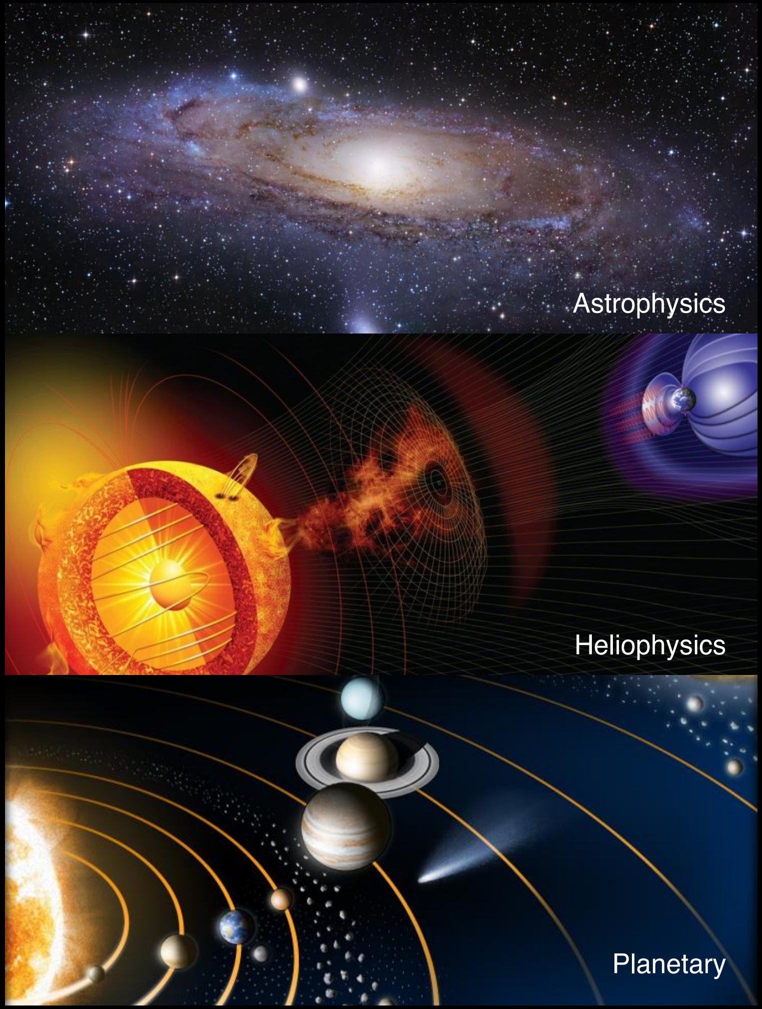
JPL's Advanced CubeSat Concepts for Interplanetary Science and Exploration Missions

CubeSat Workshop 2015

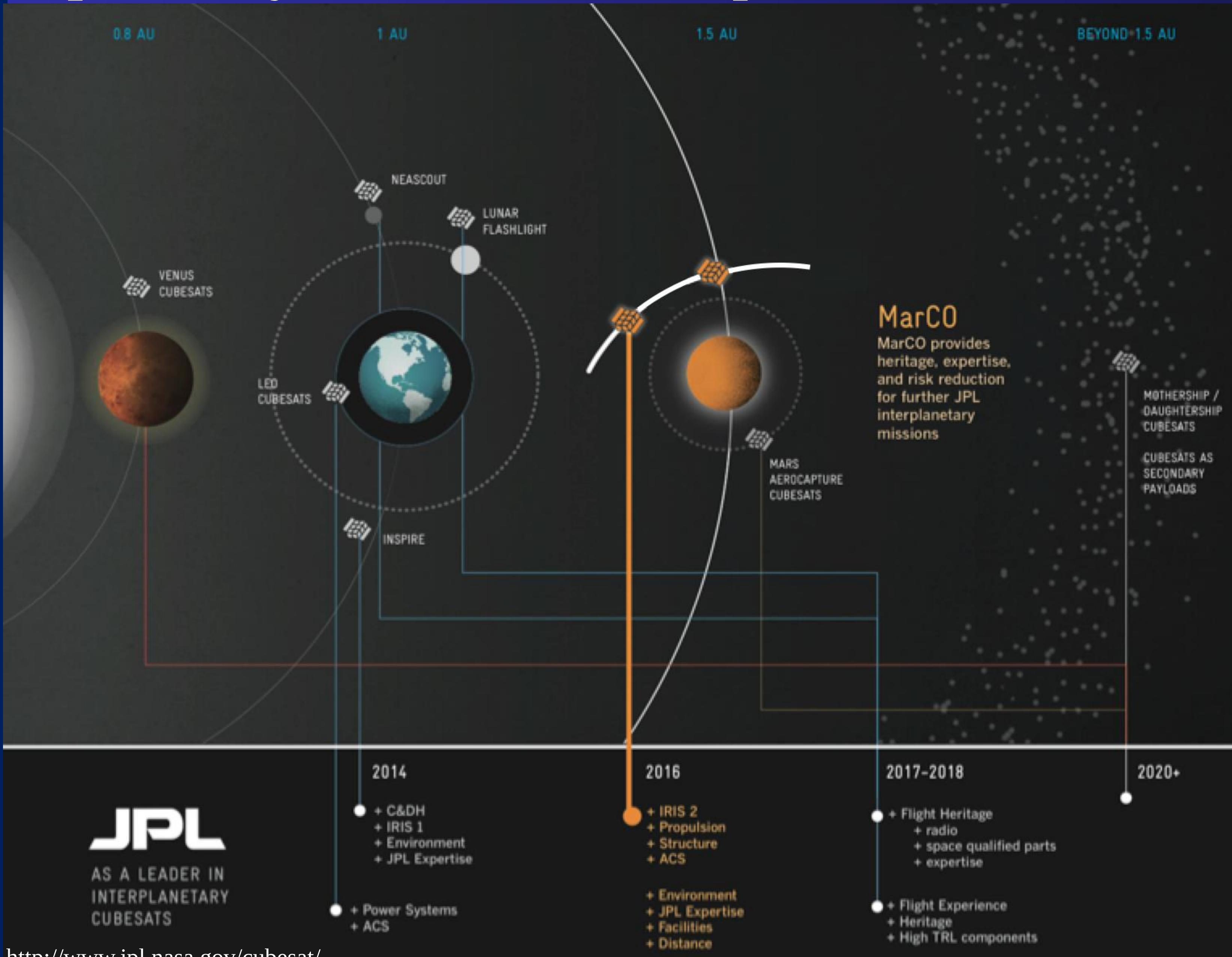


Sara Spangelo, Julie Castillo-Rogez, Andy Frick, Andy Klesh, Brent Sherwood, NASA JPL/ Caltech

CubeSat Workshop, Logan, Utah, August 2015

JPL Interplanetary CubeSat Roadmap

CubeSat Workshop 2015



http://www.jpl.nasa.gov/cubesat/

Overview of Interplanetary Small Spacecraft

Planetary small spacecraft (e.g. CubeSats) that fly as secondaries and are deployed at destinations to perform missions and communicate via mothership or direct to Earth

- Planetary Science and Exploration Value:
  - Enhance primary's science objectives
  - Enable new science and exploration in new, potentially dangerous environments
- Novel Technology Demonstrations:
  - Mature technology (TRL) of new instruments or measurements
- Accept higher risk by exploring dangerous/unknown environments
- Relatively low cost ($10-$25M, < 5-10% of primary mission costs)
- Low additive mass (5-20 kg with deployer, <10% of primary mission)

- Interplanetary CubeSats leverage:
  - CubeSat community hardware/software heritage, experience
  - Miniaturized instrumentation (imagers, sensors, etc.) at << 1 kg
  - Autonomous operations and telecommunication technologies

IPEX CubeSat (LEO)
On-Board Science Decision and Planning
(IPEX, NASA/JPL/CalPoly)

INSPIRE CubeSat
(Interplanetary)
EPS, Star Tracker

JPL's Infrared Imagers (M3, NASA/JPL)

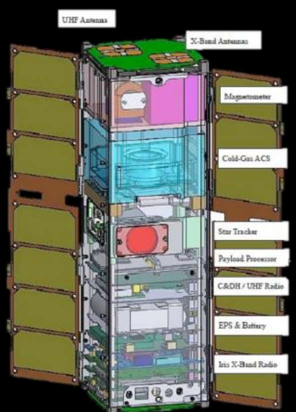
Small Infrared Imager

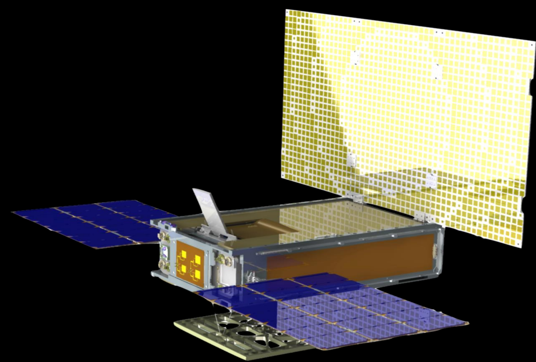
Active Interplanetary CubeSat Projects Provide Heritage

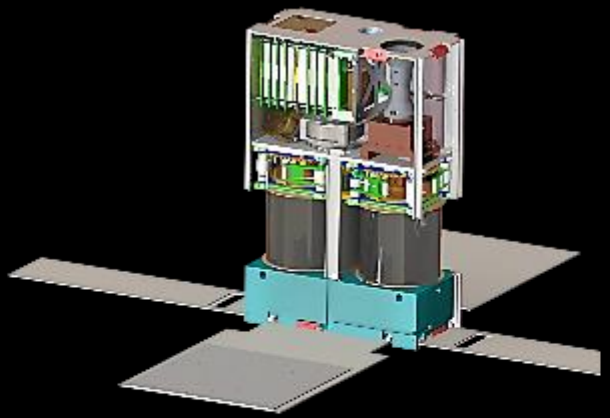
INSPIRE- Navigation demonstration with Iris beyond Moon
I&T Complete, Awaiting Launch

MarCO- InSight Insertion real-time Mars relay
Launch March 2016 to Mars

NEAScout- Asteroid Detection Mission **&** **Lunar Flashlight-** Lunar Orbiter to search for ice
Launch ~2018 to NEA/Moon







- DSN Telecom
- Cold Gas ACS
- Star Tracker
- C&DH w/Watchdog
- VHM Magnetometer

- High Data Rate DSN Telecom
- Cold Gas TCMs
- Reaction Wheels + Star Tracker
- Upgraded Electrical Power
- C&DH Upgrades

- High Resolution Imaging
- Agile Science Image Processing
- Optical Navigation
- High Performance, Rad Tolerant C&DH

Unique Challenges Faced by Interplanetary CubeSats

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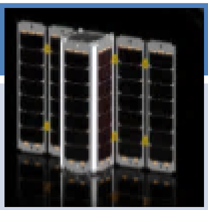
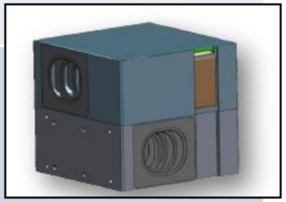
Conventional spacecraft design approaches are not applicable to small sats

- Cannot increase size, more propellant, thicker structure walls, etc.
- Multi-functional component/ subsystems (Iris, cold gas thrusters, imagers)

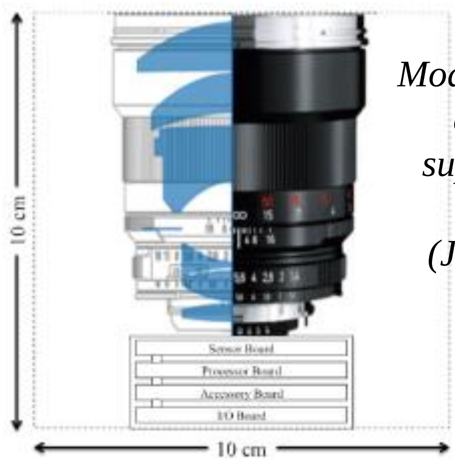
Areas	New Challenges in Deep Space	Solutions
Power	• Solar collection low a >1 AU • High power requirements (telecom, propulsion)	• Low-power modes • Power cycling • Higher energy storage capacity  *Clyde Space 30 W Solar Panels*
Telecom  *Iris Transponder*	• Direct-to-Earth (DTE) challenging at large distances • Mothership relay cooperation	• On-board data compression • Dedicated deployer telecom • Disruption tolerant networking (DTN)
Orbit & Attitude Control	• Limited mass, volume, power • Reaction wheel e-sats outside Earth's geomagnetic field	• Off-the-shelf, ACS • Cold gas thrusters (propulsion and de-sats)  *Blue Canyon XB1 Bus*
Autonomy	• No direct link for long times	• Onboard autonomous operations • Agile science algorithms
Lifetime/ Environment	• Long duration cruises • High radiation, severe thermal	• Rad-tolerant C&DH; shielding • Short mission durations
Programmatic	• Potential risk to primary	• Aligning with strategic goals of PI • Standard deployer, ΔV tip-off

Hardware Technology Infusion

Deep Space Deployable Payloads Architecture & Disruption Tolerant Network

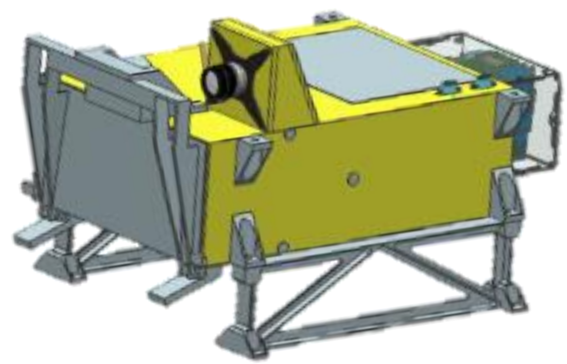
Provides common housing (heating, power, data), telecom relay at target

IntelliCam



Modular intelligent camera that supports optical navigation (Justin Boland)

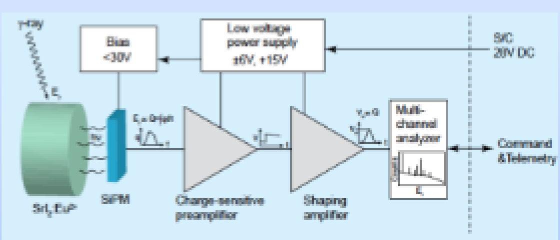
Standard Deployment (PDCS)

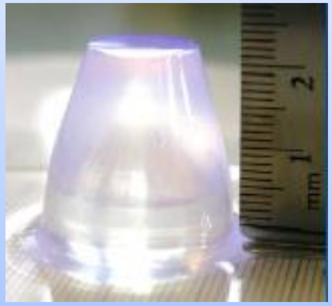


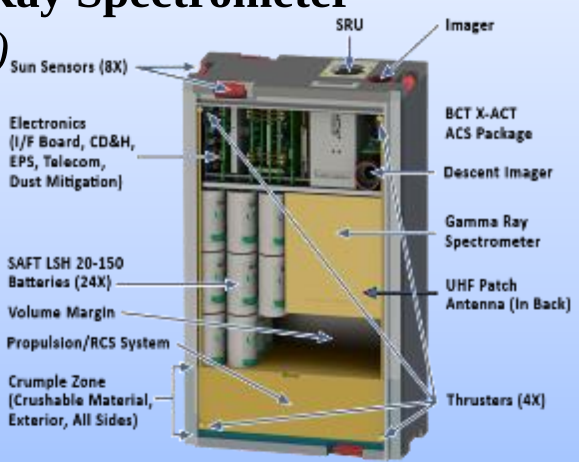
Payload Data and Communications System provides common housing (data, power, thermal), telecom relay at target

New Miniaturized SrI2 Gamma Ray Spectrometer

(PSI/Fisk U/ JPL)







Software Technology Infusion for Science Missions

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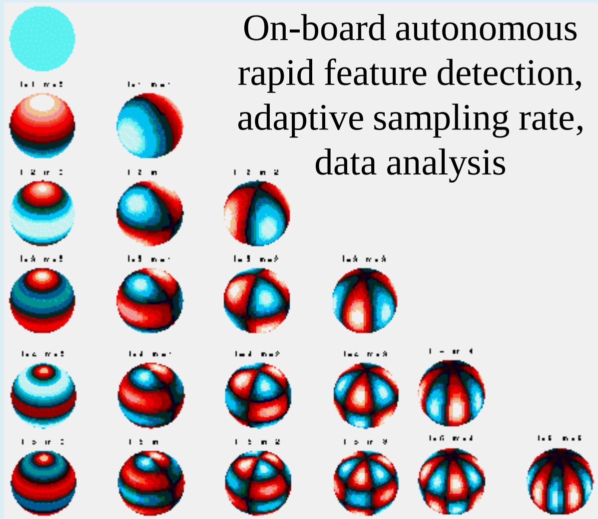
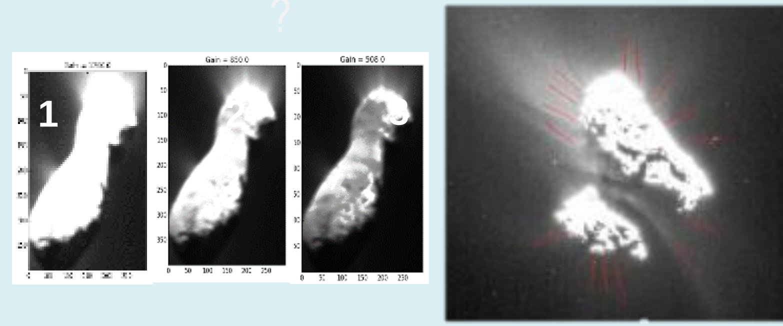
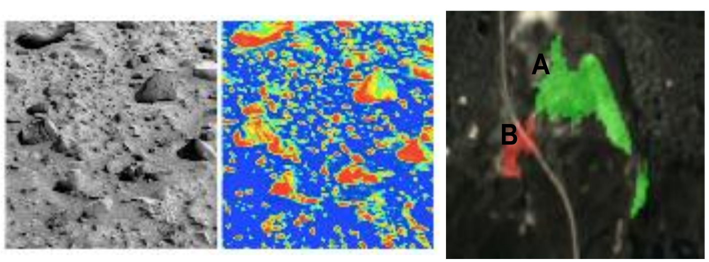
Agile Science Software enables autonomously maximizing science return



On-board autonomous rapid feature detection, adaptive sampling rate, data analysis

Dynamic Gain Setting, Autonomous Dust Detection, Data Downlink Prioritization





As demonstrated on TextureCam, NASA ASTID, *EO-1*

Disruption Tolerant Network (DTN)

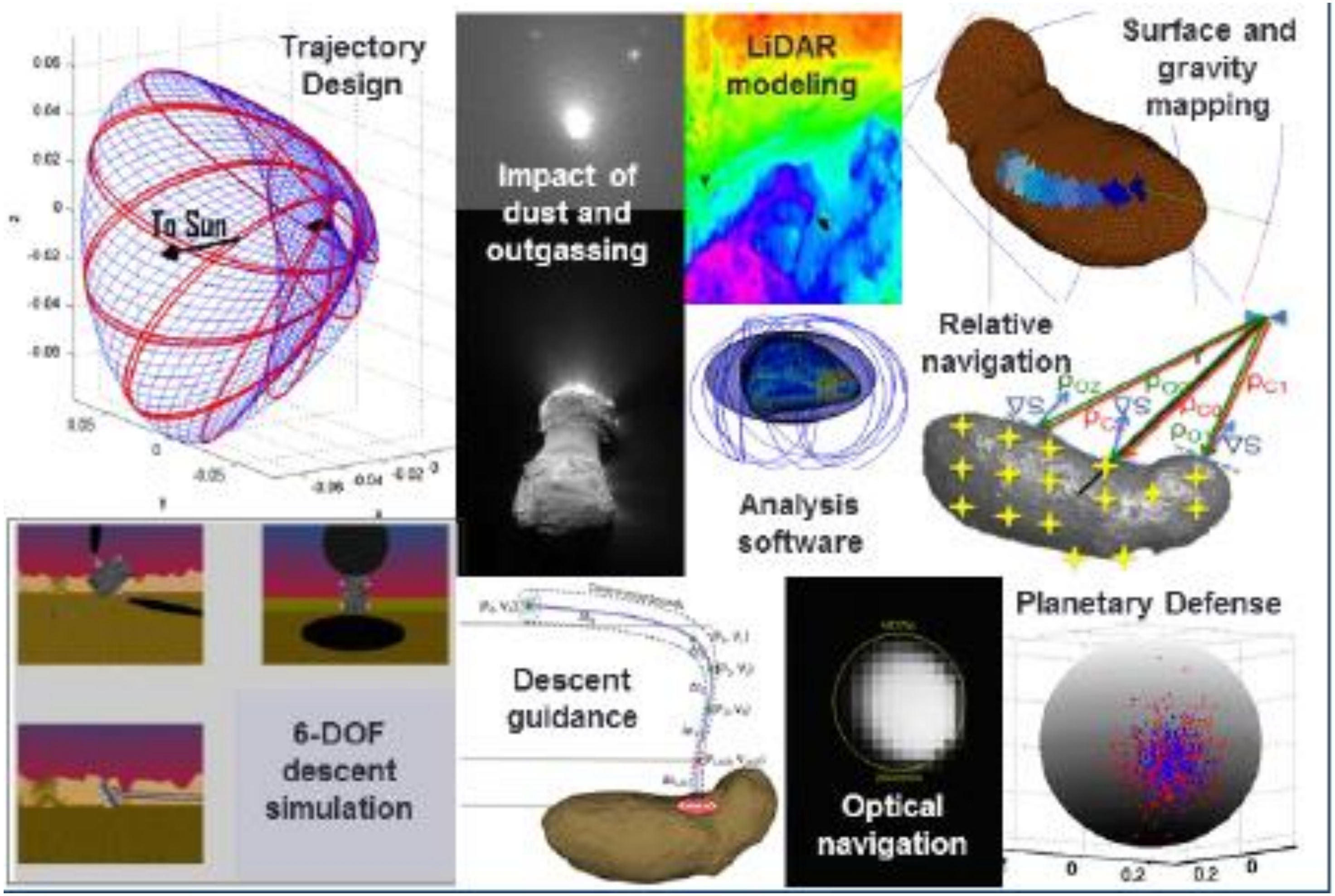
Maximizes chance of successful data return and minimizes scheduling burden for networks without continuous connectivity

Agile Science Reference: D. R. Thompson, S. A. Chien, J. C. Castillo-Rogez

Technology Infusion for Small Bodies Missions

CubeSat Workshop 2015

Primitive Bodies and Terrain-Relative Navigation



To enable autonomous navigation, trajectory planning, descent and landing, in unknown/ poorly understood gravitational environments.

Planetary CubeSat Portfolio Overview

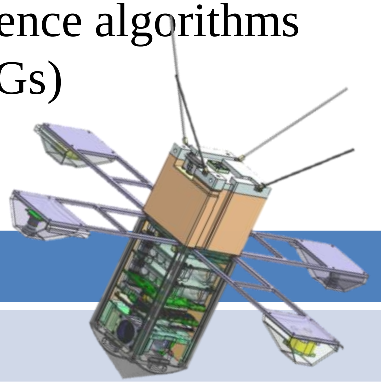
CubeSat Workshop 2015

Mission Architectures: short-lived single free-flyers, small body hoverer, pair of CubeSats flying in coordination, two landers/penetrators at small bodies, and two independent, long-lived CubeSat missions

Technology Demonstrations: mothership-daughtership telecommunication architectures, autonomous navigation and operations, miniaturized instrumentation, and software for on-board processing of science data.

Science Applications/Instruments:

- Measuring magnetic fields, high-resolution images at low altitudes
- Searching for volatiles and water ice (mini spectrometer)
- Acquiring acceleration profile optimized with agile science algorithms
- Performing controlled dust adhesion investigation (SKGs)



Parameter range for secondary CubeSats

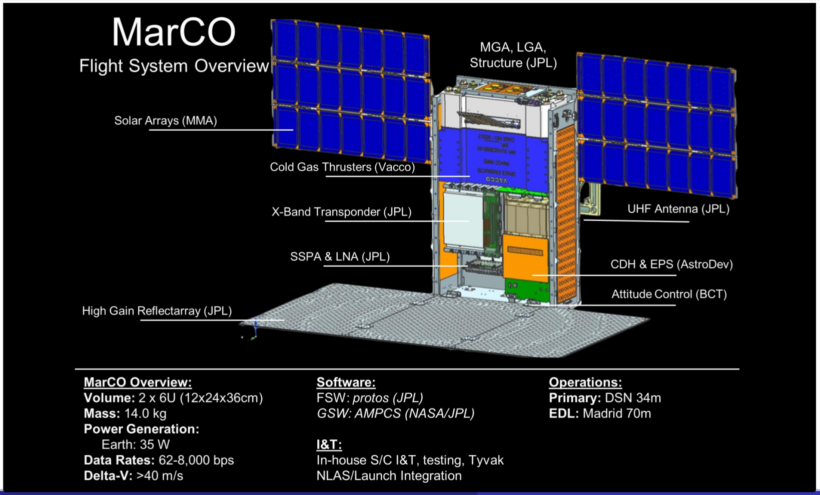
Parameter	Ranges
Dormant Cruise Duration	100-2200 days
CubeSat Mission Duration	Most 1-7 days, one 30 days, one 3 years
Sun Range	0.75-3 AU at destination

Designs Leveraged CubeSat Component "Library"

CubeSat Workshop 2015

Subsystem	Design Solution
Computing	Rad-hard LEON processor (dual core, 200 MIPS), which supports on-board autonomy and agile science algorithms
Telecommunication	UHF radio or Iris transponder (DTE); low, medium, or high gain antennas; reflect-array antennas
Attitude Control	XACT BCT attitude control unit (star trackers, reaction wheels, IMU)
Orbit Control	VACCO cold gas thrusters (0.25-0.5U; $\Delta V \leq 80$ m/sec)
Power Systems	Solar arrays, primary/secondary batteries (average consumption: 1-5 W)
Structure	3U-6U Al CubeSat structure
Carrier/ Deployer	PDCS and avionics (5-10 kg for 3U-6U)

Designs leverage components and design from MarCO and other JPL CubeSats



Components from JPL CubeSat Database

Planetary CubeSat Portfolio "Family Portrait"

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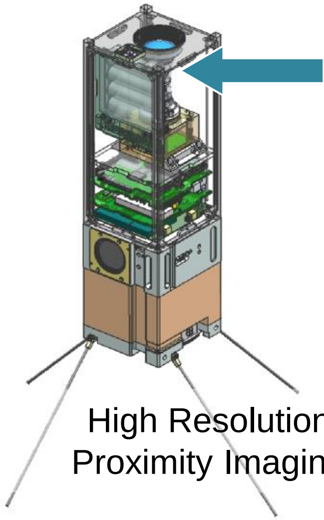
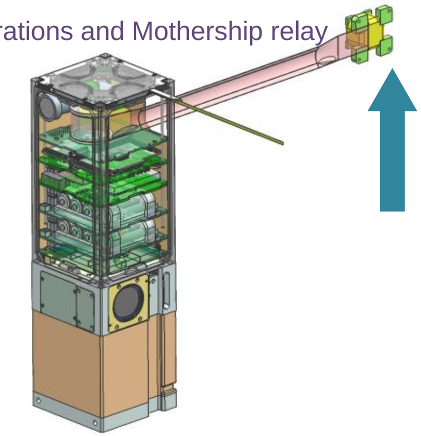
Secondary Orbiter/Flyby Pairs

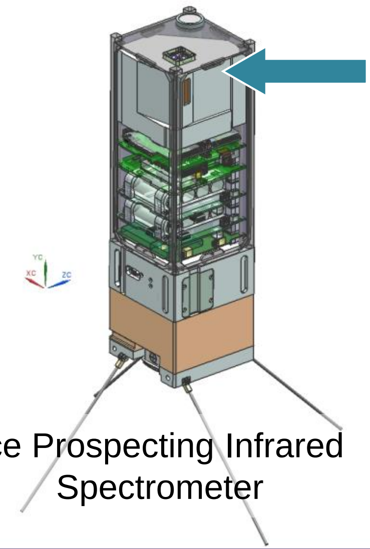
~48-72 hour operations with (semi-)autonomous operations and Mothership relay



High Resolution Proximity Imaging



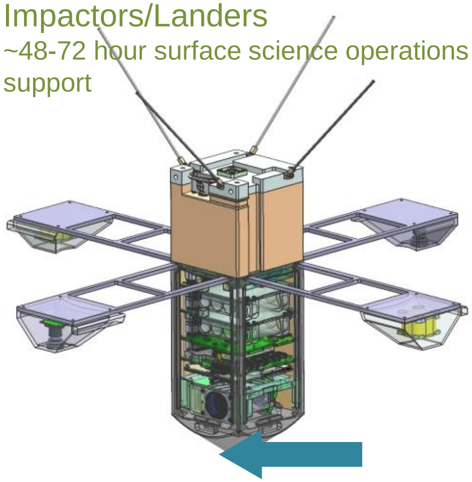
Distributed, Simultaneous Particles & Fields Measurements



Ice Prospecting Infrared Spectrometer

Impactors/Landers

~48-72 hour surface science operations with mothership localization and relay support

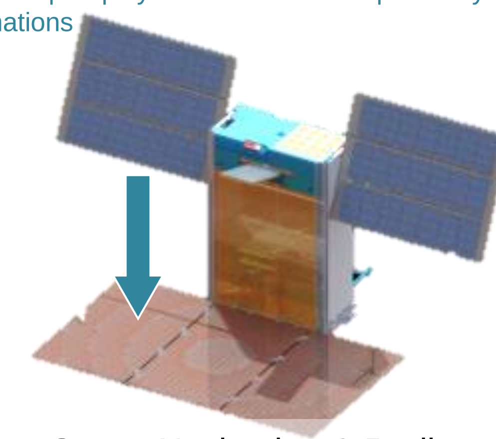


Asteroid/Comet Instrumented Surface Penetrator

Phobos Surface Landing w/ Gamma Ray Spectrometer

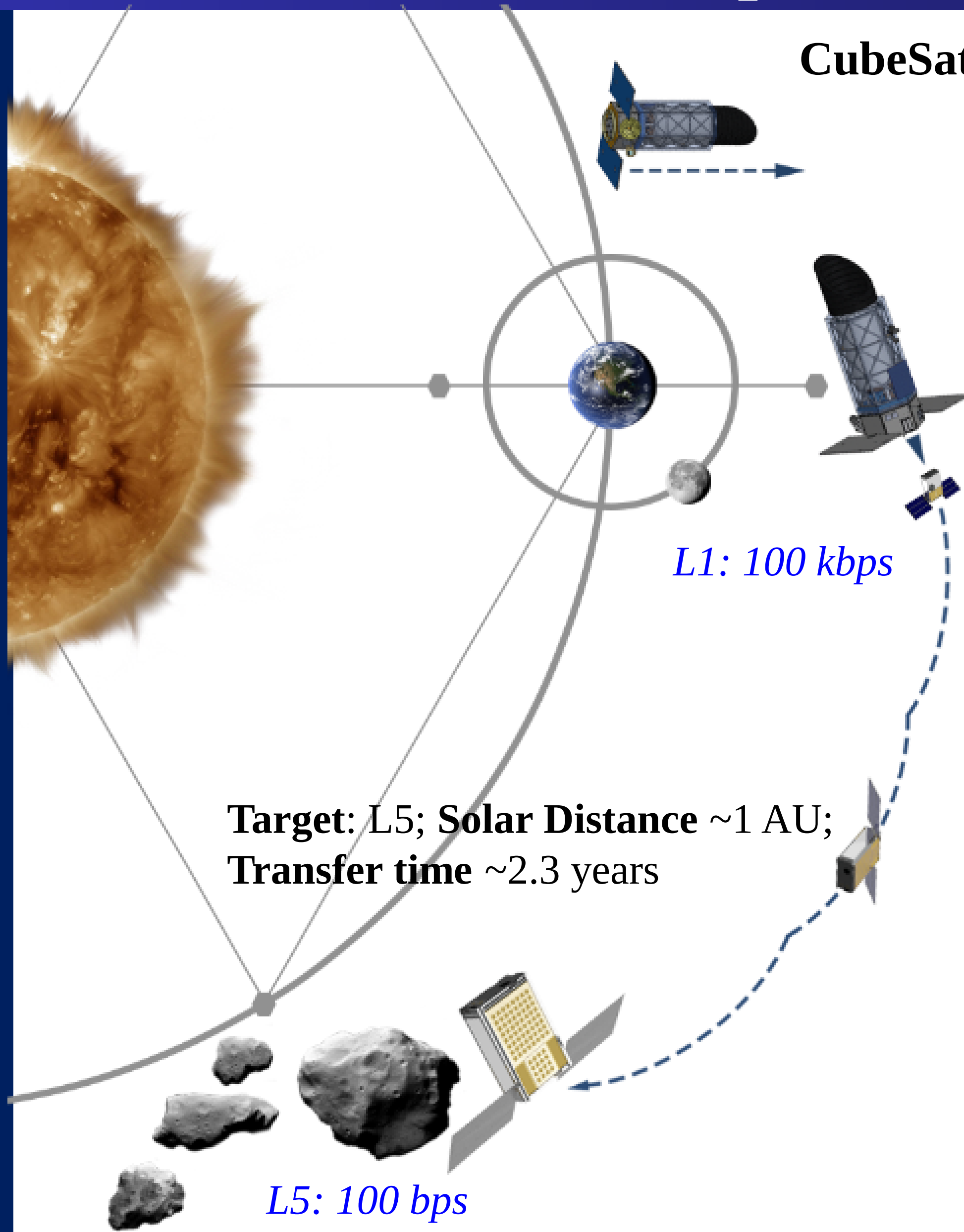
Hitchhiking Deep Space Nano-Satellite

Mothership-deployed s/c to other interplanetary destinations



Deep Space Navigation & Radio Science Demonstrations

Representative Mission Concept: Kuiper Tech Demo



CubeSat (6U) AutoNav Demonstration

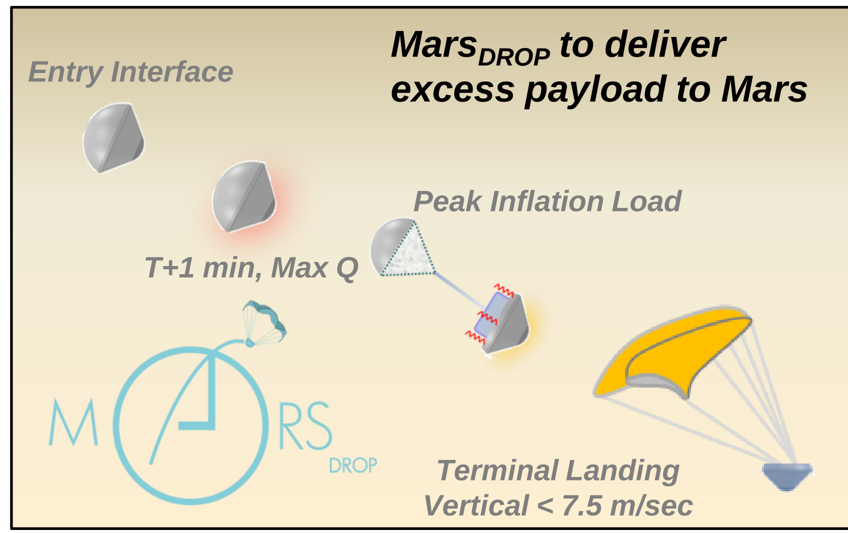
- Hitches ride to Earth-Sun L1 on Discovery-class mission
- Demonstrates orbit determination on 6U CubeSat to avoid expensive (time, power) tracking to the DSN.
- Paves the way to operations cost reduction for future small interplanetary CubeSats.
- Introduces the IntelliCam, tailored to reference target acquisition.
- JPL's new CubeSat C&DH supplies processing performance needed for orbit determination and autonomous maneuver planning and execution.

Image Credit: Lucy Burton

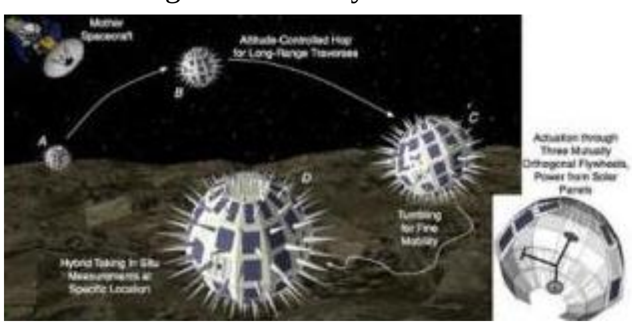
Future Impact of Science-Driven Small Spacecraft

- ***Performing significant ΔV and high-precision attitude control enables:***
  - Hovering, landing, large orbit transfers to Moon, Mars, asteroids
  - Creating and maintaining swarms, constellations, formation flight
- ***Autonomous Operations enabling:***
  - Autonomous navigation: orbit determination and trajectory planning
  - Agile Science for on-board autonomy to locate Earth, detect objects (*e.g.* plumes)
  - Dynamic observation planning, disruption-tolerant networking (DTN)
- ***Future potential to accomplish high-priority (Explorer, Discovery-class) science:***
  - Multi-spacecraft architectures: constellations, mother-daughtership, swarms
  - Pre-cursor missions to explore dirty/dangerous/unknown environments

Comet 46P Wirtanen Orbital Transfer
Image Credit: Lucy Burton



$Mars_{DROP}$ enters, steers, and targets locations to deliver science payloads to Mars surface. Credit: Aerospace Corp. & JPL



Robotic hedgehogs for Phobos Exploration; Credit: Stanford University & JPL

Acknowledgments

CubeSat Workshop 2015

- Partners: Blue Canyon Technologies, Aerospace Corp. PSI, KSC, Ames, universities
- Ross Jones, Susan Jones, Kim Reh for study definition and management
- Lucy Barton for proposal artwork
- Gregory Lantoine and Damon Landau for trajectory support
- Steve Chien, David Thompson, and Jay Wyatt for agile science expertise
- Courtney Duncan for telecom support
- Murray Darrach, Rob Staehle, Justin Boland, Lee Johnson + Tom Prettyman (PSI) and Carlos Calle et al. (KSC)for instrument support
- Shyam Bhaskaran for AutoNav support
- JPL scientists and PIs for their support

Previous Presentations on Deep Space CubeSats:

- JPL Missions in Implementation: MarCO, NEAS, LF (Frick et al.)*
- NanoSpacecraft as secondary payload on planetary mission (Discovery TDO CubeSat Portfolio) – (Frick, et al.)*
- OCCAM: A flexible, responsive architecture for comet/NEA reconnaissance (Castillo, et al.)*
- Hybrid Spacecraft/Rover for Small Body Exploration (Pavone, et al.)*
- Asteroid Kinetic Impactor Missions (Chesley et al.)
- A system of technologies for future robust deep space spacecraft (Beauchamp et al.)
- NanoSats and MicroSats in Deep Space – on track for exponential growth (Freeman et al.)
- Multiplying Mars Lander Opportunities with MARSdrop Microlander (Staehle et al.)

Questions?

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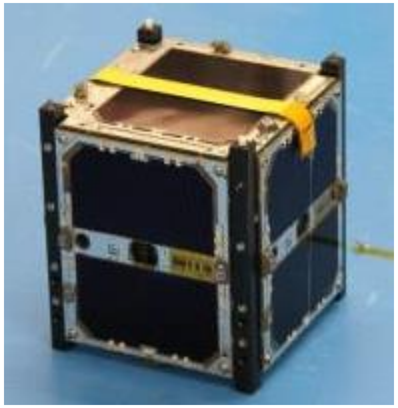
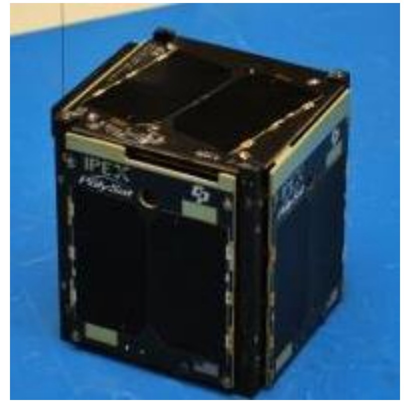
Active Low Earth Orbit (LEO) CubeSat Projects

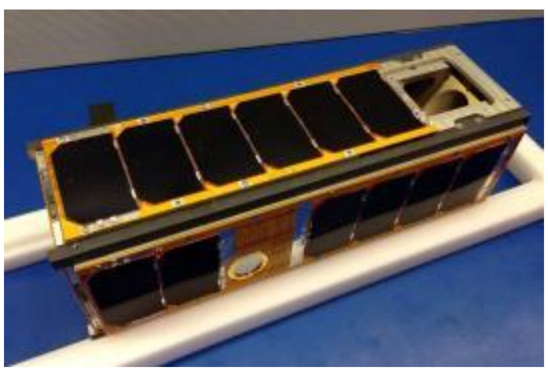


M-Cubed/COVE-2 (NASA ESTO)
High data-rate on-board processing
P. Pingree: JPL, U. Michigan
Launched VAFB: Dec. 5, 2013 (NASA CLI)

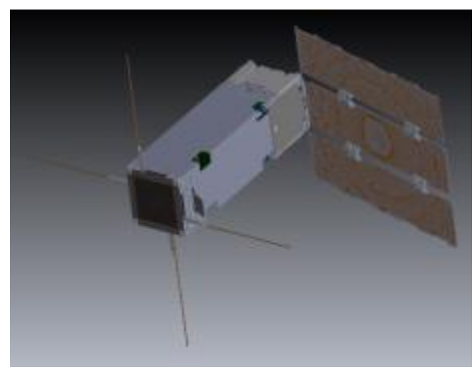


IPEX/CP-8 (NASA ESTO)
Autonomous low-latency product generation
S. Chien: JPL, GSFC, Cal Poly SLO, Tyvak
Launched VAFB: Dec. 5, 2013 (NASA CLI)

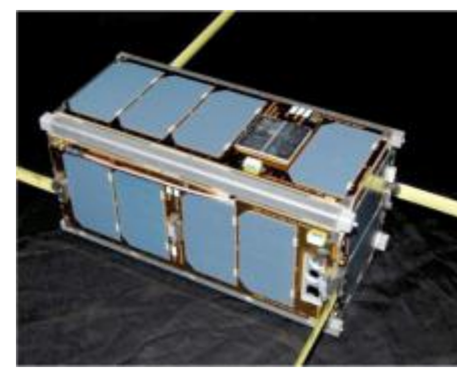
GRIFEX (NASA ESTO)
Unprecedented frame-rate ROIC/FPA
D: Rider JPL, U. Michigan
Launched VAFB: Jan. 31, 2015 (NASA CLI)



RACE
Hydrometric Atmospheric Radiometer
B. Lim: JPL, UT Austin
Launch Failure WFF: Oct. 2014 (NASA CLI)

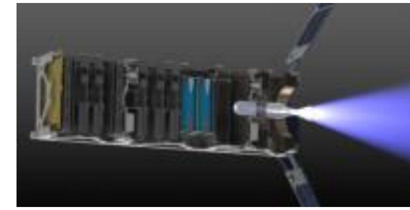


ISARA (EDISON)
Integrated Solar Array & Reflectarray Antenna
R. Hodges: JPL, Aerospace Corp., Pumpkin Inc.
Launch Manifest: Aug. 2015 (NASA CLI)



LMRST
Low Mass Radio Transponder
C. Duncan: JPL, Stanford
Launch Manifest: 2015 (NASA CLI)

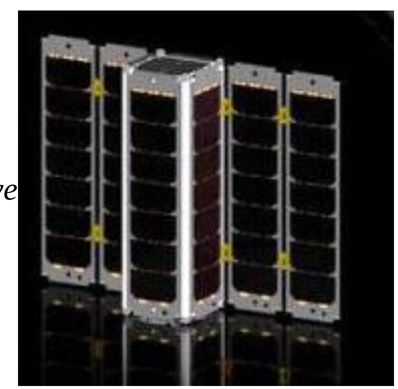
Emerging & Enabling Technologies

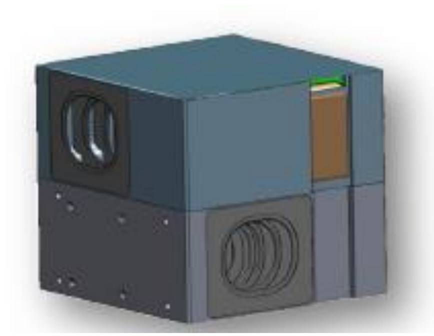


CAT Thruster

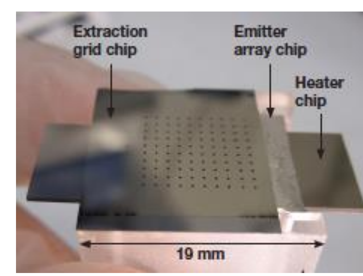
- Telecommunication and Navigation systems
  - Iris Transponder (JPL) and high gain antennas
  - High-rate S/Ka-Band radios (50+ Mbps dld from LEO)
- CubeSat Propulsion systems (ΔV>3 km/sec in 3U)
  - VACCO Cold Gas Systems (low ΔV for TCMs/ de-sats)
  - NASA-funded MEP (MIT- S-iEPS, JPL- MEP, Busek- HARPs)
  - CubeSat Ambipolar Thruster (CAT), Busek CHAMP, Chemical Thruster
- High-accuracy attitude control technology
  - Blue Canyon's XB1: 7.2 arcsec accuracy, 1 arcsec stability, <2.5 kg, ~1 U, <2.5 W
- Solar arrays that are deployed and are gimbaled for Sun-tracking
  - Deployable Solar Arrays (Clyde Space, MMA up to 130 W/kg)
- Integrated bus architectures and radiation-tolerant components
  - Blue Canyon XB1 Bus (GNC, C&DH, Telecom, Power, ACS)
  - Companies offering buses like Tyvak, Blue Canyon, etc.
- Standard deployers (JPL's PDCS, Planetary System's CSD, Tyvak's Deployers)

Clyde Space Double Deploye 2-Sided 30 W Solar Panels





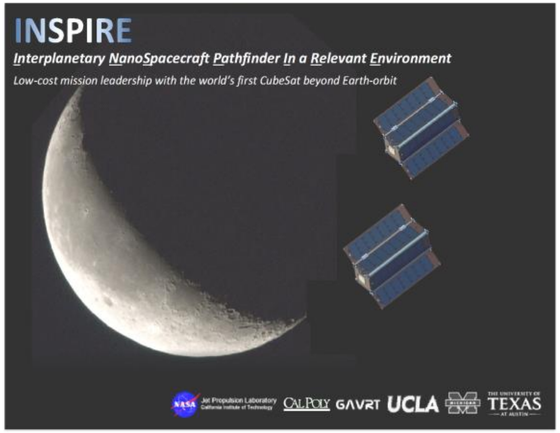
Blue Canyon XB1 Bus



JPL's MEP Thruster

Image Credit: Clyde Space, ISIS, Blue Canyon, PEPL

Active Interplanetary CubeSat Projects Provide Heritage

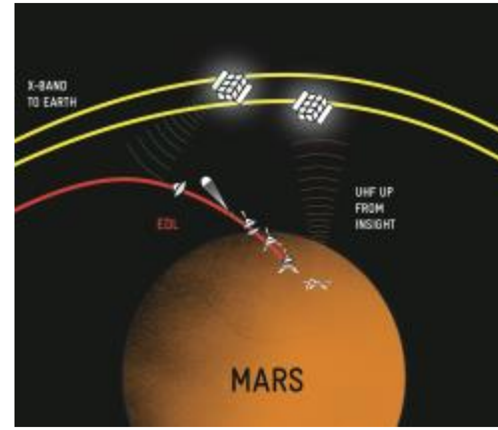


INSPIRE (JPL)[1]

Navigation demonstration with the IRIS radio beyond the Moon

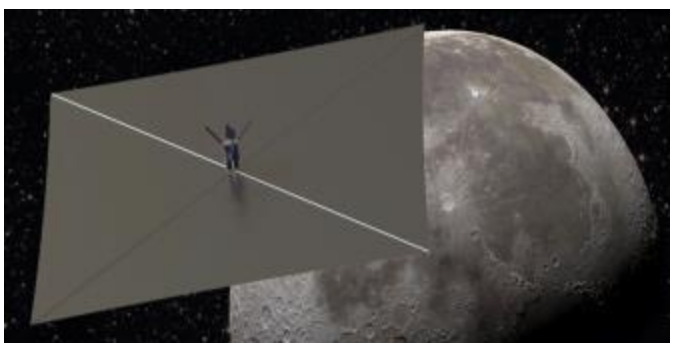
NEA Scout (MSFC/JPL) [2,3]

Asteroid characterization mission [EM-1]



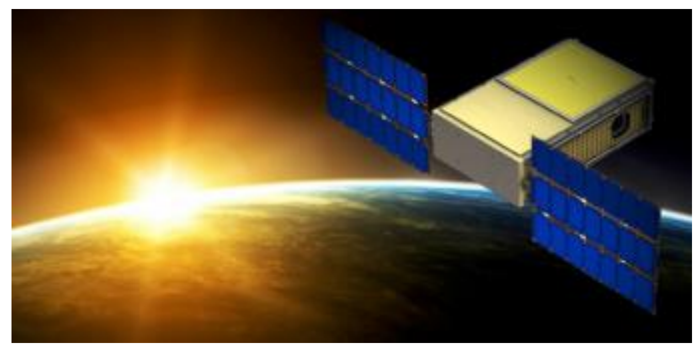
MarCO (JPL)[2]

InSight insertion real-time Mars relay



Lunar Flashlight (JPL/MSFC) [2,3]

Lunar orbiter to search for ice in lunar craters [EM-1]



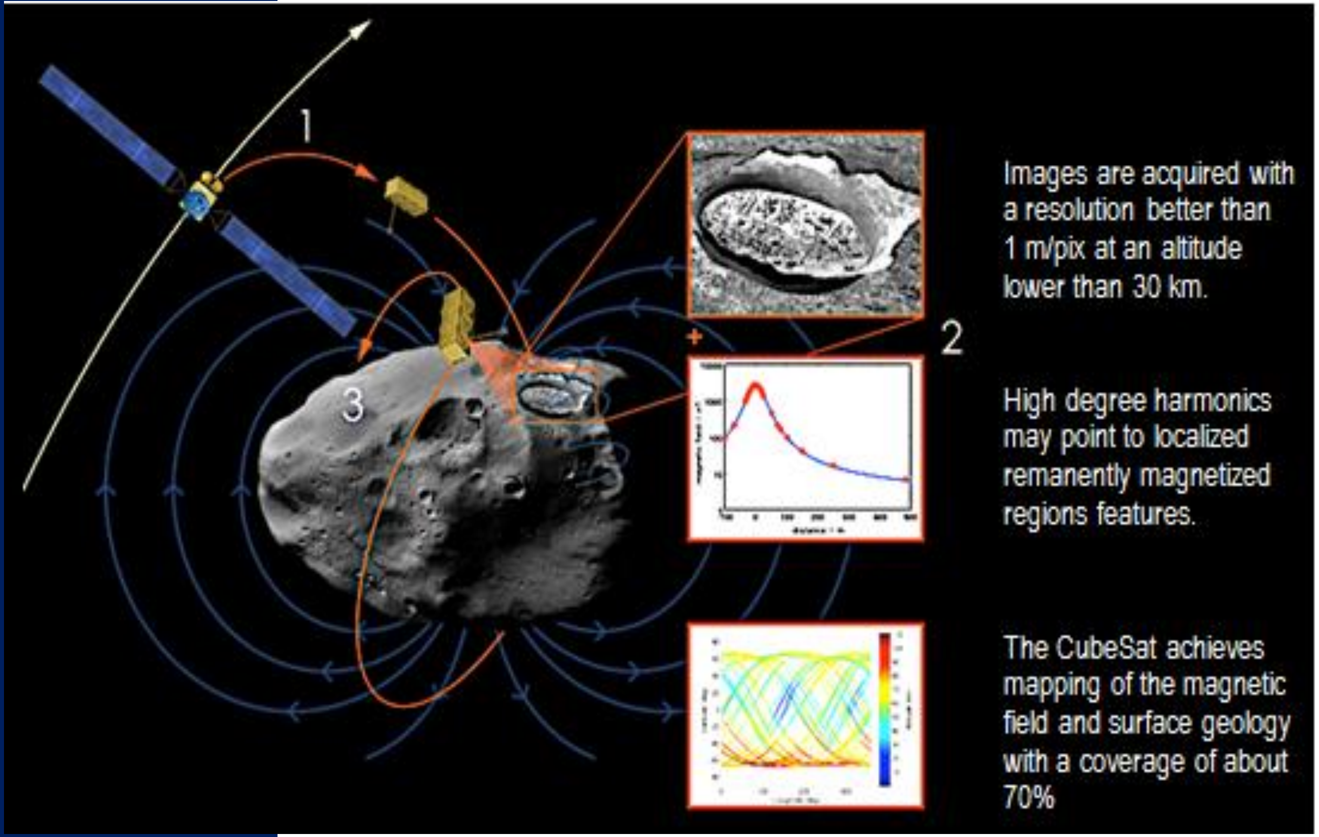
BioSentinel (Ames) [2,3]

Biosensor to study impact of radiation on living organisms [EM-1]

[1]JPL/NASA Planetary Science Division, [2]JPL, [3]NASA's Advanced Exploration Systems (AES)

Psyche

The Psyche TDO paves the way for future investigations that are best addressed with mother–daughter architectures and automated science data handling (e.g., multi-site magnetic field measurements in Europa's system).
Target: 16 Psyche; **Solar Distance** ~3 AU; **CubeSat Lifetime** ~48 hours

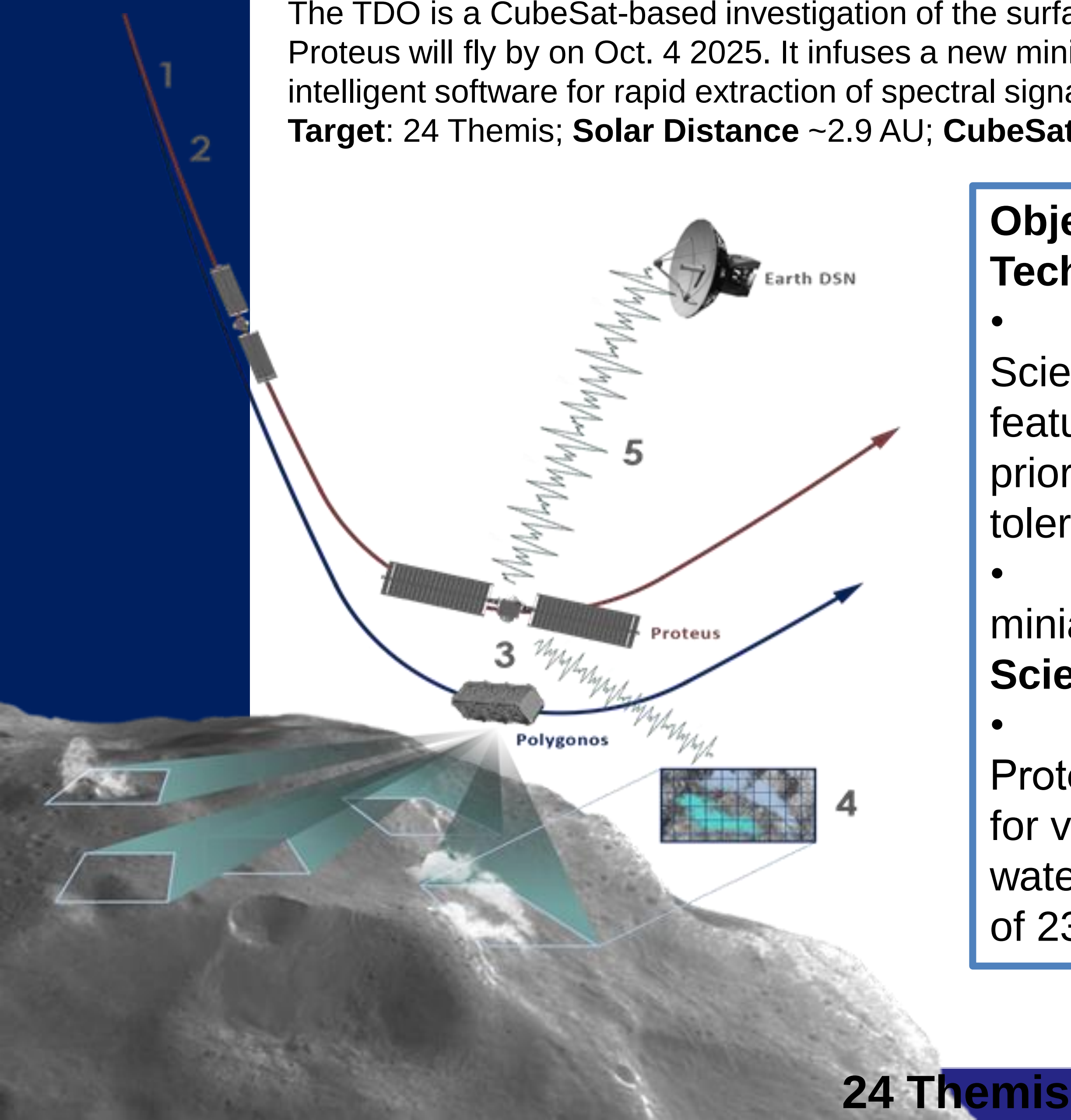


Objectives
Technology Demonstrations
* Demonstrate a mother-daughter architecture leveraging the form factor, subsystems, and standards introduced by the CubeSat community but upgraded to withstand the environment and constraints specific to a mission in the main belt of asteroids
* Implement Agile Science algorithms for automated feature detection, adaptive data collection and disruptive tolerant networking.
Science Enhancements
* Acquire magnetic field measurements at high spatial resolution complementary to the low-degree harmonics acquired by the mothership
* Acquire images with a resolution better than 1m/pix at an altitude lower than 30 km

Proteus

The TDO is a CubeSat-based investigation of the surface composition of 24 Themis, which Proteus will fly by on Oct. 4 2025. It infuses a new miniaturized spectrometer enhanced with intelligent software for rapid extraction of spectral signatures.

Target: 24 Themis; **Solar Distance** ~2.9 AU; **CubeSat Lifetime** ~24 hours



Objectives:

Technology Demonstrations:

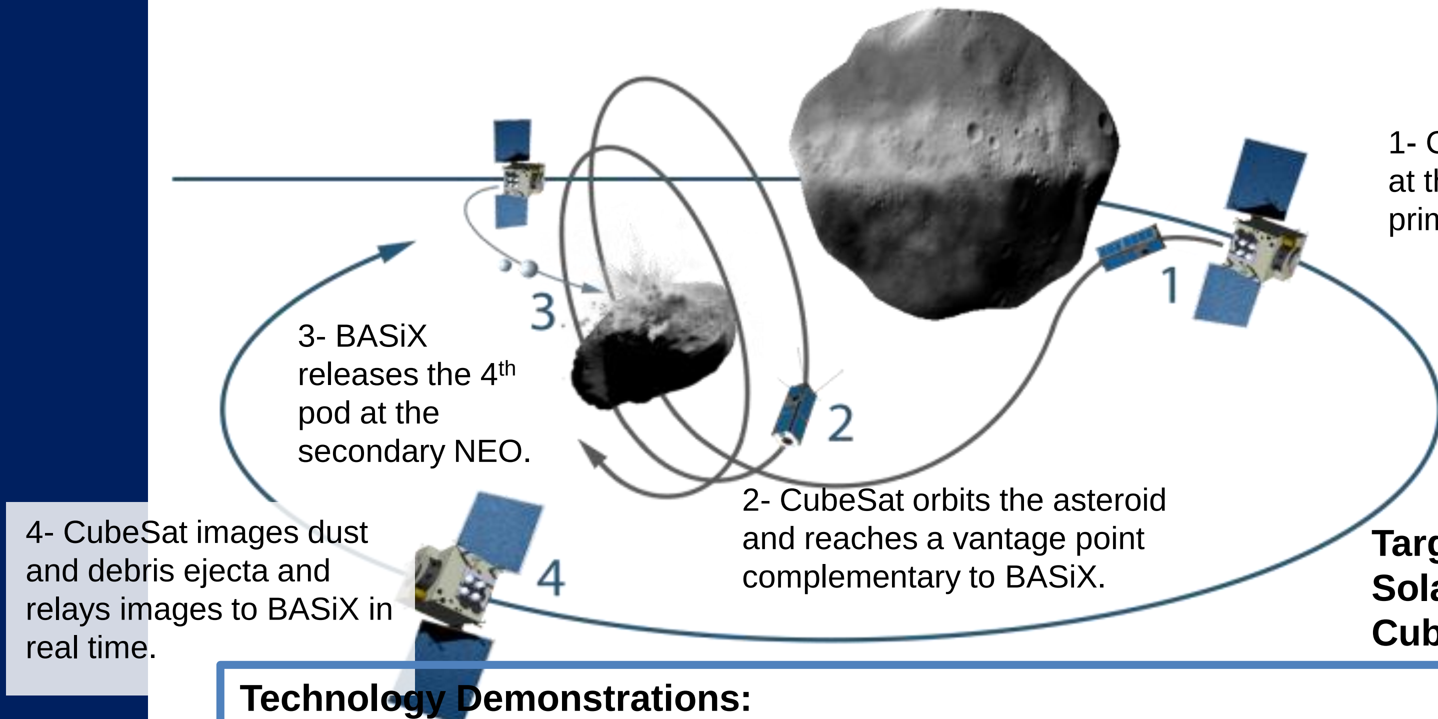
- Implement Agile Science algorithms for surface feature detection and prioritization and disruption-tolerant networking.
- Demonstrate a new miniaturized spectrometer

Science Enhancement:

- This TDO enhances Proteus' science by searching for volatiles, and especially water ice, at the putative parent of 238P/Read.

BASiX

The BASiX TDO will demonstrate hovering in close proximity (<500 m) to a micro-g body using Autonomous Navigation and primitive body navigation technology developed at JPL under NASA sponsorship and implemented with a deep space CubeSat. This demonstration will lower the risk of close proximity operations at small bodies for future NASA missions.



Target: NEO secondary
Solar Distance ~1 AU
CubeSat Lifetime ~7 d

Technology Demonstrations:

- Implement AutoNav algorithms to enable autonomous close proximity operations and controlled hovering at targeted sites near a micro gravity body.
- Implement Agile Science algorithms for: 1) autonomous plume detection, 2) adaptive data collection, 3) adaptive gain/framing and 4) disruption-tolerant networking.

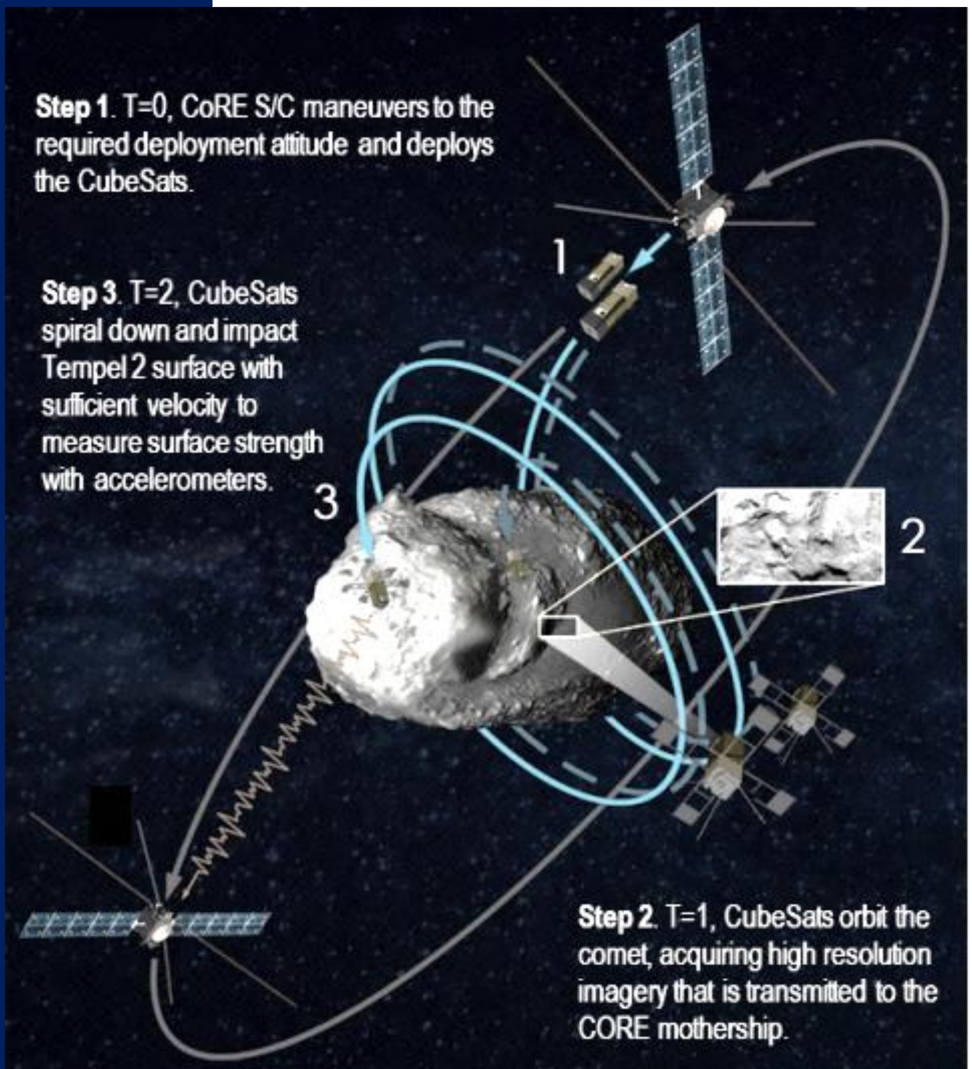
Science Enhancement:

- Acquire high-resolution imaging of the crater created by the explosion.

CORE

CoRE's TDO will demonstrate NASA sponsored primitive body navigation technology for controlled impact and survival of an instrumented penetrator at a small body

Target: Tempel 2; **Solar Distance** ~3 AU; **CubeSat Lifetime** ~48 hours



Objectives

Technology Demonstrations

Perform close proximity operations and controlled targeted impact on a low-gravity body

Implement agile science algorithms for: 1) multi-asset coordination, 2) adaptive gain/framing and 3) disruption-tolerant networking (DTN)

This TDO infuses primitive body navigation (PBN) software sponsored by NASA's NEO program and agile science algorithms, which will expand NASA's core competencies in deep space navigation and science data handling.

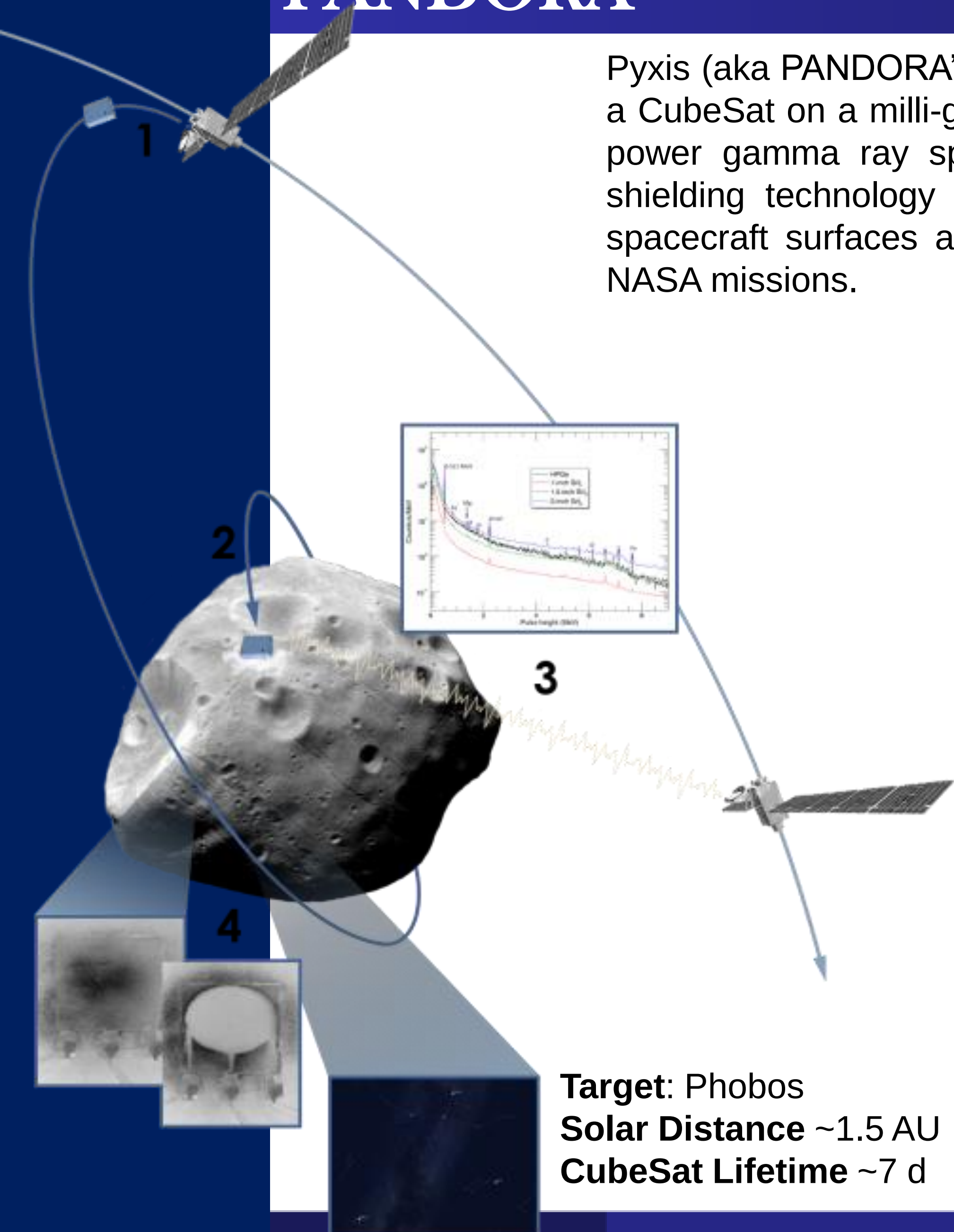
Science Enhancements

Measure the surface strength of Tempel 2 via acceleration profile upon impact

Acquire stereo imaging during descent, optimized with Agile Science algorithms

PANDORA

Pyxis (aka PANDORA's "box") will demonstrate autonomous soft landing of a CubeSat on a milli-g body. The CubeSat carries a new miniaturized, low power gamma ray spectrometer (JPL/PSI/Fisk U) and electrodynamics shielding technology (NASA/KSC) for demonstrating dust mitigation on spacecraft surfaces and mother-daughter system architecture for future NASA missions.



Objectives:

Technology Demonstration

- Implement AutoNav algorithms for autonomous targeted soft landing on a milli-g body.
- Implement Agile Science algorithms for disruption-tolerant networking (DTN).

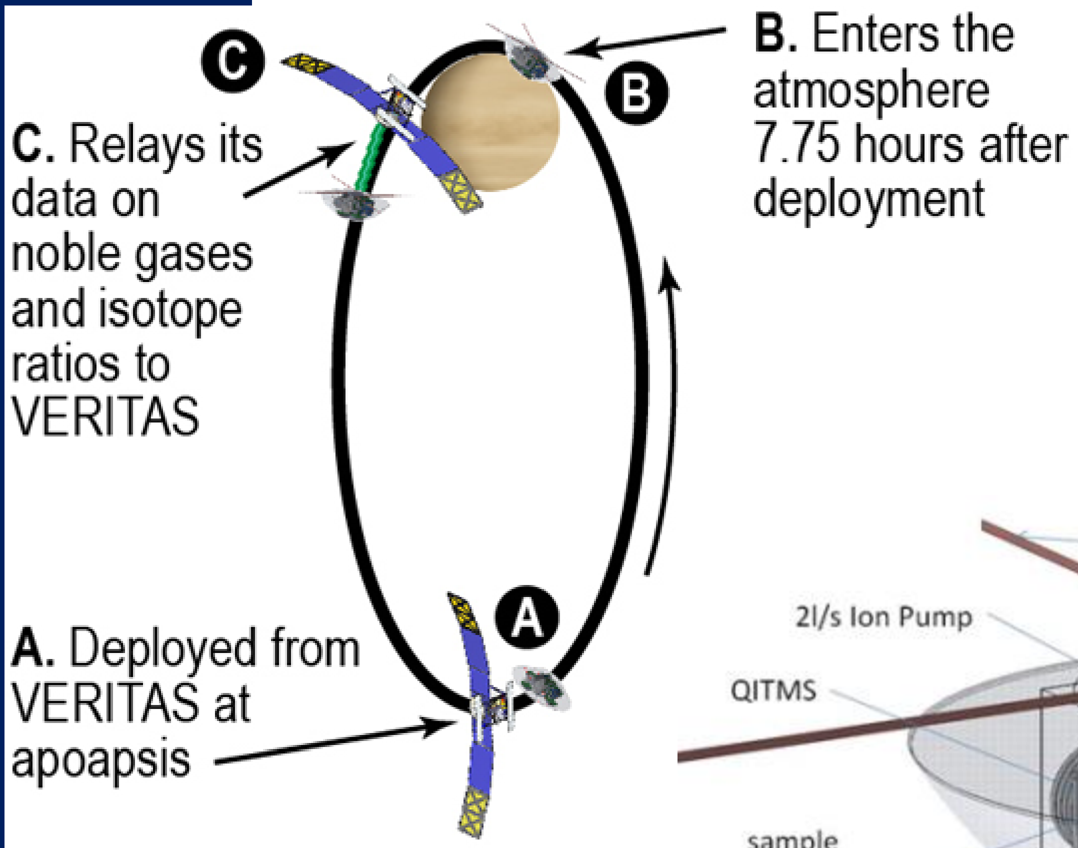
Science Enhancements

- Measure the elemental composition of a landing site on Phobos and the galactic cosmic ray environment
- Perform a controlled dust adhesion investigation that helps retire key SKGs related to charging in low gravity environment
- PANDORA's observation of Pyxis' interaction with the surface yields direct insight on Phobos' geotechnical properties.

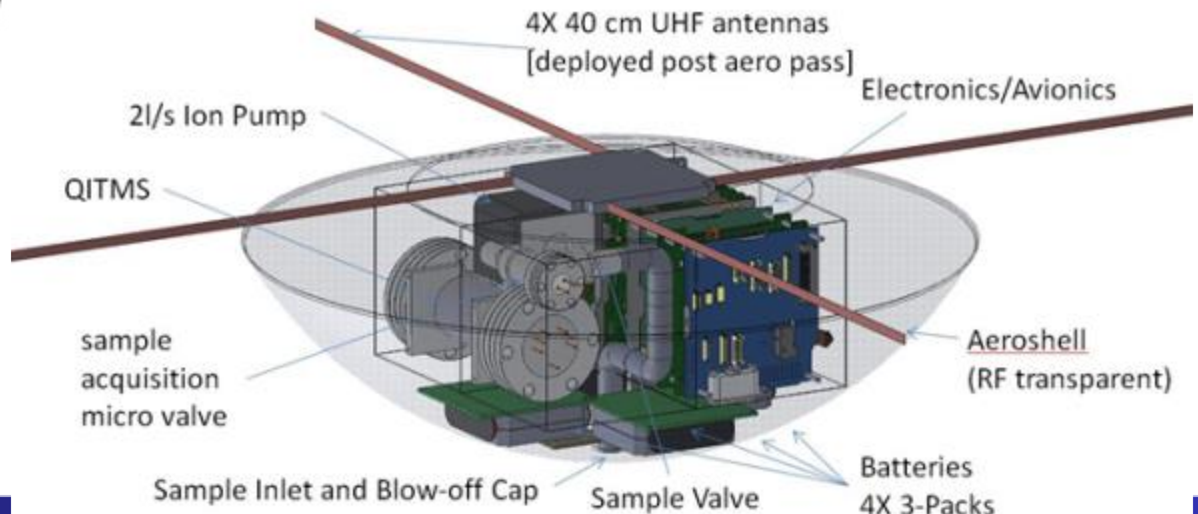
Target: Phobos
Solar Distance ~1.5 AU
CubeSat Lifetime ~7 d

VERITAS

Our TDO (Cupid's Arrow) is a high value investigation to sample the noble gases in Venus' atmosphere at low cost using a nanosat. Inventorying the noble gases is the highest-priority investigation for Goal I/Objective A identified by the VEXAG.
Target: Venus; **Solar Distance** ~0.75 AU; **CubeSat Lifetime** ~30 d



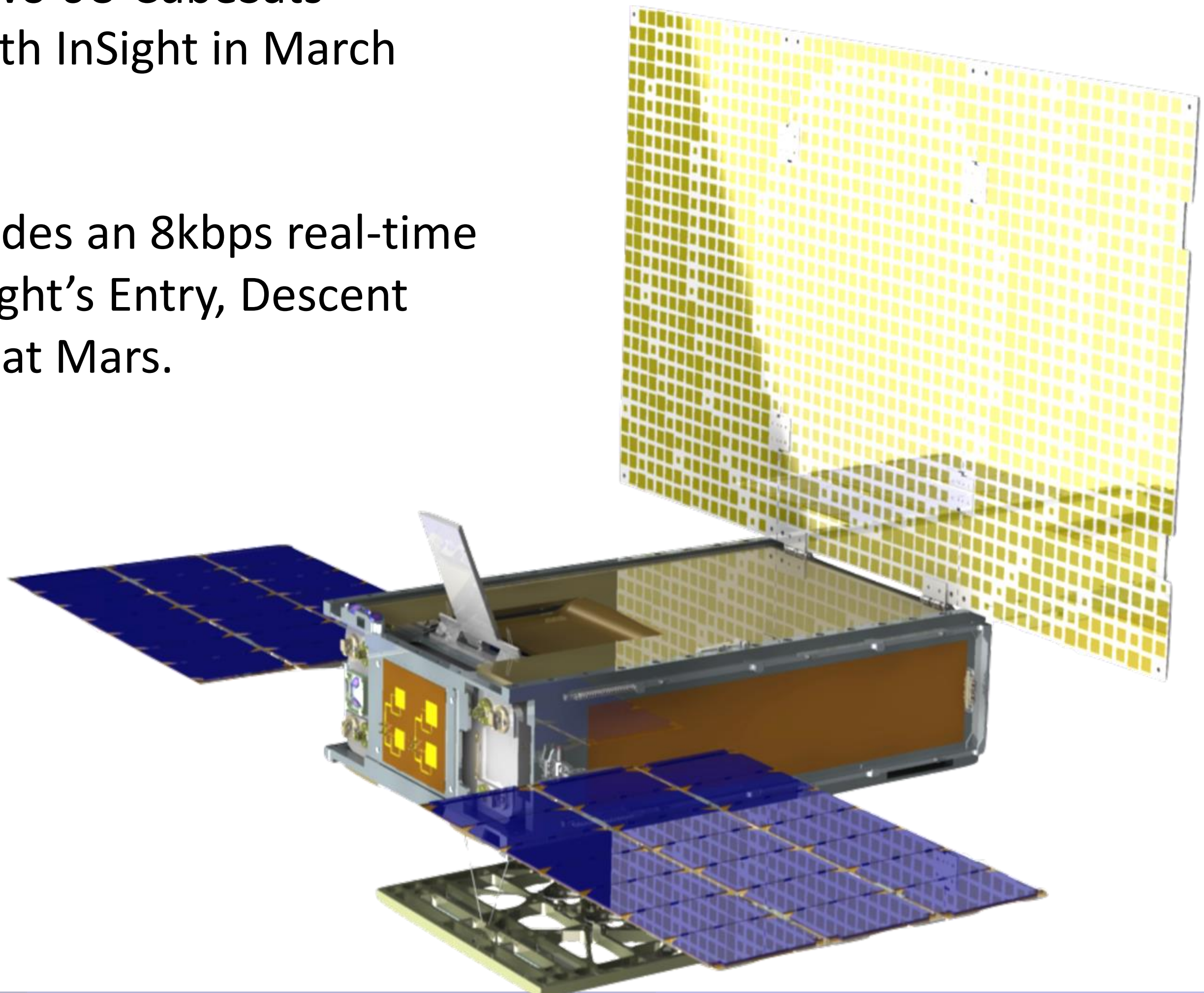
Objectives
Technology Demonstration: a new ultracompact quadrupole ion- trap mass spectrometer (QITMS) hosted on a nanosat.
Science Enhancement: Sample the Venus atmosphere and measure the noble gases (^{4}He, ^{20}Ne, ^{36}Ar, ^{40}Ar, ^{84}Kr, ^{130}Xe) abundances and their isotopic ratios with precision <1-5%.



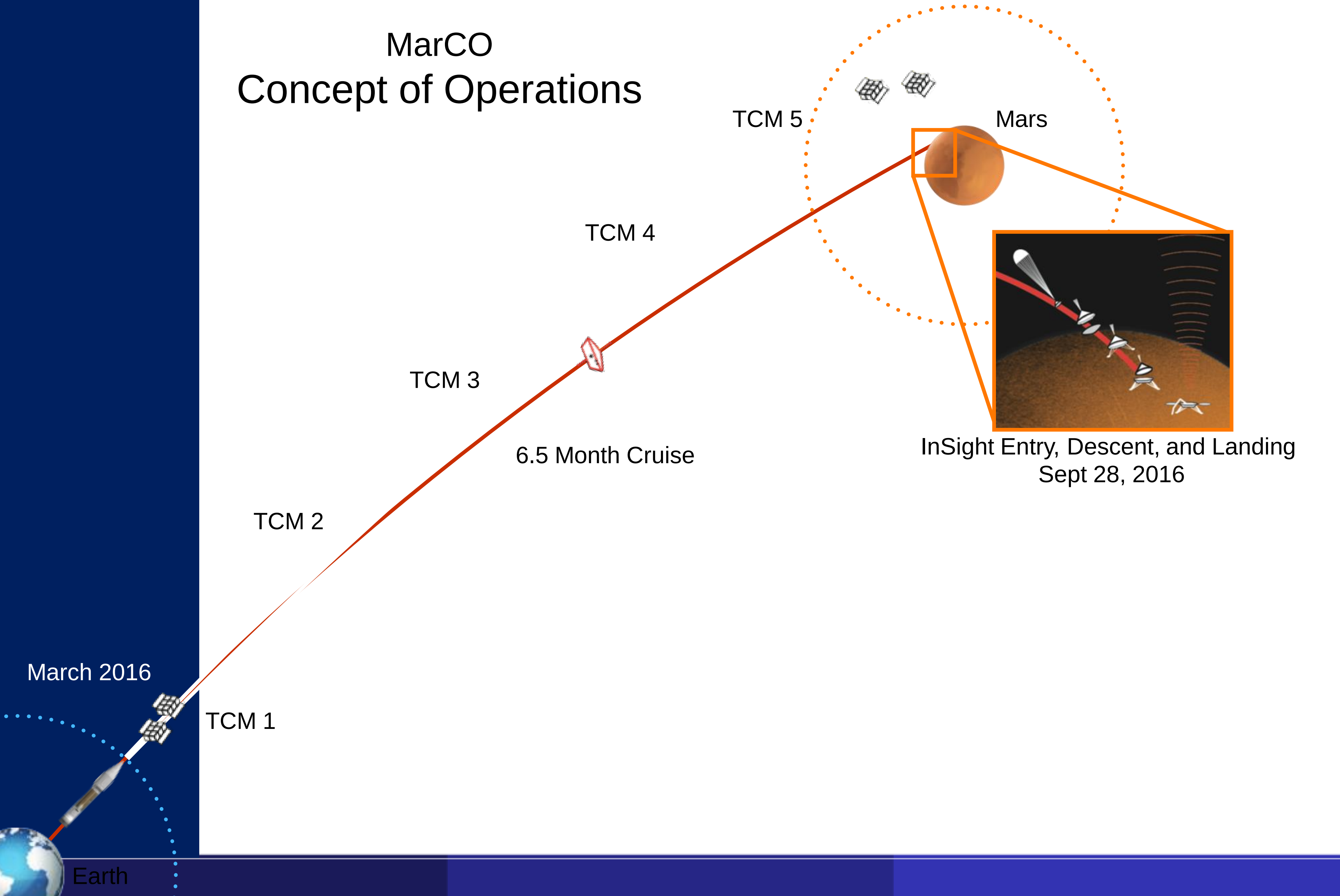
MarCO: CubeSats to Mars

The "Mars CubeSat One" Mission consists of two 6U CubeSats launching with InSight in March 2016.

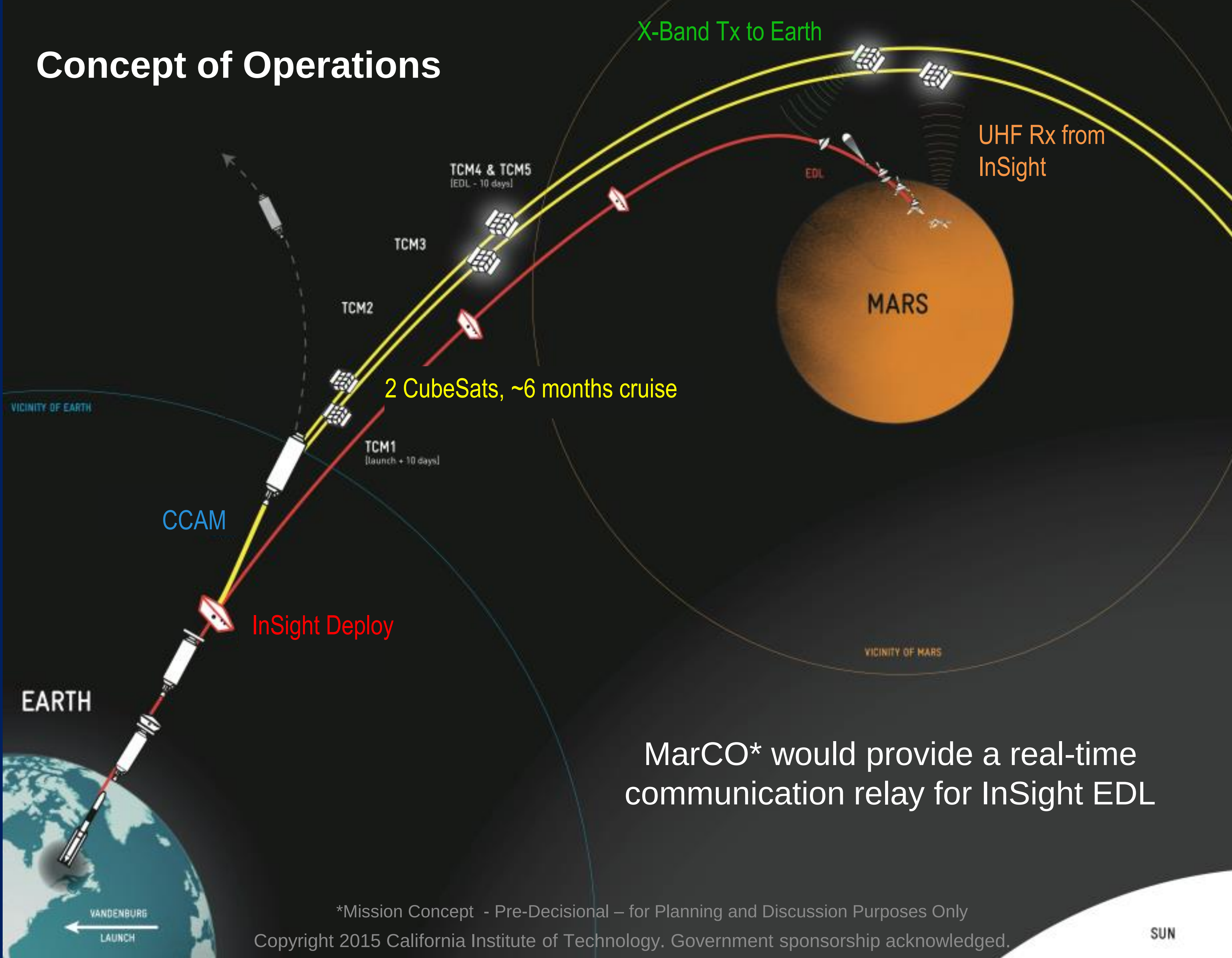
MarCO provides an 8kbps real-time relay for InSight's Entry, Descent and Landing at Mars.



MarCO
Concept of Operations



Concept of Operations

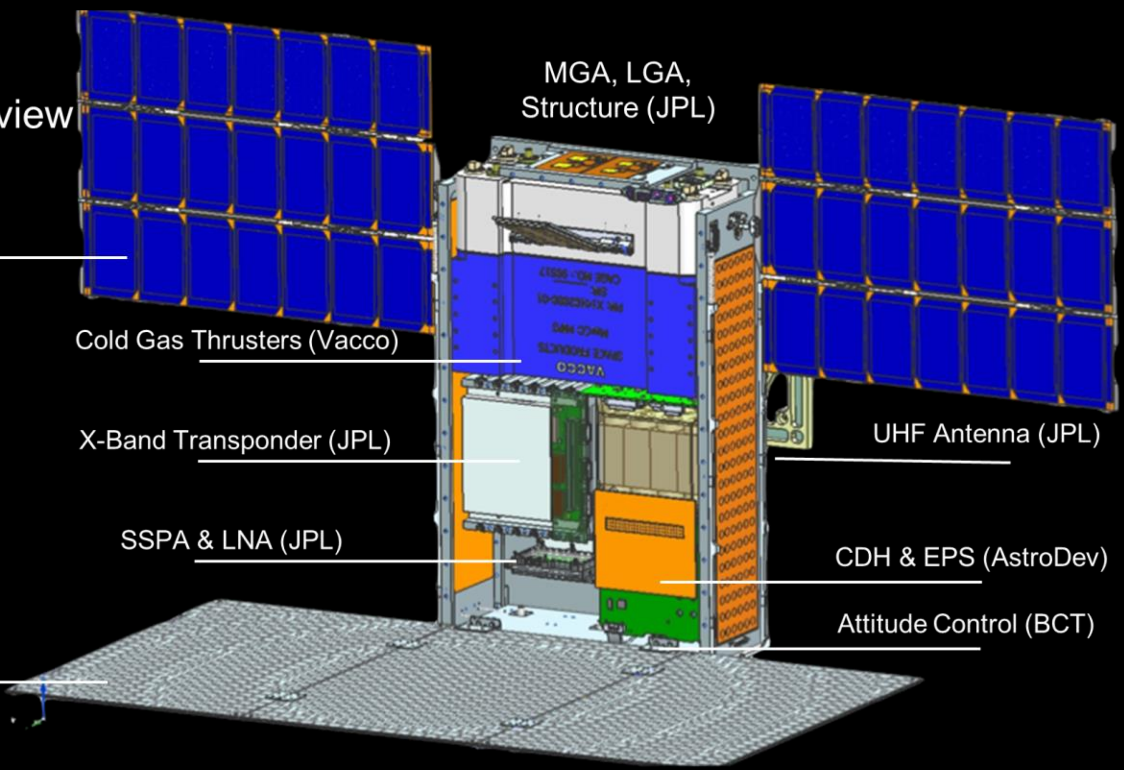


MarCO* would provide a real-time communication relay for InSight EDL

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

MarCO

Flight System Overview



MarCO Overview:
Volume: 2 x 6U (12x24x36cm)
Mass: 14.0 kg
Power Generation:
Earth: 35 W
Data Rates: 62-8,000 bps
Delta-V: >40 m/s

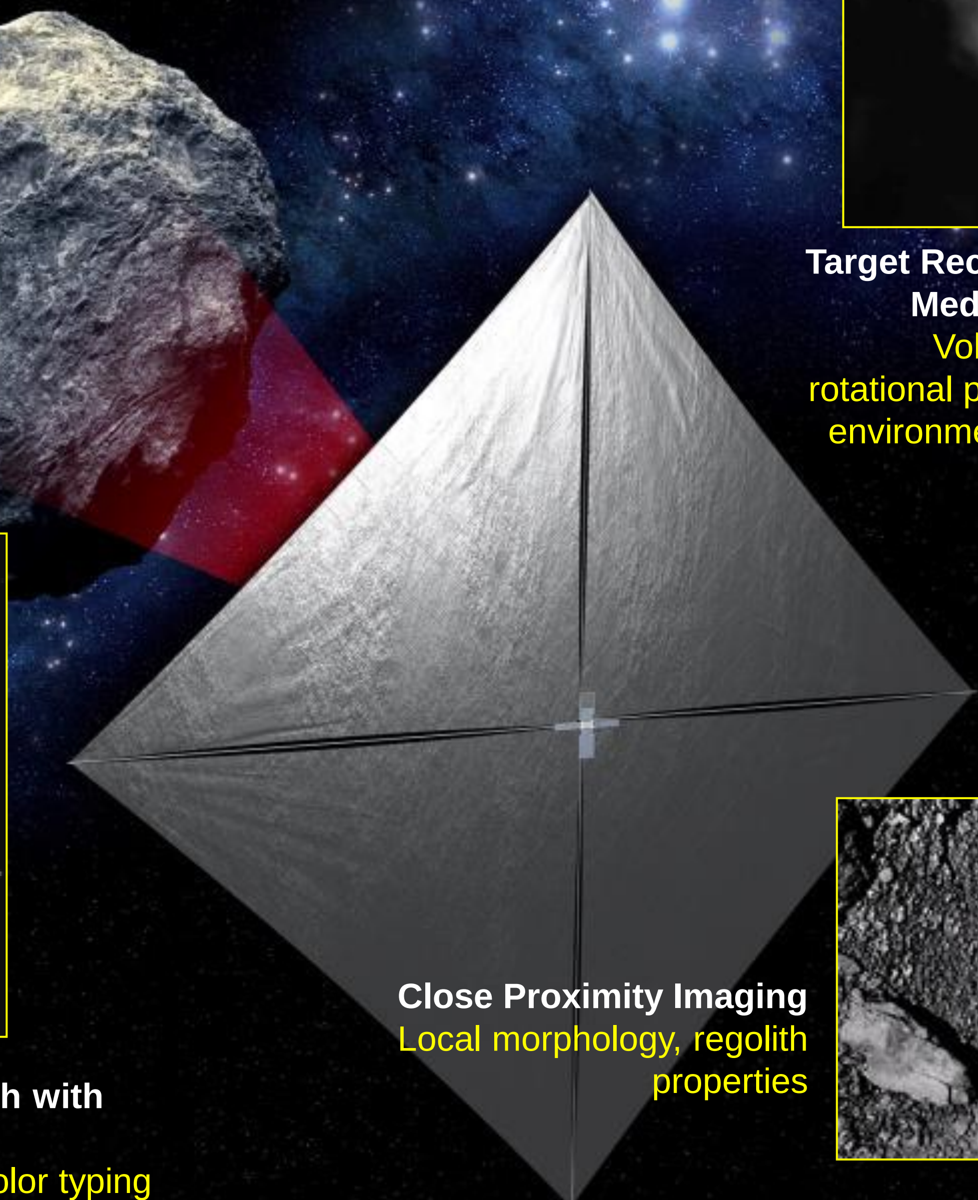
Software:
FSW: *protos (JPL)*
GSW: AMPCS (NASA/JPL)

I&T:
In-house S/C I&T, testing, Tyvak NLAS/Launch Integration

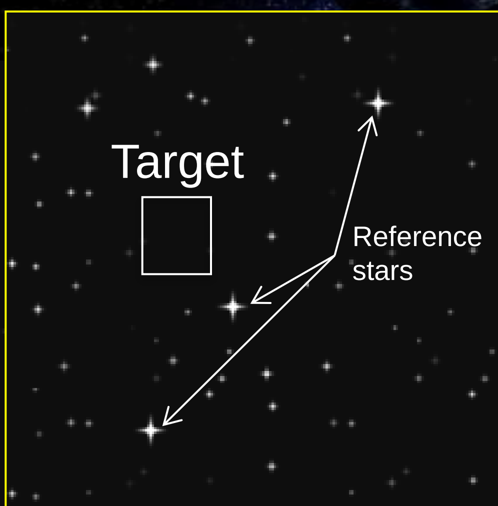
Operations:
Primary: DSN 34m
EDL: Madrid 70m

NEA Scout (MSFC/JPL)

Near Earth asteroid reconnaissance via imaging



Target Reconnaissance with Medium Field Imaging
Volume, global shape, rotational properties, and local environment characterization



Target Detection and Approach with Wide-Field Imaging
Ephemeris determination and color typing

Close Proximity Imaging
Local morphology, regolith properties

Lunar Flashlight*

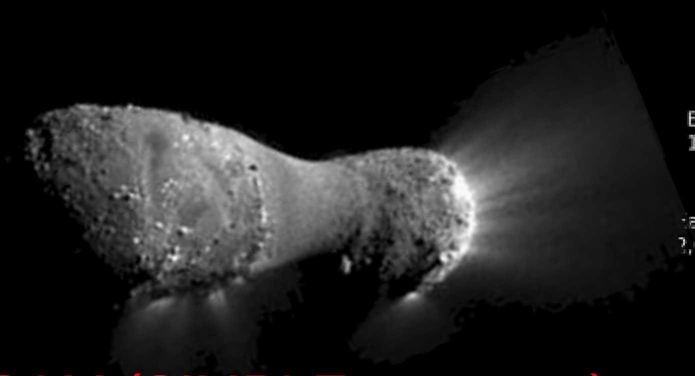
A CubeSat with a solar sail to "shine light" on the distribution of water and other volatiles in the Moon's permanently shadowed regions

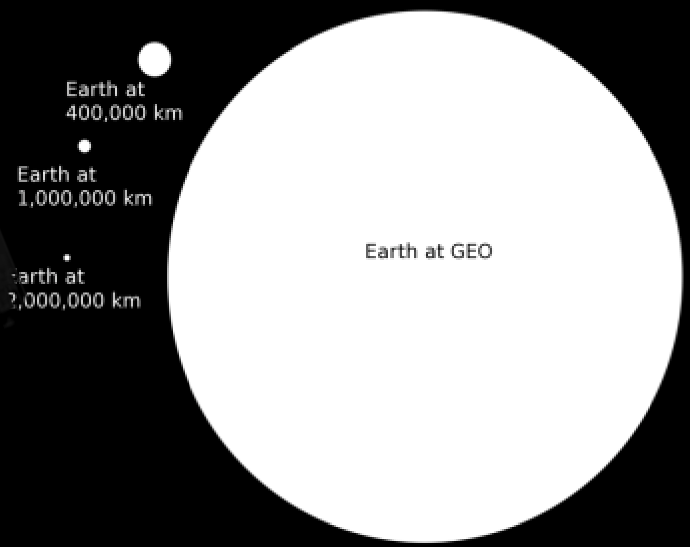
*Mission Concept - Pre-Decisional – for Planning and Discussion Purposes Only

IPEX Future Impact on Beyond LEO Exploration

INSPIRE: On-Board Autonomy to Locate Earth in Star Field

For further information see
S. Chien, J. Doubleday, D. R. Thompson, or J. Castillo-Rogez





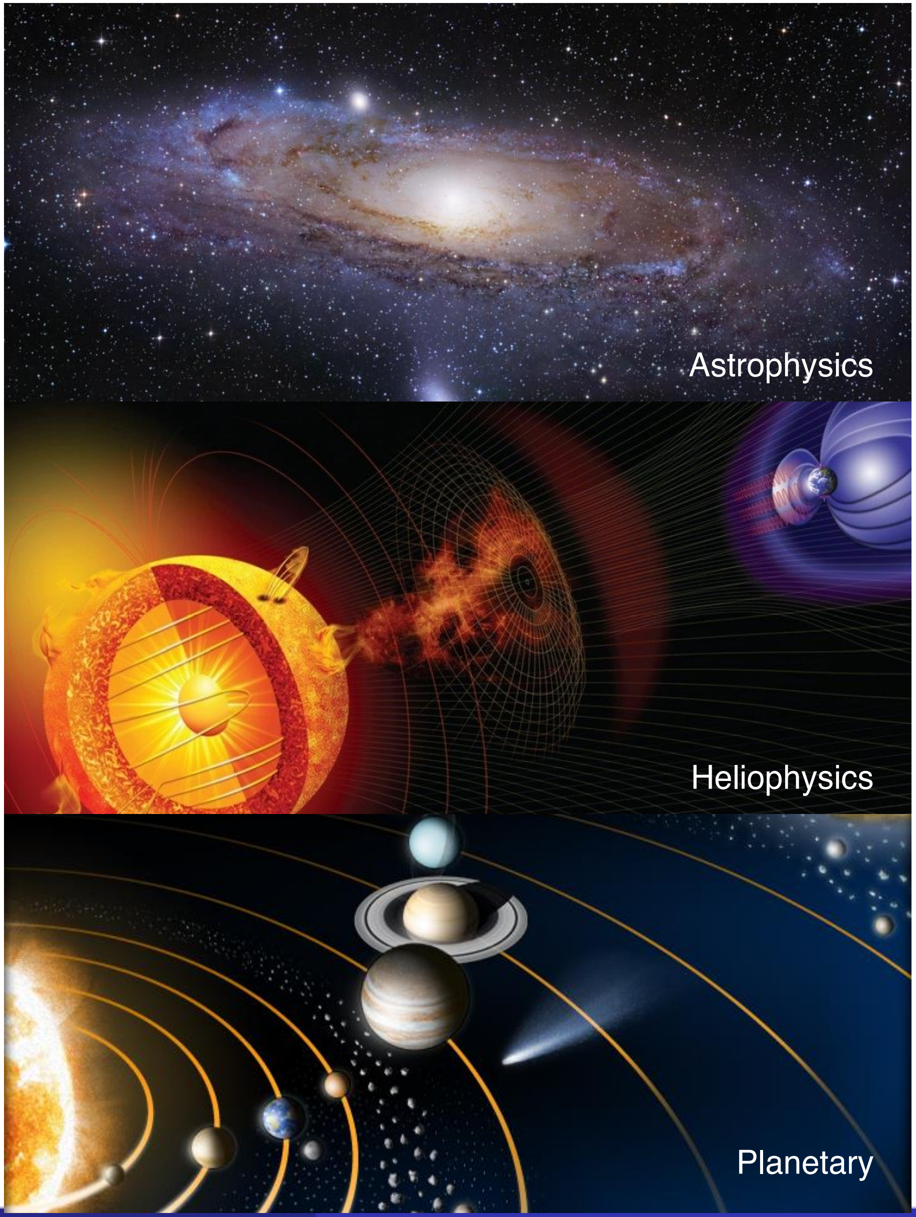
OCCAM (SIMPLEx concept): Rapid Science Re-Planning Following Plume

Apparent size of Earth in camera frame Shown for different mission phases

Keck Institute for Space Studies Final Report

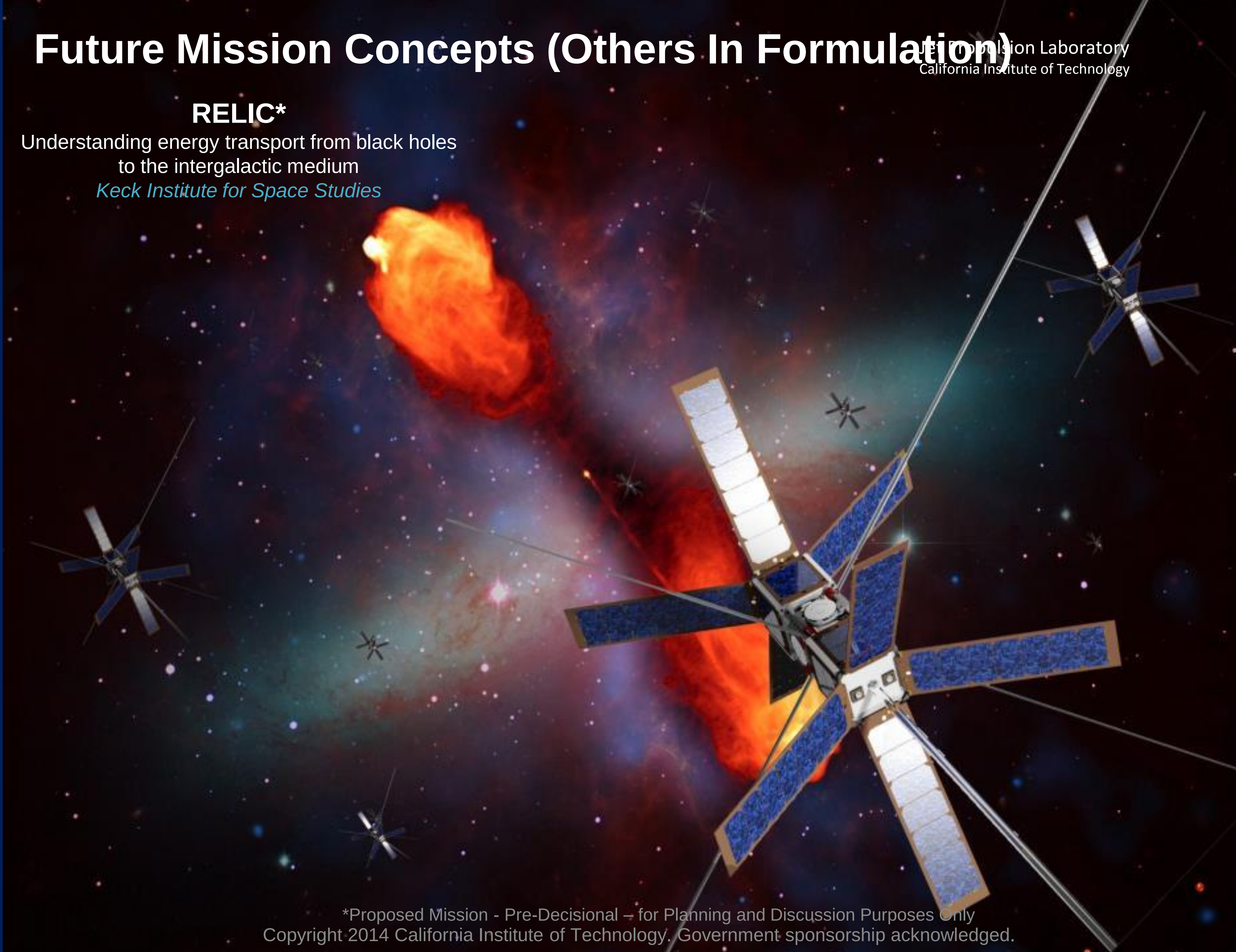
www.kiss.caltech .edu/study/smallsat

Jet Propulsion Laboratory
California Institute of Technology



Future Mission Concepts (Others In Formulation)

Jet Propulsion Laboratory
California Institute of Technology



RELIC*

Understanding energy transport from black holes to the intergalactic medium

Keck Institute for Space Studies

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

Future Mission Concepts (Others In Formulation)

L5SWS*

Fractionated Earth-Sun L5 space weather base for prediction and understanding solar variability effects

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