tracker

Upper right 1U: radios, C&DH, EPS

Bottom: S-band patch
Helical UHF patch

The MEP Technology



MEP Thruster Prototype

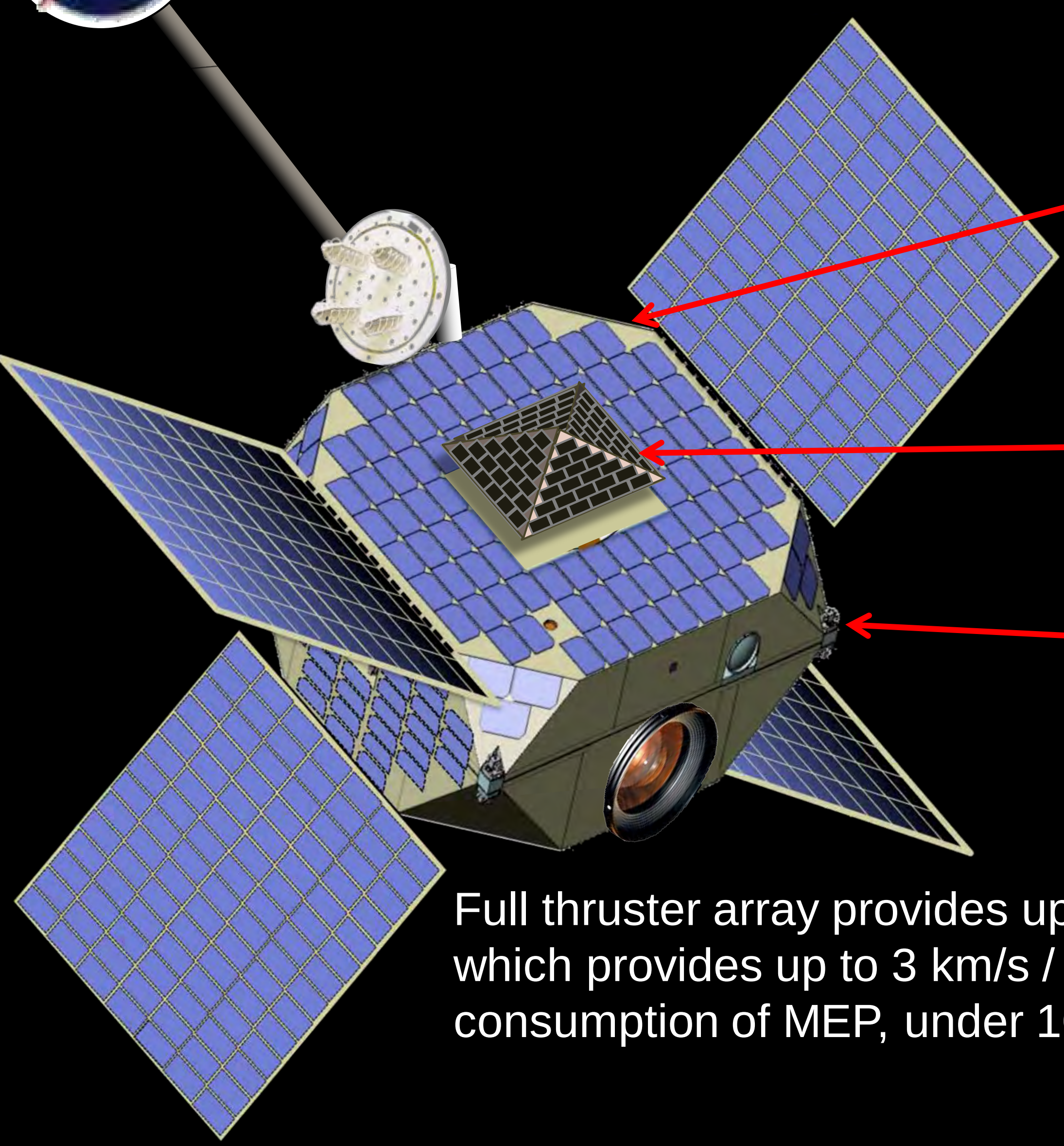
MEP Thruster technology is under development for precision pointing, slewing, and orbit transfer of very small to very large deployable spacecraft with a highly distributed architecture capability.

MEP is highly scalable with a low mass, simple and compact architecture

- Scalable microfabricated components
- Highly integrated capillary force driven feed system
- 6 parts total in head, feed system and reservoir
- No valves or pressurized reservoir
- High density solid indium propellant, 7 g/cm^3
- Micronewtons to millinewtons of thrust, per element – elements can be arrayed in any-size propulsion system
- 100 micronewton thruster mass < 10 grams

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

MEP Notional Thruster Cluster



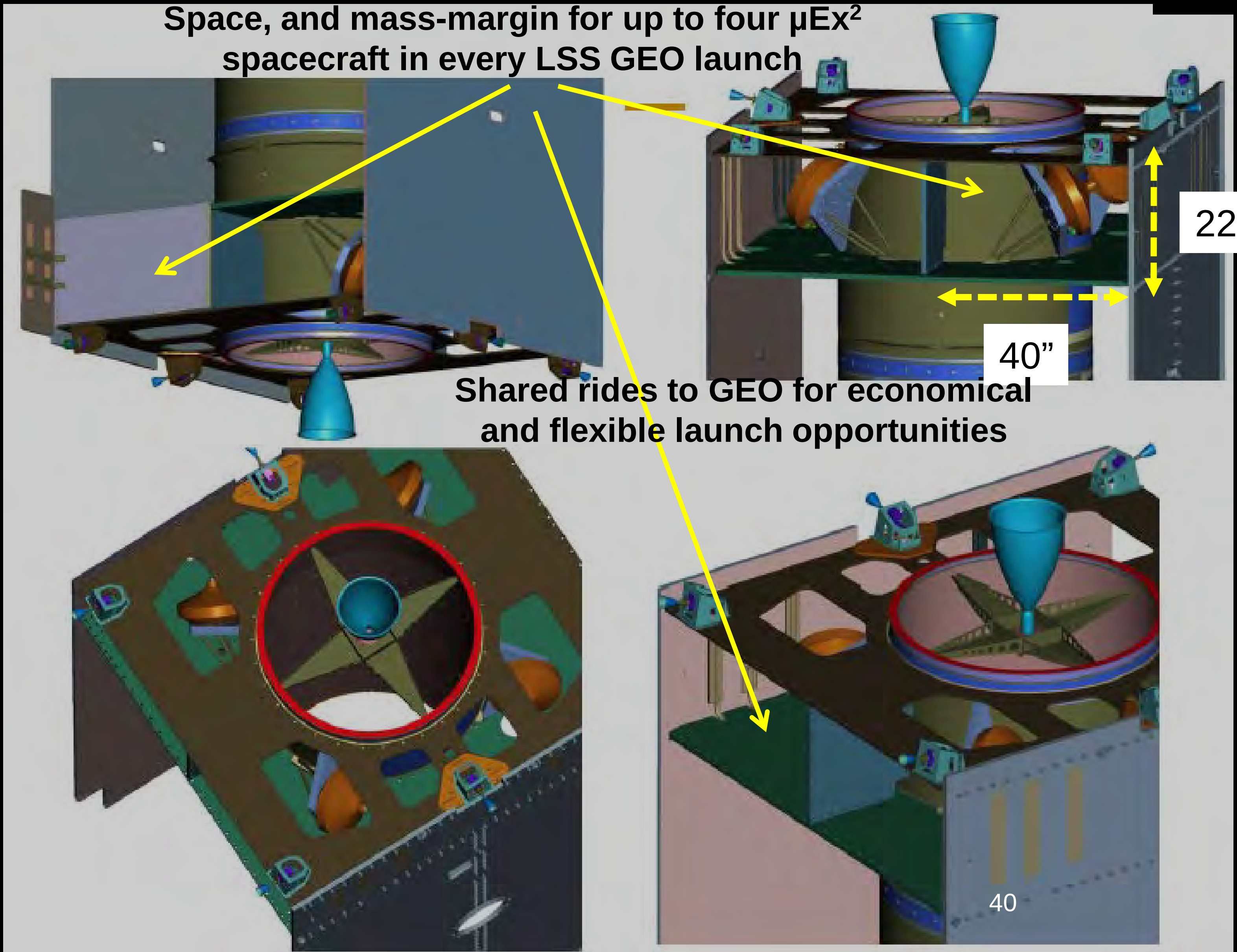
3D Array of MEP thrusters, arranged to allow removal of 3 dimensions of torque via bank-wise off-pulsing via Indium propellant heater cycling

Individual MEP solid-state thruster chips, for propulsion and limited attitude control

Butane micro-thruster clusters for proximity operations and rapid attitude changes

Full thruster array provides up to 5 mN thrust, which provides up to 3 km/s / year. Total power consumption of MEP, under 100 W (for 2 mN)

Other Launch Opportunities

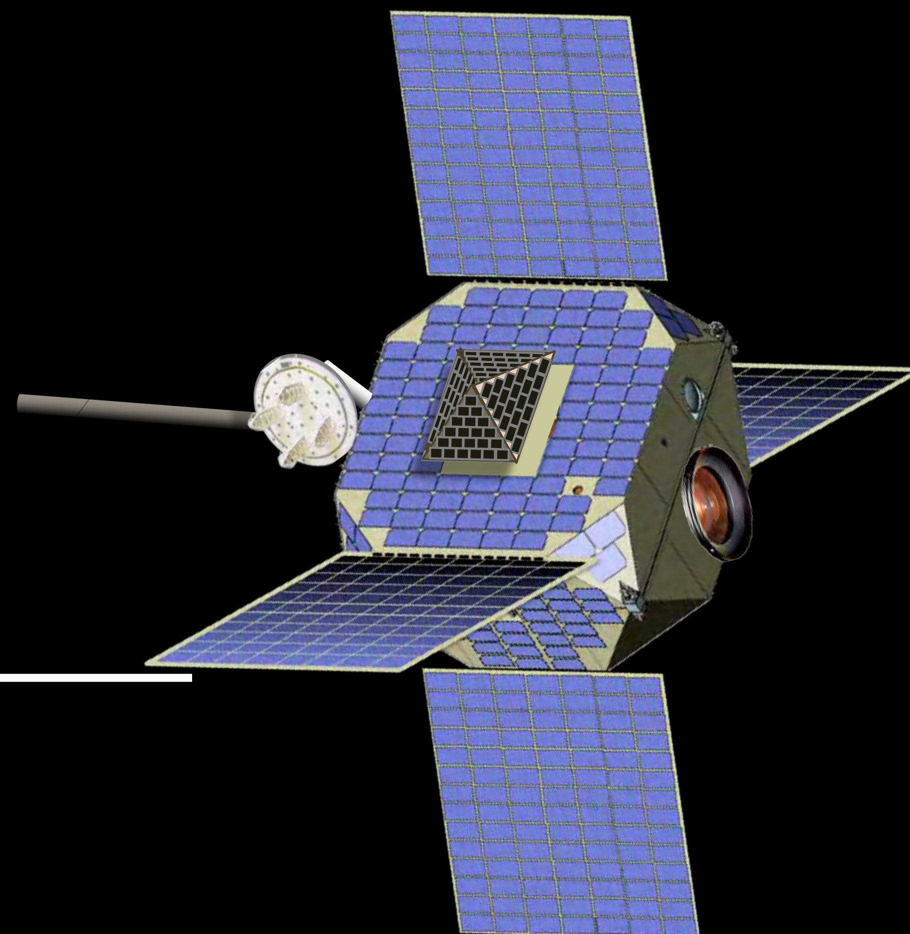


National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology

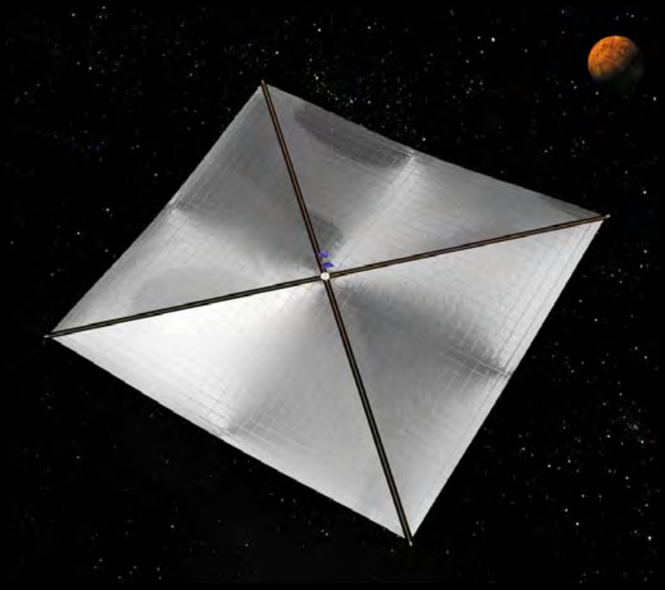
μEx^2 Mass Overview

Structure, Power, Antennas:	6.9 kg
Science and Navigation Payloads:	6.0 kg
Avionics	4.4 kg
MEP (main and ACS)	4.4 kg
Butane propulsion system	5.4 kg
Miscellaneous	1.0 kg
Butane Propellant	5.0 kg
Indium Propellant	8.0 kg
Total (Maximum Expected Value)	41.1 kg
Total Allocated Wet/Loaded Mass	50.0kg



JPL Innovation Foundry

The Future – Lunar Science Concepts



Cosmology, radio science, and other topics

Ground Segment: Morehead 21 M

- Full-Motion, High Precision Dish
- Designed and Built with NASA assistance
- Operational in 2006
- Replaceable feeds including L-band, S-band, C-band,and Ku-band
- Provides Experimental and IOAG Compatible TT&C Services
- Operated Largely by Cost-effective Undergraduate Students
- High Gain and Extreme Accuracy reduce comms link with small, low power, distant S/C
- Station is ideal for LEO and lunar spacecraft experiments and operations

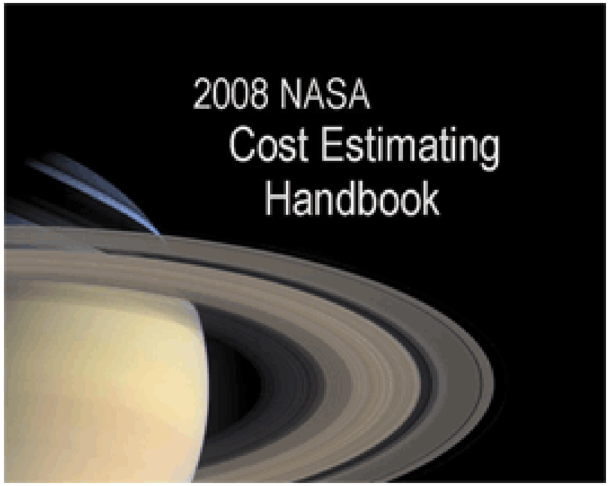
Benjamin Malphrus/Morehead State Univ

On-going Initiatives

Dedicated Facilities
Community Labs and Environmental Test Capabilities

CubeSat Tracking Station
UHF/VHF (receive-only) and other capabilities

Deep Space Network (DSN)
Standard Interfaces, Services, Ops & Nav Support beyond LEO



Cost Model Development
New models relevant to small missions

Conclusions

INSPIRE would enable a new class of interplanetary explorer,
while providing components to reduce the size and cost of traditional missions

- Deep space NanoSpacecraft are scientifically compelling – but they must be proven before PI / reviewer acceptance
- INSPIRE would demonstrate survivability, navigation and communication utilizing the CubeSat platform, and in partnership with the CubeSat community
- INSPIRE is partnering with the CubeSat community to extend capabilities to deep space
  - Peach Mountain and DSS-13 receive stations
  - Robust low-power C&DH
  - Monitored high-power processing
  - 3-axis cold-gas system
- JPL is developing novel technologies to support these and future missions
  - X-band Nav/Comm radio
  - Vector-Helium Magnetometer
  - DSN Compatible Ground Data System and Flight Software