Jet Propulsion Laboratory
California Institute of Technology

CubeSats and Small Satellites as a vehicle for space innovation and exploration of space beyond Earth oribt

Leon Alkalai, JPL Fellow
Charles Norton, Anthony Freeman, JPL

Rationale for CubeSat Development

Enable decadal-class focused science via new mission architectures including constellations and access to extreme environments

Advance new technologies to enhance the capabilities of future missions

Utilize CubeSats as a stepping-stone to more capable small satellite missions in all science areas

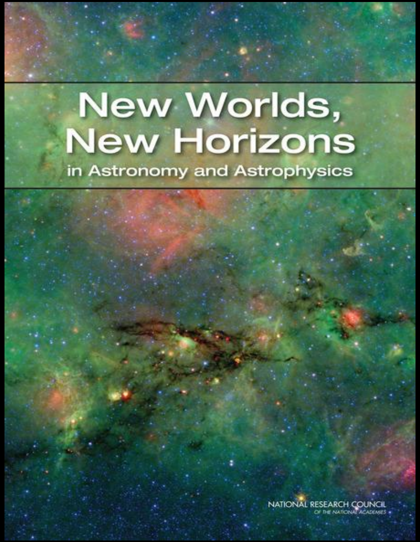
Develop the next generation of explorers and revitalize the existing ones

Increase the pace of scientific discovery and technology maturation within a constrained budget environment

Enhance the science return of future flagship missions

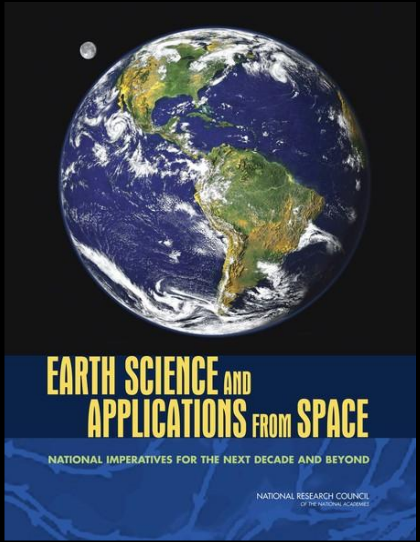
The Decadal Surveys

Astrophysics



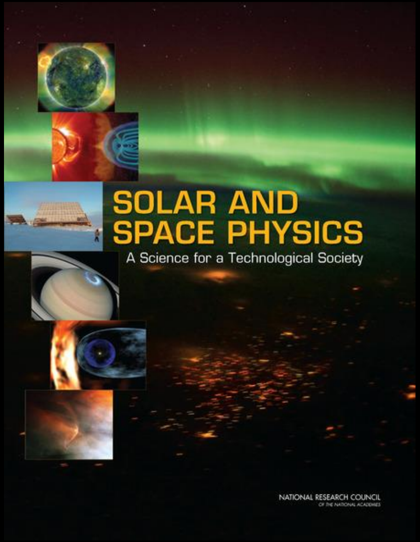
2012 – 2021

Earth Science



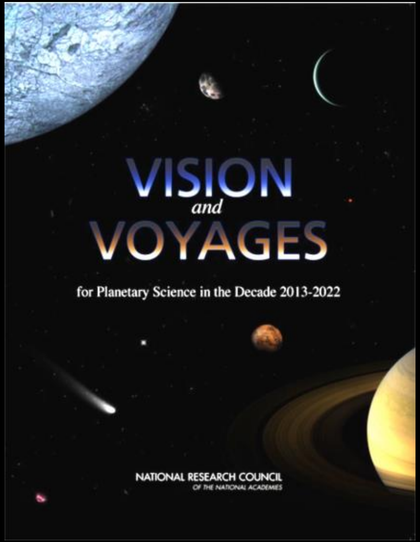
2007 – 2016

Heliophysics



2012 – 2021

Planetary



2013 – 2022

Organized by the National Academies on behalf of NASA establishing USA national priorities for scientific observations, as identified by the community, within a 10-year time frame

Portfolio of Remote Sensing Explorers

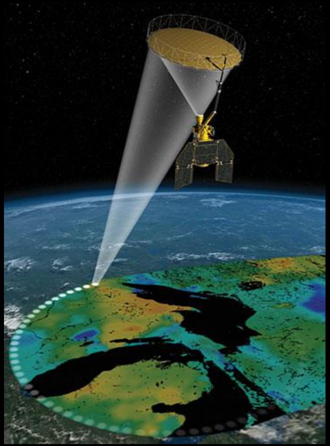
Small satellites are a growing component of space exploration

CubeSat / SmallSat

CP-6
10+ cm (linear)
1 – 180 kg
5 – 200 W

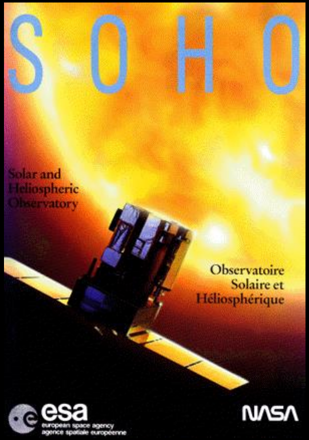
MiniSat / ESPA-Class

LCROSS
2 meters (linear)
585 kg (dry mass)
600 W



Medium-Class

SMAP
9.7 meters (linear)
944 kg
550 W (radar peak)



Large-Class

SOHO
4.3 meters (linear)
1850 kg
1,500 W

Flagship-Class

Aura
17.37 meters (linear)
2,967 kg
4,600 W

The NRC Achieving Science Goals With CubeSats Study

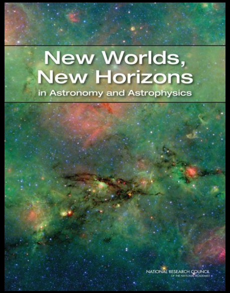
Key elements of charge to the committee

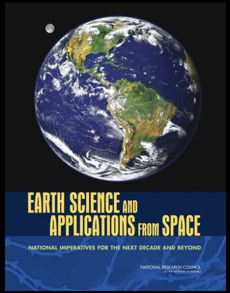
Review the current state of scientific potential and technological promise of CubeSats

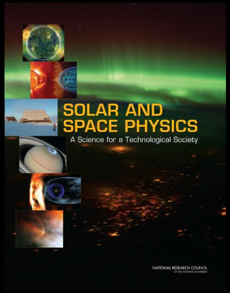
Review the potential of CubeSats as platforms for obtaining high-priority science data

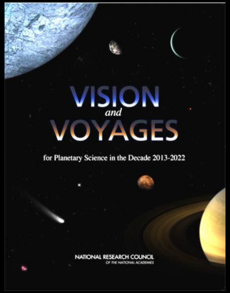
- From recent decadal surveys
- Science priorities from 2014 NASA science plan

Provide a set of recommendations on how to assure scientific return on future federal agency support of CubeSat programs









The NRC Achieving Science Goals With CubeSats Study

CubeSats as a Disruptive Innovation

"Process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up the market […]." Clayton Christensen, 1995

Describes many shifts in targeted markets of the economy:

- Emergence of laptops over desktop computers, but supercomputers still exist
- Smartphone cameras replace low-end camera, but high-end cameras still exist

CubeSat exemplify Disruptive Innovation:

- (Initially) poorer performance, lower cost, emerged from non-traditional sources, driven by enabling technologies, matured and developed in new ways.
- Need not replace mainstream technology
- The "end-state" and level of disruption remains unclear

The NRC Achieving Science Goals With CubeSats Study

Sample Near-Term Science Opportunities

Earth Science

- Multi-point high temporal resolution of Earth processes
- Mitigation of data gaps and continuous monitoring

Solar and Space Physics (Heliophysics)

- Measurement of plasma processes in the magnetosphere-ionosphere system

Planetary Science

- In situ investigation of planetary surfaces or atmospheres

Astronomy and Astrophysics

- Low-frequency radio science and the search for extra-solar planets

Biological and Physical Sciences

- Survival and adaptation of organisms to space

National Academy of Sciences

Achieving Science with Cubesats*

- **Key Findings:**
  - "CubeSats have already produced high-value science as demonstrated by peer-reviewed publications that address decadal survey science goals"
  - "CubeSats are… enabling new kinds of measurements, and they may have the potential to mitigate gaps in measurements where continuity is critical"
  - "All science disciplines benefit from innovative CubeSat missions"
  - However, they "cannot address all science objectives and are not a low-cost substitute for all platforms"
  - "CubeSats share characteristics of Disruptive Innovations"

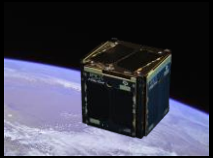
*Zurbuchen, T. H. et al, Achieving Science with CubeSats: Thinking Inside the Box, National Academy of Sciences Space Studies Board Report, June 2016

Portfolio of Missions with JPL

Externally-Led Mission

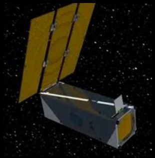
JPL-Led or with key JPL participation

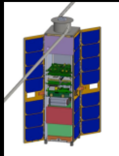

M-Cubed/COVE (2)


IPEX

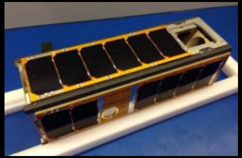

GRIFEX


CSUNSat-1

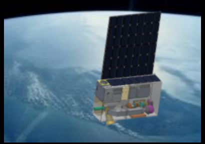

ISARA

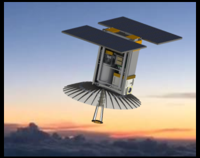

DHFR

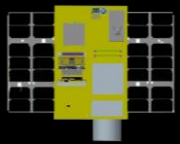

CuSP

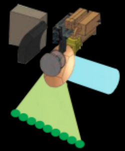

RACE


INSPIRE

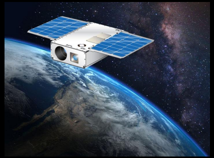

CIRAS

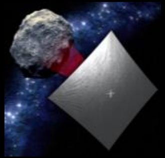

RainCube

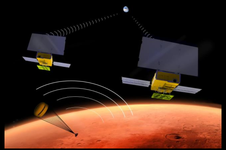

CubeRRT

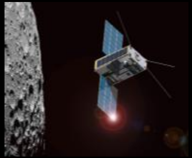

TEMPEST-D


LMRST


ASTERIA


NEA Scout

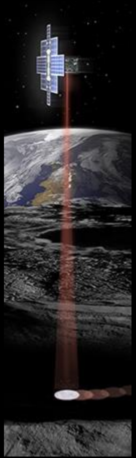

MarCO


Lunar IceCube


LunaH-Map


AAREST


MiTEE


Lunar Flashlight

RainCube

Ka-Band Precipitation Radar

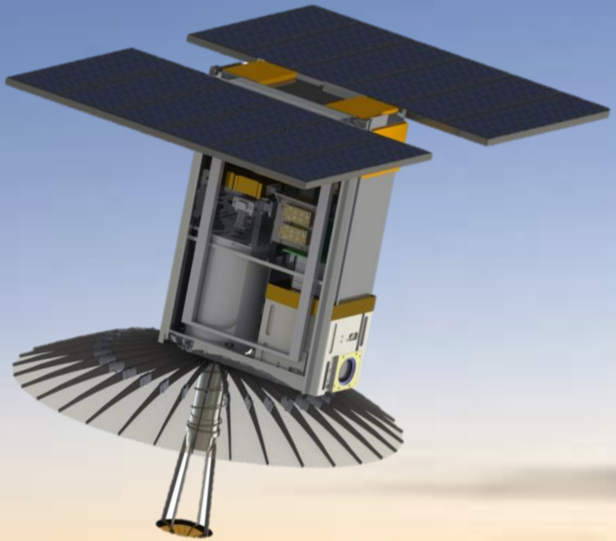
Design Capability

1st CubeSat radar capability at 20 dBZ or better

Spatial: 10km (Horiz) x 250m (Vert)
Spectral: 35.75 GHz
SWAP: 6U, <20 kg, <50W, <100 kbps

Key Technologies

Ka-Band deployable antenna, Offset IQ processing capability



Enables precipitation profiling down to the near-surface, at all latitudes, and at various sub-daily scales

Jet Propulsion Laboratory
California Institute of Technology

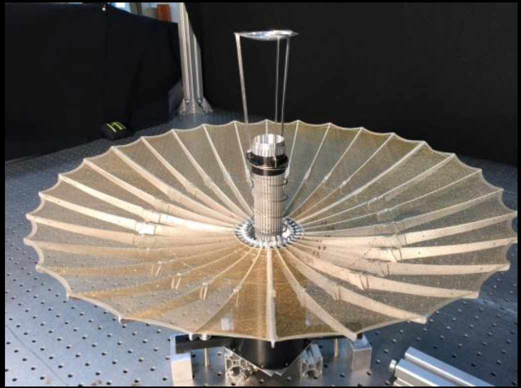
NASA

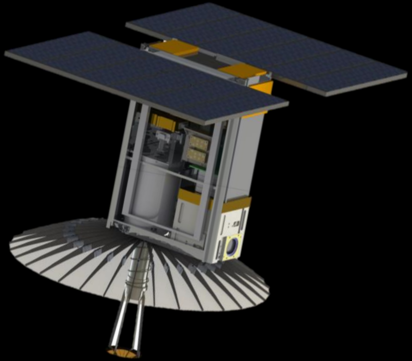
ESTO
Earth Science Technology Office

KaPDA Antenna Deployment

0.5 meter Ka-Band antenna development for RainCube

16x speed





Courtesy: Jonathan Sauder, JPL

Infrared Sounding

Captures severe weather events and improves operational forecasts

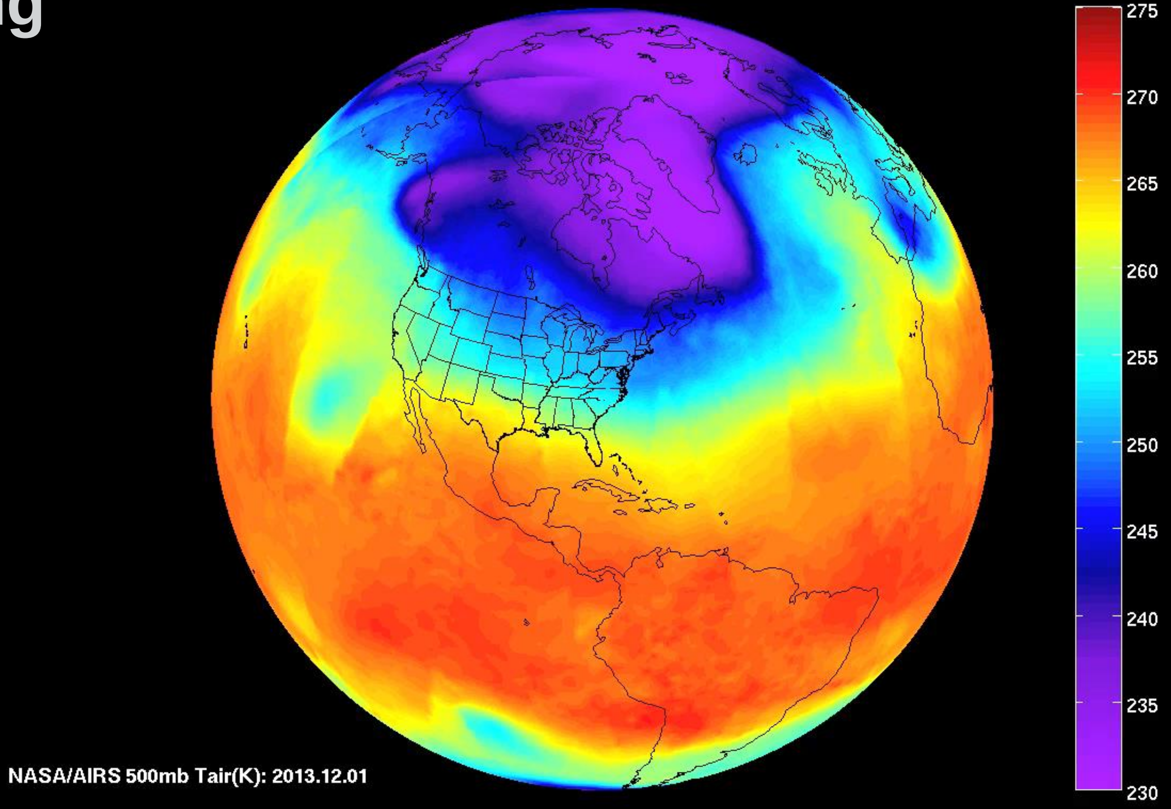
Polar vortex of 2013-2014

Dec 4, 2013: Denver weather: Temperature hits minus 13 — record low for the date

Dec 24, 2013: Record Low Tied at Cedar Rapids This Morning | Iowa Weather Blog

Jan 6, 2014: Chicago Record Low Temperature: City Hits -16 Mark

Jan 29, 2014: Atlanta, Georgia, historic weather for the past week



Courtesy: Tom Pagano, JPL

CIRAS

Infrared Atmospheric Sounder

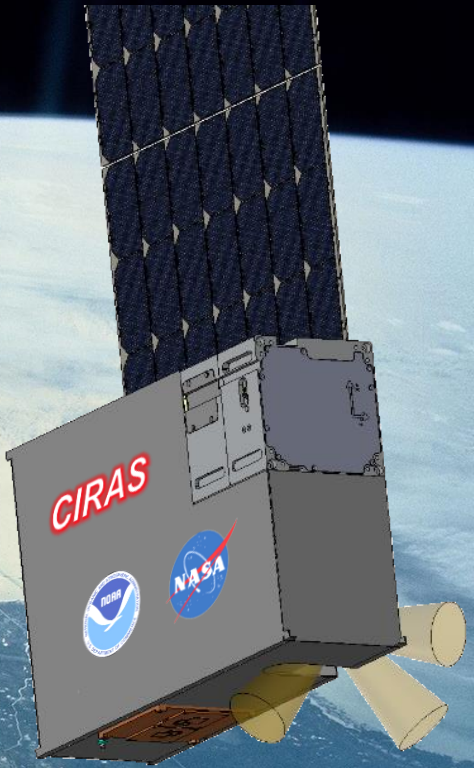
Design Capability

Accuracy comparable to legacy IR sounders, e.g. AIRS on AQUA and CrIS on JPSS, but only in the lower troposphere (< 300 mb)

Spatial: FOV: 15˚, GSD: 13.5 km
Spectral: 625 Channels, 4.9-5.1 µm
SWAP: 6U, <14 kg, <50 W, <2 Mbps

Key Technologies

MWIR grating spectrometer, HOT-BIRD detectors, cryocoolers, black silicon IR blackbody



Enables capability to measure spectrum of upwelling infrared radiance from the Earth (temperature and water vapor profiles)

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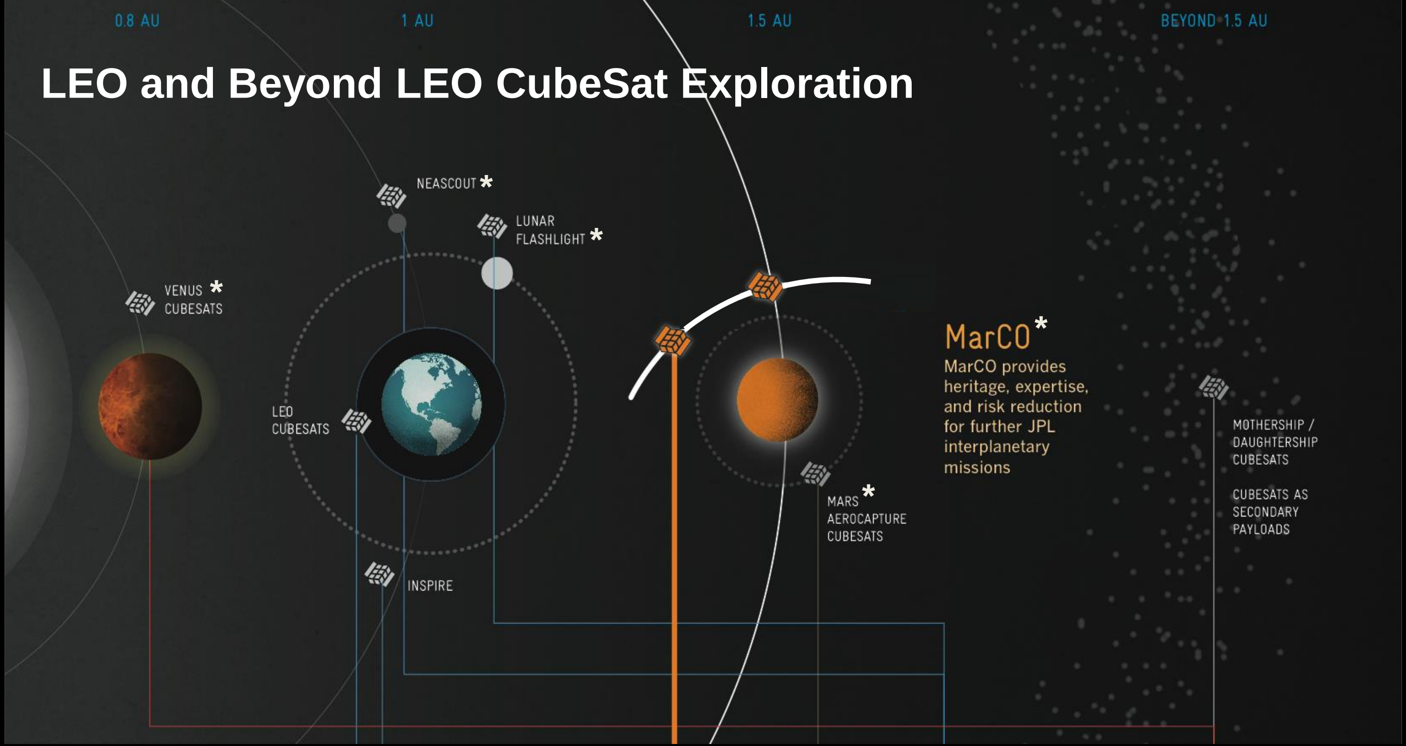
California Institute of Technology

ESTO
Earth Science Technology Office

Jet Propulsion Laboratory
California Institute of Technology

Beyond Earth Orbit

LEO and Beyond LEO CubeSat Exploration



Known Challenges

- Propulsion, Communications
- Environments, Power, ADACS
- Thermal, Energy storage
- Proximity operations and autonomy

Less Obvious Challenges

- Mission assurance and reliability
- Multi-mission ground operation systems
- Planetary protection, Hazard avoidance
- Flight software standards

INSPIRE Flight Systems

INSPIRE Design Overview

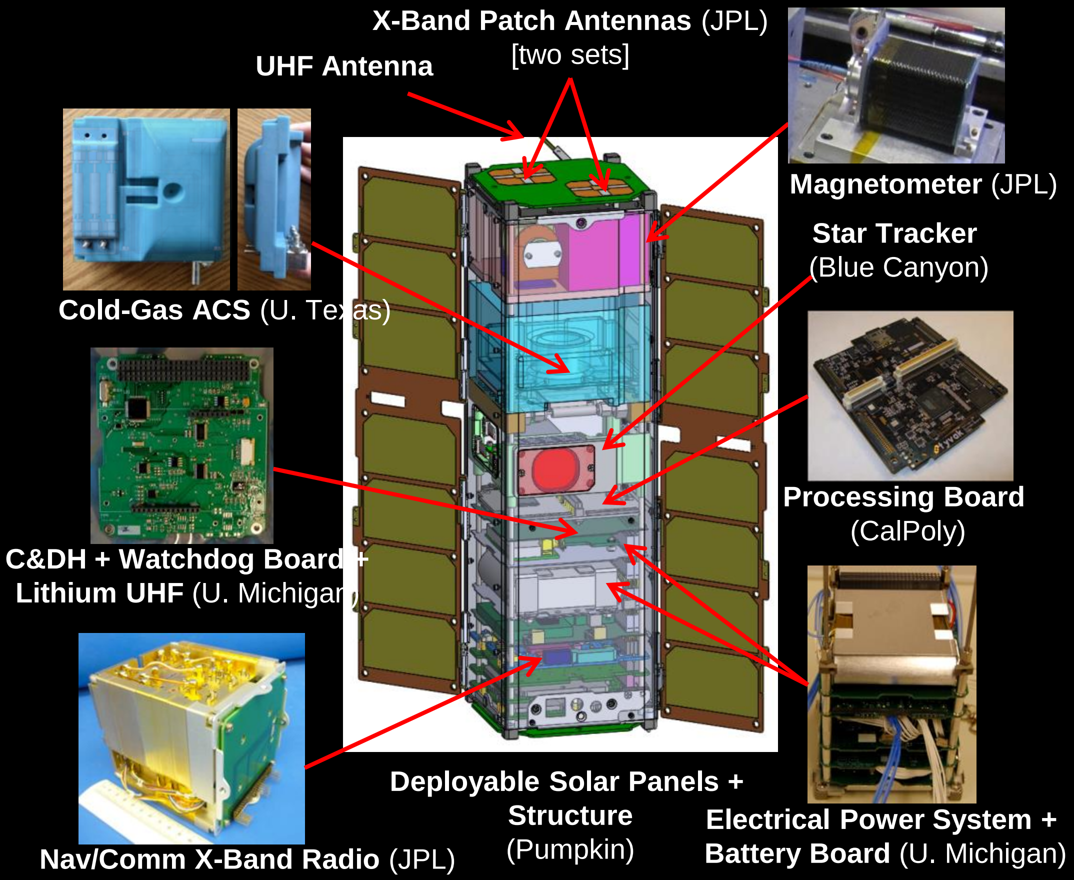
<u>CubeSat Overview:</u>
Volume: 3U (10x10x30cm)
Mass: 5 kg
Power Generation: 20 W (@1 AU)
Data Rate: 62-256000 bps

<u>Software:</u>
Developed in-house

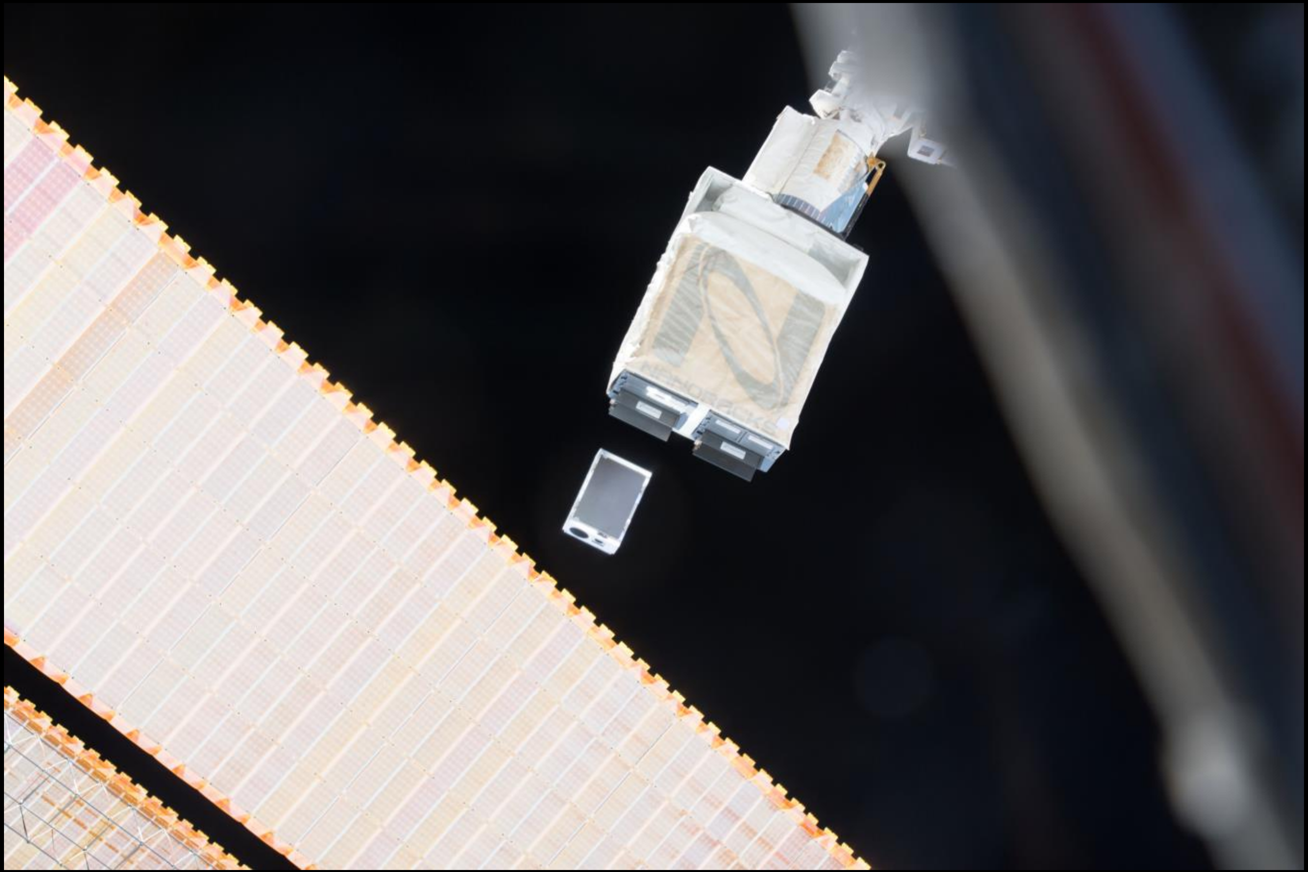
<u>I&T:</u>
In-house S/C I&T, CalPoly P-Pod/Launch Integration

<u>Operations:</u>
DSN, DSS-13 (JPL), & Peach Mountain (U. Michigan)

S/C components provide ***the basis for future high-capability, lower-cost-risk missions*** beyond Earth expanding and ***provide NASA leadership in an emergent domain***



ASTERIA – successfully deployed



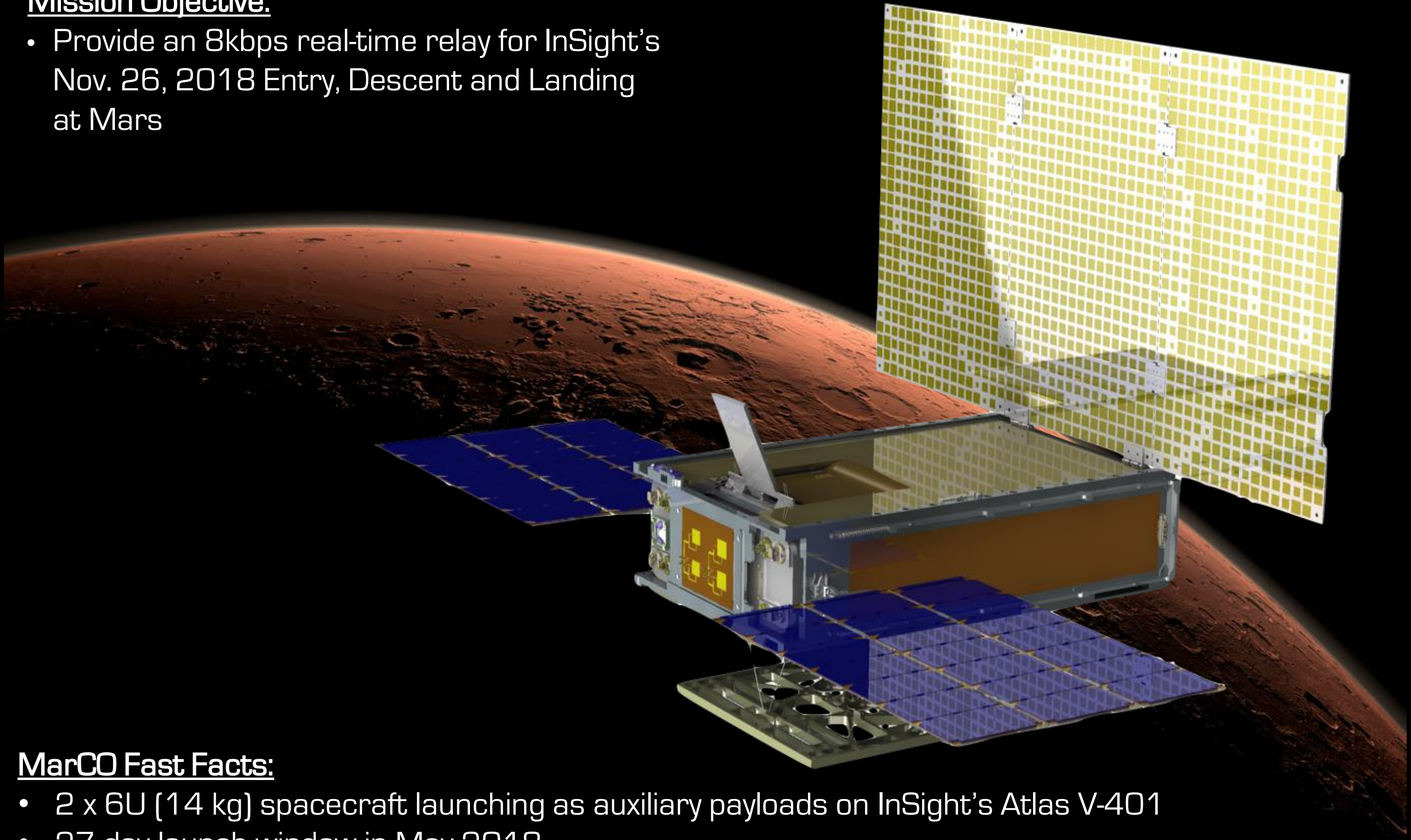
MarCO

CubeSats to Mars in 2018

Jet Propulsion Laboratory
California Institute of Technology

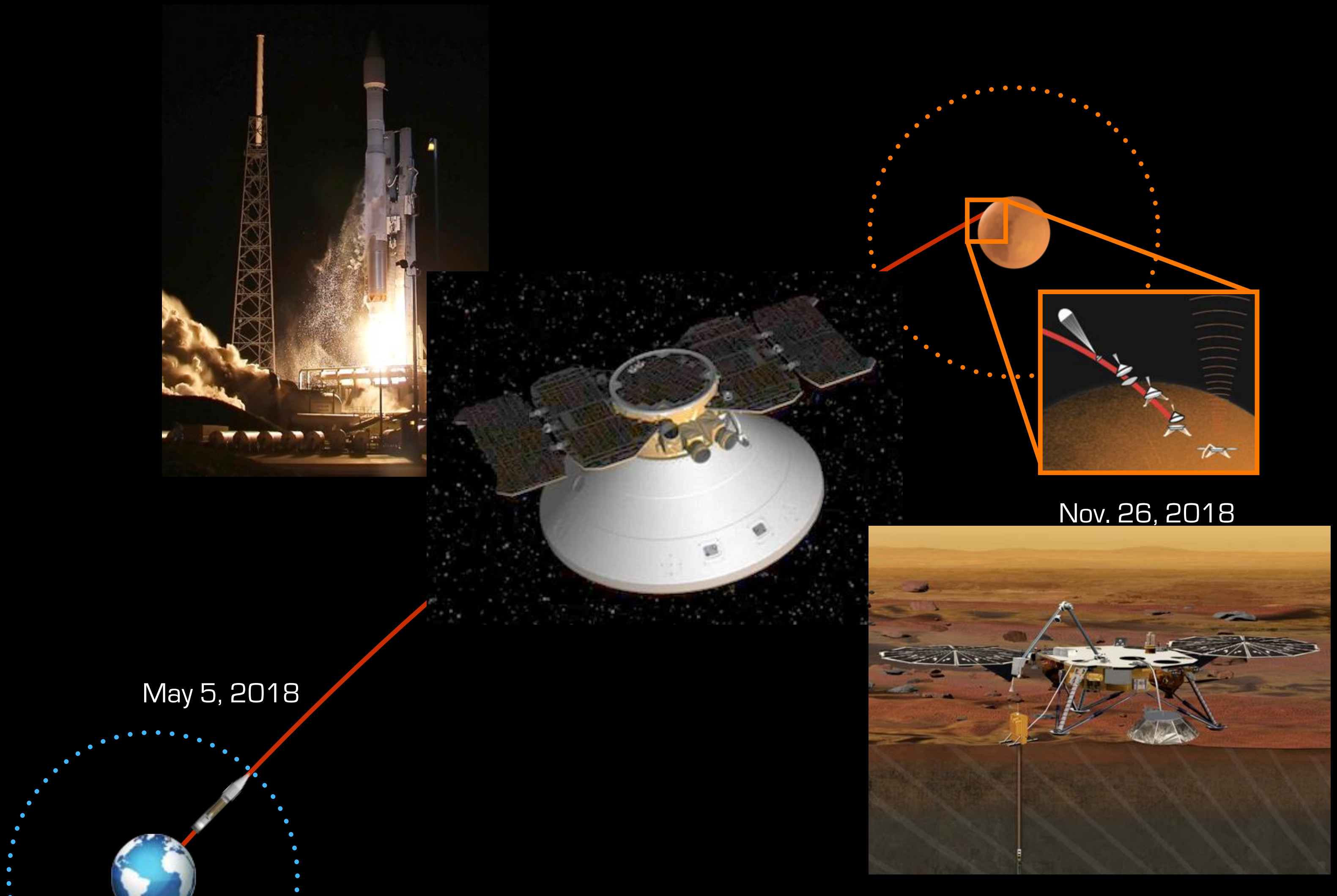
Mission Objective:

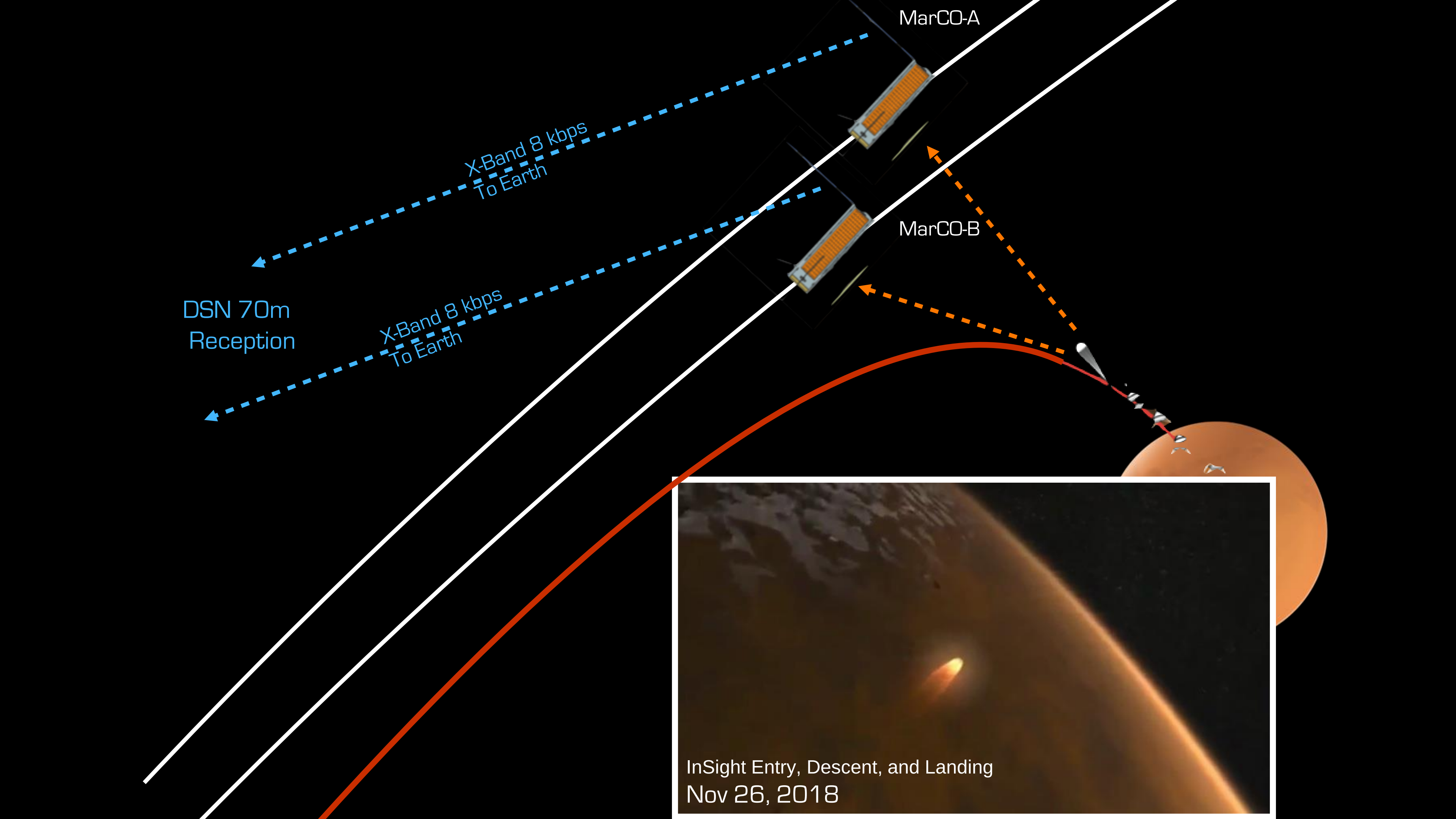
- Provide an 8kbps real-time relay for InSight's Nov. 26, 2018 Entry, Descent and Landing at Mars



MarCO Fast Facts:

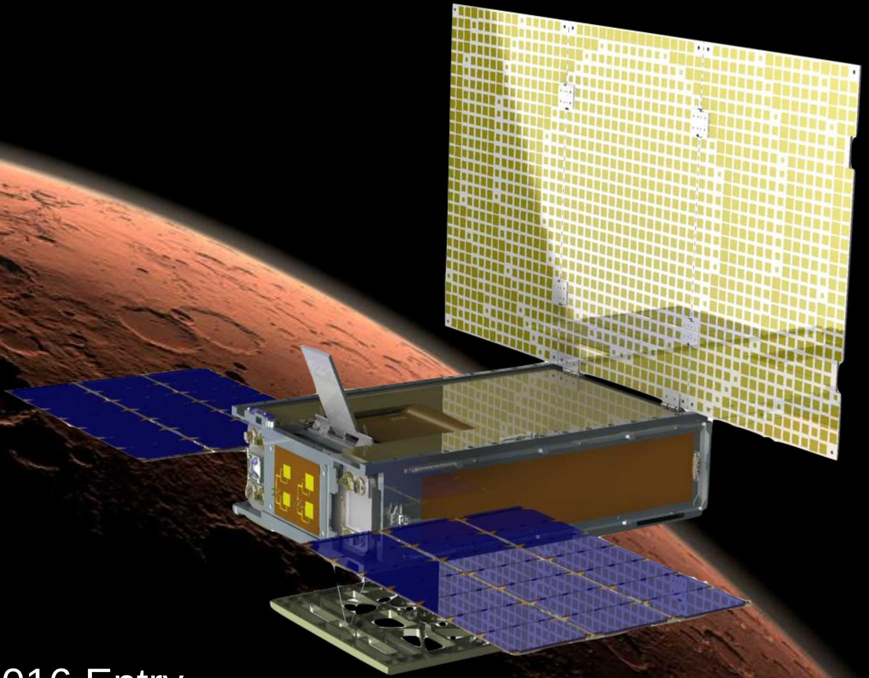
- 2 x 6U (14 kg) spacecraft launching as auxiliary payloads on InSight's Atlas V-401
- 27 day launch window in May 2018
- Separation approximately 95 min after launch
- 6.5 month cruise (157 million km) to Mars
- 5 Trajectory Correction Maneuvers to establish Mars-flyby heliocentric orbit
- Flying by Mars November 26, 2018


Nov. 26, 2018
May 5, 2018


MarCO-A
X-Band 8 kbps
To Earth
MarCO-B
DSN 70m
Reception
X-Band 8 kbps
To Earth
InSight Entry, Descent, and Landing
Nov 26, 2018

MarCO

CubeSats to Mars in ~~2016~~ 2018

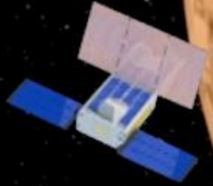


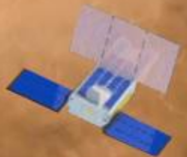
Provides an 8 kbps real-time relay for InSight’s 2016 Entry, Descent, and Landing at Mars

MarCO

Mars Cube One

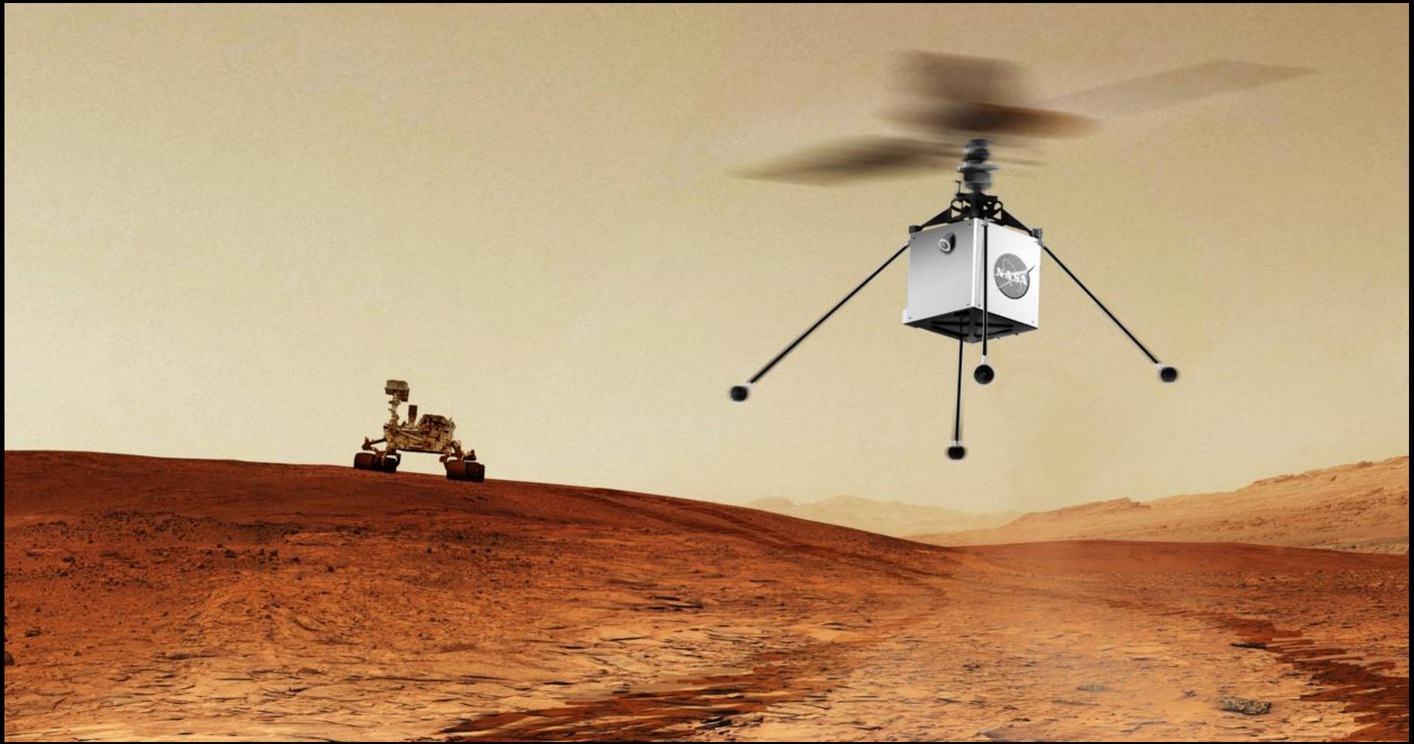
First Interplanetary CubeSat Mission





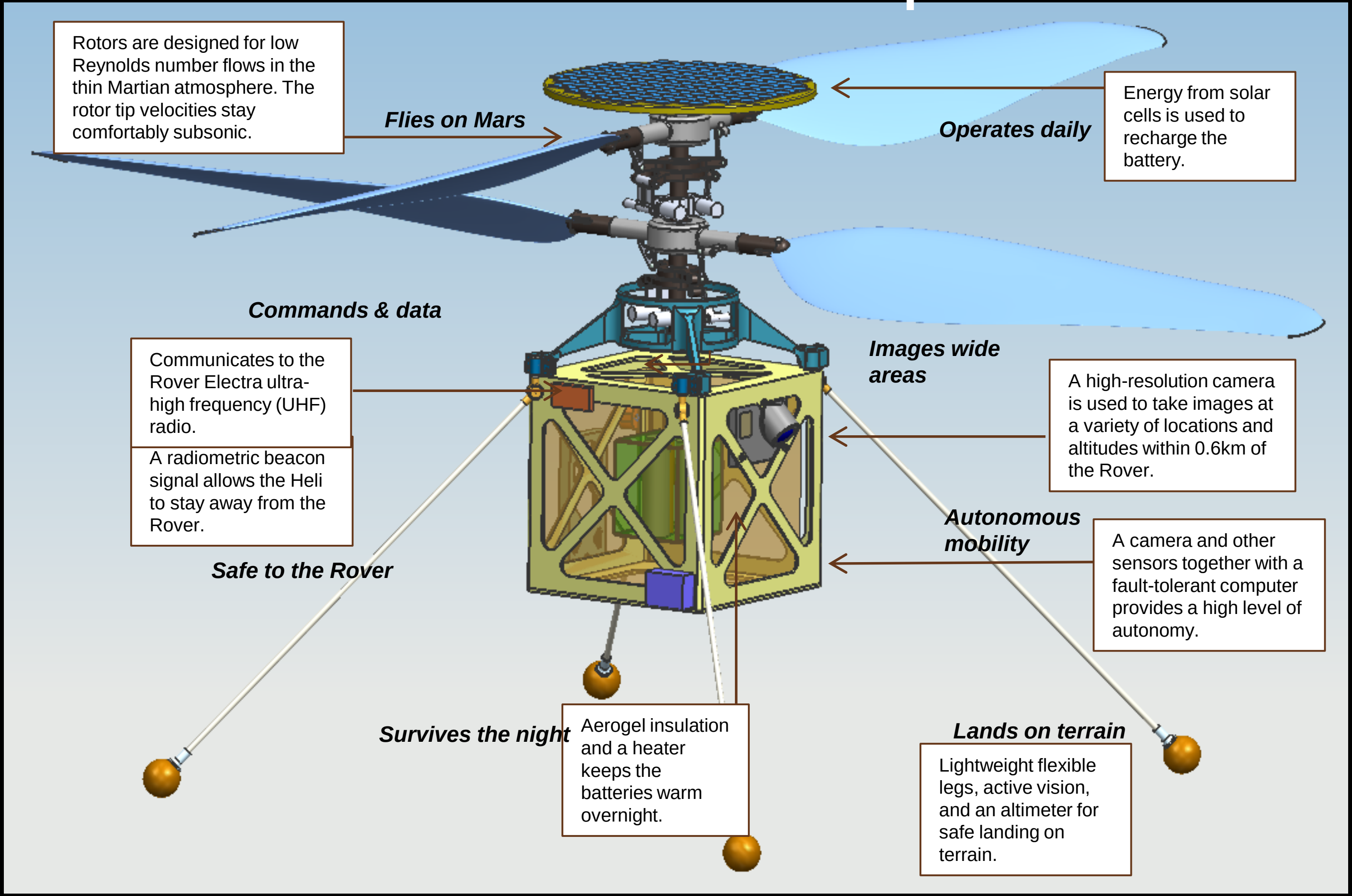
Jet Propulsion Laboratory
California Institute of Technology

Autonomous Aerial Platforms



Helicopter aerial mobility as rover assistants.

M2020 Scout - Helicopter



Deep-Space CubeSats on EM-1

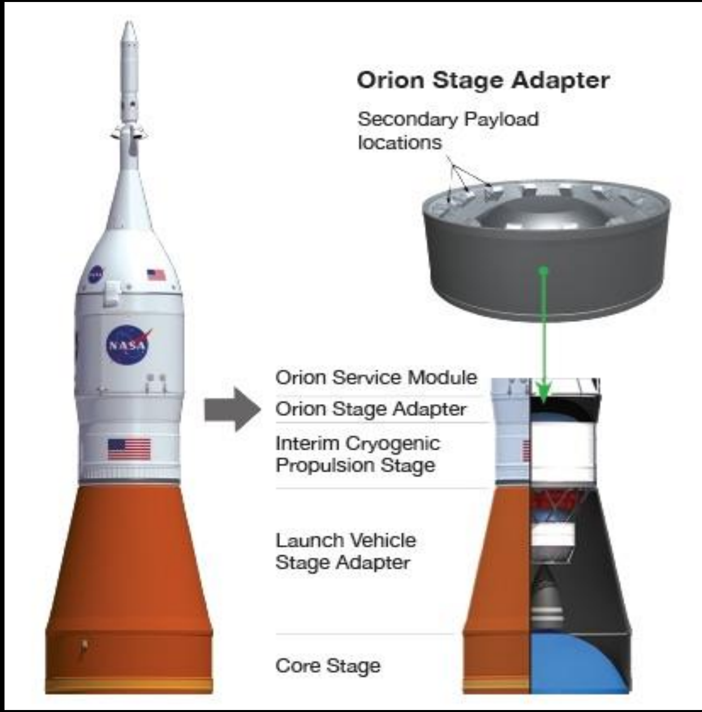
68th International Astronautical Congress

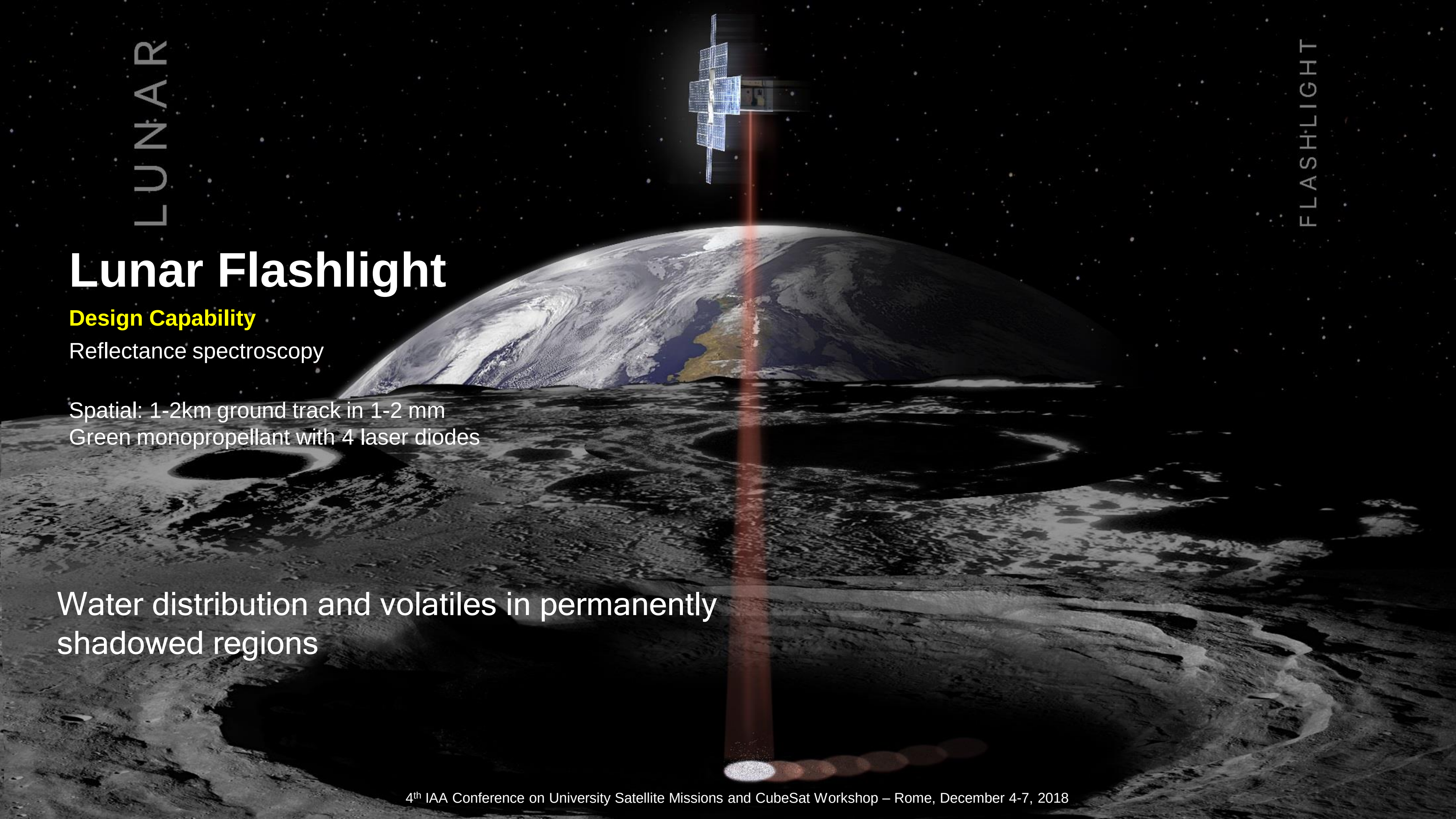
September 29, 2017

Nicole Herrmann
Chris Moore
Jitendra Joshi

CubeSats on Exploration Mission-1 (EM-1)

- 13 deep-space CubeSats will be deployed from NASA's Space Launch System rocket on its first flight in 2019.
- The EM-1 CubeSats are being developed by NASA and its industry, university, and international partners.
- The EM-1 CubeSats will be launched as secondary payloads in the Orion Stage Adapter.
- Each CubeSat has a six-unit (6U) configuration.
- The EM-1 CubeSats will be the first to ever visit the Moon and cislunar space, heliocentric orbit, and a near-Earth asteroid.





Lunar Flashlight

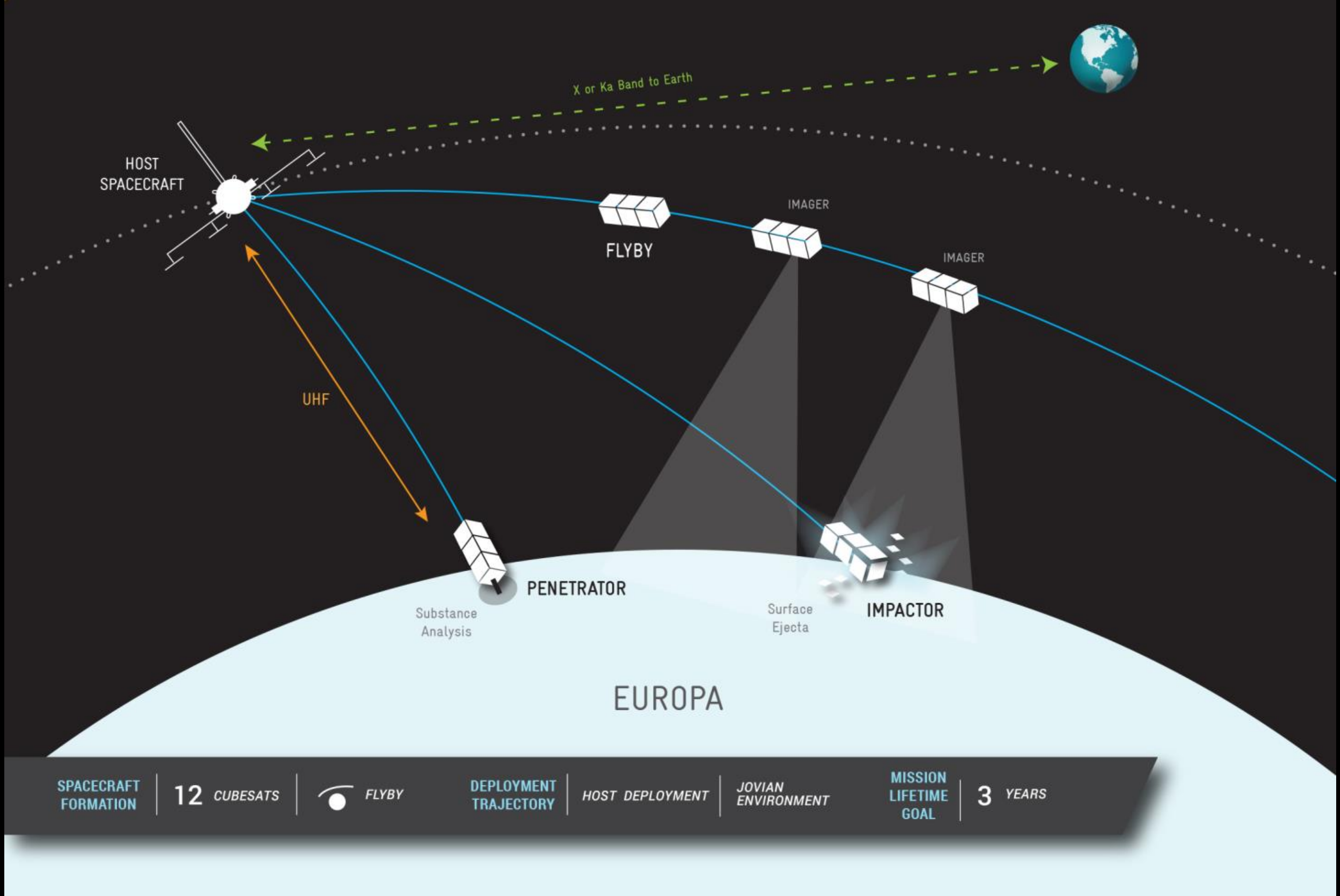
Design Capability

Reflectance spectroscopy

Spatial: 1-2km ground track in 1-2 mm
Green monopropellant with 4 laser diodes

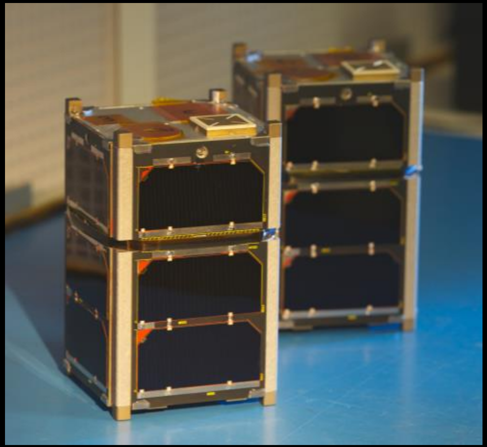
Water distribution and volatiles in permanently shadowed regions

ExCSITE


X or Ka Band to Earth
HOST SPACECRAFT
FLYBY
IMAGER
IMAGER
UHF
PENETRATOR
Substance Analysis
Surface Ejecta
IMPACTOR
EUROPA
SPACECRAFT FORMATION
12 CUBESATS
FLYBY
DEPLOYMENT TRAJECTORY
HOST DEPLOYMENT
JOVIAN ENVIRONMENT
MISSION LIFETIME GOAL
3 YEARS

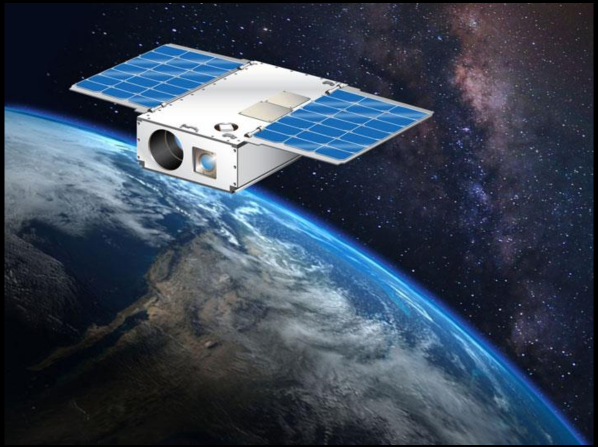
Trends in Heliophysics, Astrophysics, Planetary Science

Flights and studies for small missions including beyond LEO



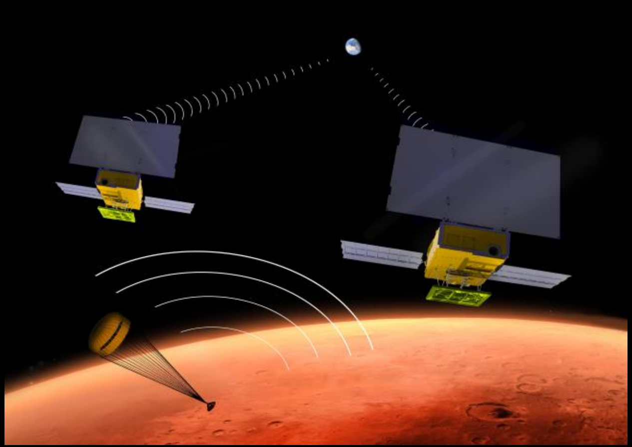
Firebird(s)

Exploring the physics of relativistic electron microbursts



ASTERIA

Arcsecond space telescope technology to enable the search for Earth-like planets

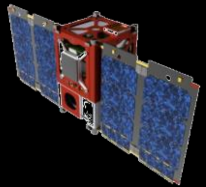


MarCO

Two 6U CubeSats, flying with the InSight mission to Mars, to act as real-time EDL telecom relays

For beyond LEO observation many technologies must be advanced so current work is targeted, often focusing on enhancing current Decadal-scale measurements

Team Xc – Fast Formulation

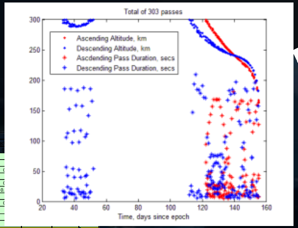


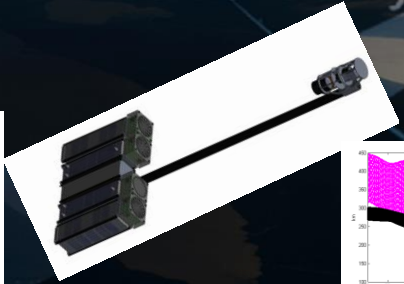
Agile, collaborative design team built on Team X infrastructure

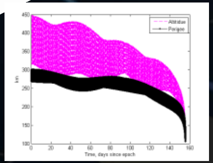
- Fast turnaround for mission concepts and studies (~2 weeks)
- Adaptable to a wide variety of Smallsat/Nanosat/CubeSat customers
- Cost Effective (Team X study cost/2)
- Quickly assess feasibility, trade space, point designs, operations concept

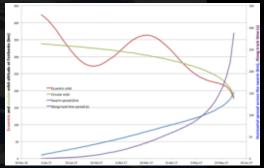
TEAM Xc
Jet Propulsion Laboratory

Mechanical	Antenna Deployment	0	0	2	0				
	Solar Panel Deployment	0	0	9	0				
Avionics	GomSpace Battery	0.1	0.1	0.1	0.1				
	Michigan C&DH	0.1	0.1	0.1	0				
	Novatel GPS	0.1	0.1	0.1	2				
	GomSpace EPS	0.125	0.125	0.125	0.125				
ACS	BCT XACT	0.5	2	0.5	2				
Telecom	L3 Cadet S band	0.3	0.3	0.3	0.3				
	Patch Antenn	0	0	0	0				
Instruments	Faraday cup	0	0	0	0				
	Magnetometer	0	0	0	0				
Total W		1.23	2.73	12.23	4.53	2.63	14.43	2.83	2.63
Total W+Cont (30%)		1.59	3.54	15.89	5.88	3.41	18.75	3.67	3.41
Total W-hr		1.23	2.73	2.04	1.13	1.97	1.44	0.19	1.14



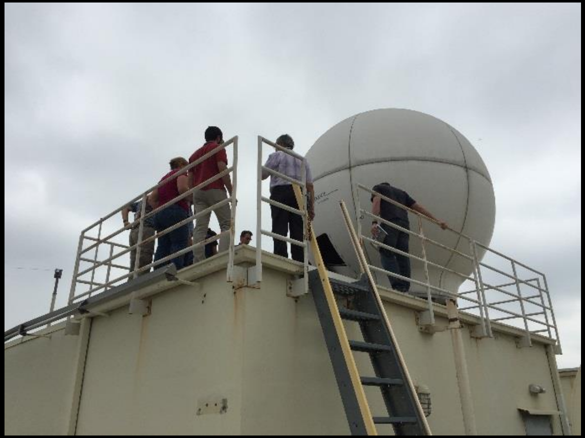




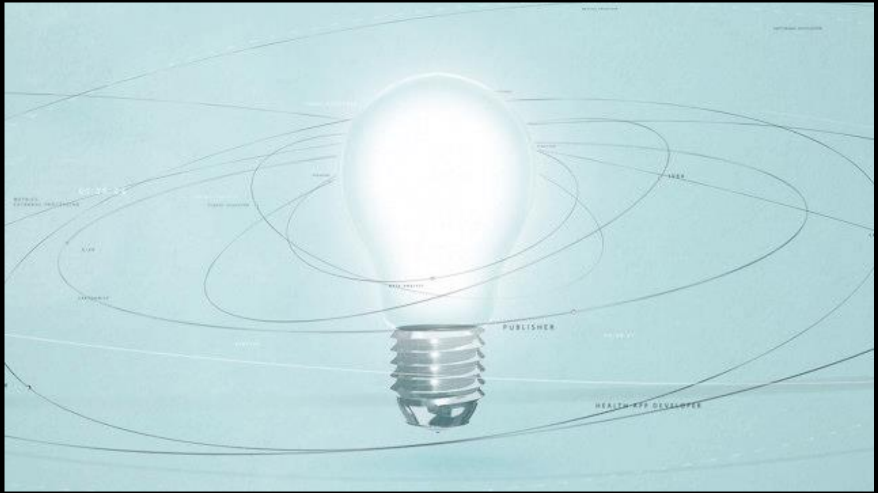


CubeSat Development Lab

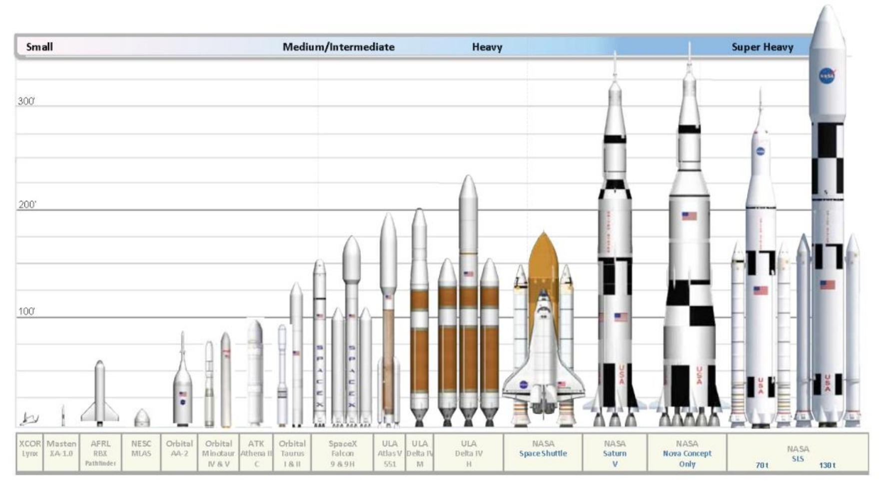
Photos of X-Band Station Work



CubeSats for rapid Innovation 2 Flight (I2F) Program



Rapid Innovation



Flight Portal

JPL Cubesat Strategy (draft 2017)

- Recognize cubesats as a disruptive innovation vehicle; here to stay
- Accelerate innovation to flight infusion: “Innovation to Flight (I2F)”
- A great opportunity to work with academia, interns, international community, high-schools, public outreach
- Excellent opportunity to train for new JPL employees
- Opportunity for high-value science as recommended by NAS
- Work with industry suppliers, stimulate economic growth
- Focus on JPL-hard problems, payload, miniaturized science instruments
- Build workforce of the future: look 10-20 years ahead

Some References:

Additional Recent Reading Material:

- "Global Trends in Small Satellites," Bhavya Lal et al., Science & Technology Policy Institute, July 2017, IDA Paper P-8638, Log: H17-000435
- "*CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions*," Armen Poghosyan, Alessandro Golkar, Progress in Aerospace Sciences 88 (2017) 59-83.
- "*Planetary CubeSats Come of Age*," by Brent Sherwood et. al (JPL), IAC-15, A3,5,8x30103, October 14th, 2015
- "*An Overview of CubeSat Projects at JPL*," by Leon Alkalai, Charles Norton and Anthony Freeman, IAC-15, B4,8,1x31604, October 12th, 2015
- "*Achieving Science with CubeSats: Thinking Inside the Box*," Zurbuchen, T. H. et al,, National Academy of Sciences Space Studies Board Report, June 2016

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Future Concepts

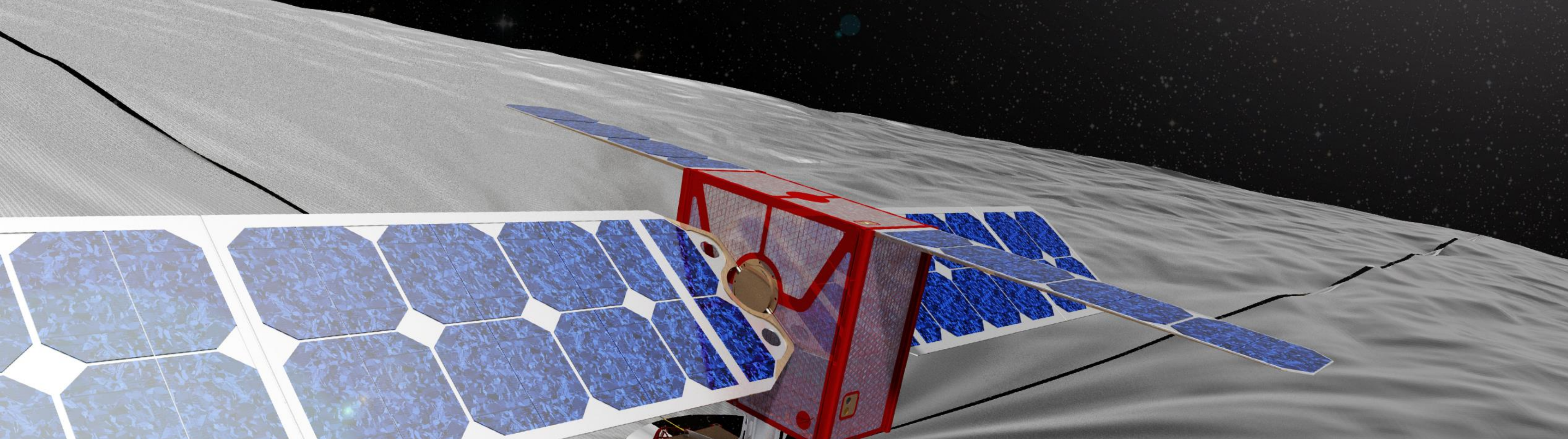
L5 Space Weather Sentinel (L5SWS)

L5SWS*

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

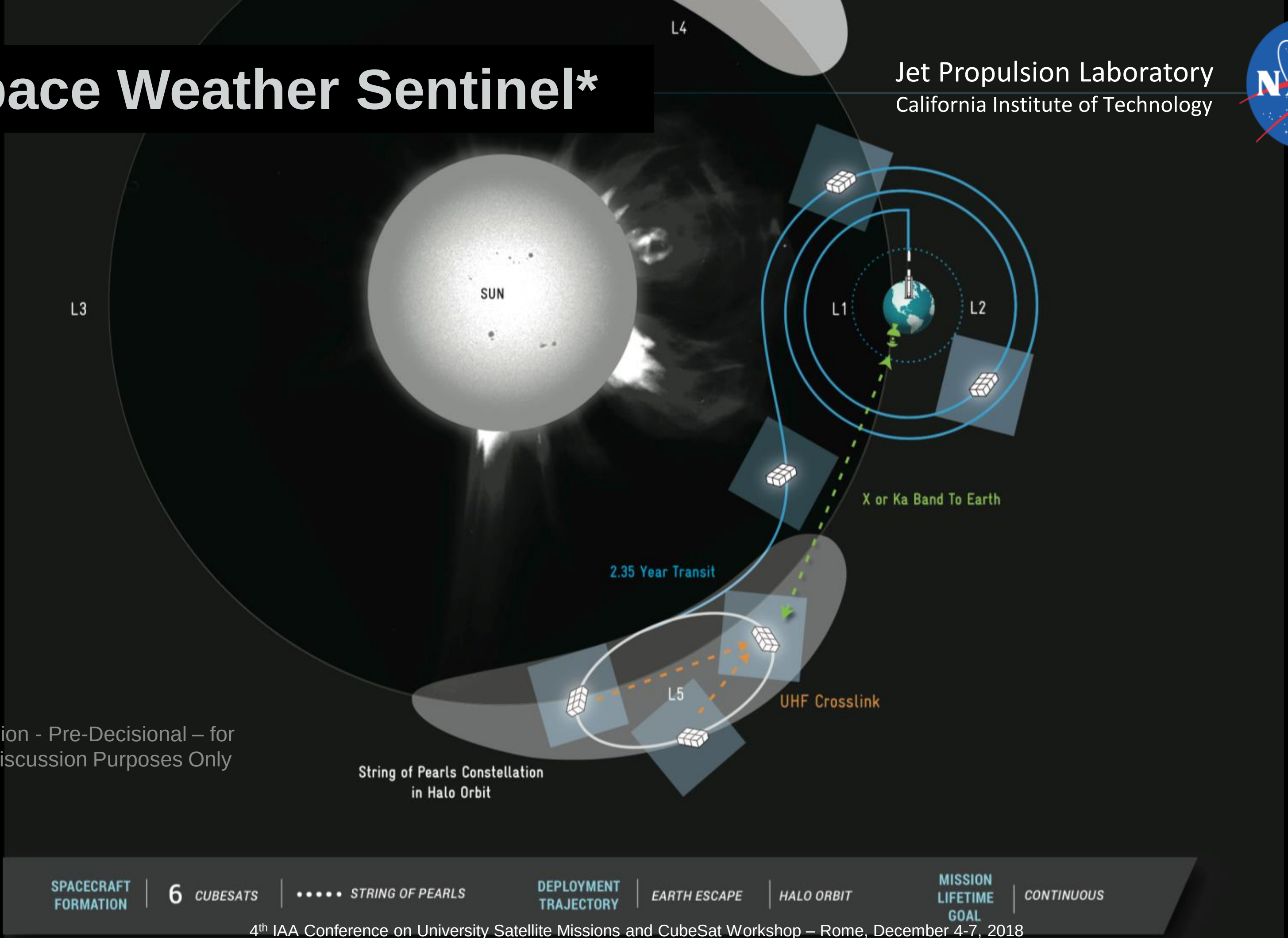
Keck Institute for Space Studies

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



L5 Space Weather Sentinel*

Jet Propulsion Laboratory
California Institute of Technology



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

Closing Comments

NASA's recent investments, such as TROPICS, show the potential of CubeSats as a disruptive technology

TROPICS – NASA EVI-3 Award (March 10, 2016)

PI: Bill Blackwell

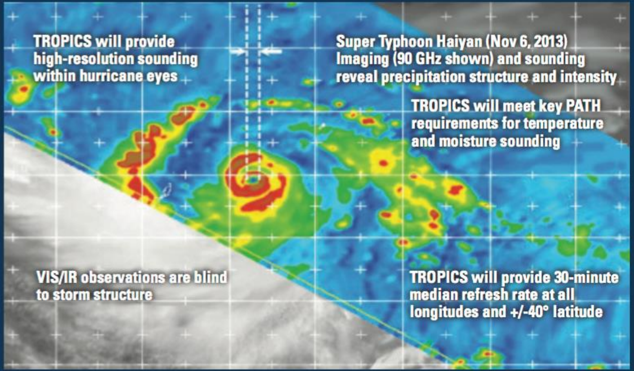
MIT Lincoln Labs

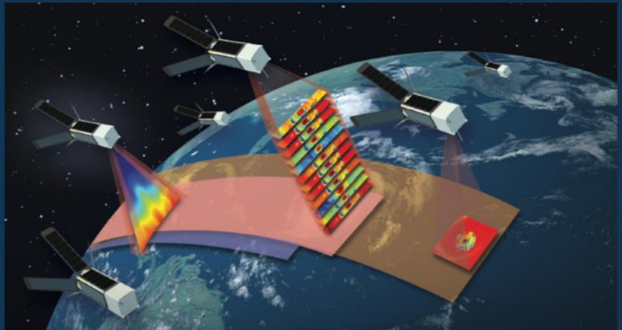
12 satellite constellation for Time Resolved Observations of Precipitation Structure and Storm Intensity

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

Science Objectives

- Relate precipitation structure evolution, including diurnal cycle, to the evolution of the upper-level warm core and associated intensity changes
- Relate the occurrence of intense precipitation cores (convective bursts) to storm intensity evolution
- Relate retrieved environmental moisture measurements to coincident measures of storm structure (including size) and intensity
- Assimilate microwave radiances and/or retrievals in mesoscale and global numerical weather prediction models to assess impacts on storm track and intensity





12 identical 3U CubeSats provide sounding (left CubeSat has a temperature profile of a simulated Tropical Cyclone (TC) from a Numerical Weather Prediction (NWP) model) and 12-channel radiometric imagery (center CubeSat has simulated radiances from NWP model and radiative transfer model and the near right CubeSat has a single channel radiance image of a TC) with 30-minute median revisit rate to meet most PATH requirements

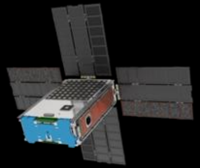
Significance to NASA

- First high-revisit microwave nearly global observations of precipitation, temperature, and humidity
- Fulfills most of PATH Decadal Survey mission objectives using a low-cost, easy-to-launch CubeSat constellation
- Complements GPM, CYGNSS, and GOES-R missions with high refresh, near-all-weather measurements of precipitation and thermodynamic structure
- Increases understanding of critical processes driving significant and rapid changes in storm structure/intensity

Exploration CubeSats

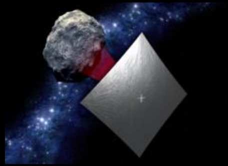
Five of the EM-1 CubeSats will address human exploration objectives by filling gaps in our knowledge about the availability of resources, environmental conditions, and the presence of hazards at potential destinations for future human missions.

- BioSentinel (ARC): Investigating the effects of deep space radiation on yeast DNA beyond Earth's protective magnetosphere.
- Lunar Flashlight (JPL): Searching for ice from lunar orbit using lasers to illuminate permanently shadowed lunar craters.
- NEA Scout (MSFC): Demonstrating a low-cost way to scout potential destinations for future human missions by using a solar sail to fly by a near-Earth asteroid and image its surface.
- LunIR (Lockheed Martin): Flyby of the Moon to test a new technology infrared camera and map solar illumination of the surface. Public-private partnership with NASA.
- Lunar IceCube (Morehead State University): Detecting water and other volatiles from lunar orbit using a broadband infrared spectrometer. Public-private partnership with NASA.



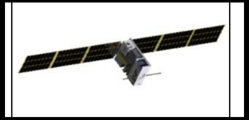
BioSentinel

Lunar Flashlight



NEA Scout

LunIR

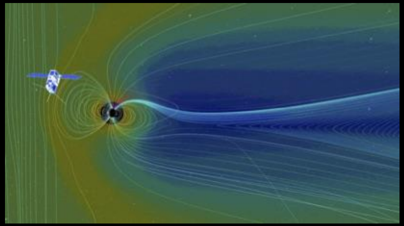


Lunar IceCub
e

Science CubeSats

Two of the EM-1 CubeSats will address science objectives to increase our knowledge of space weather and to map the distribution of hydrogen on the Moon.

- **CubeSat for Solar Particles - CuSP (Southwest Research Institute):** CuSP will be launched into interplanetary space to observe energetic particles and magnetic fields from the sun. Low-cost CubeSats such as CuSP could enable a large network of space weather stations.



CuSP

- **Lunar Polar Hydrogen Mapper - LunaH-Map (Arizona State University):** Mapping the abundance and distribution of near-surface hydrogen in the permanently shadowed regions at the Moon's south pole using neutron spectrometers.

LunaH-Map

Cube Quest Challenge

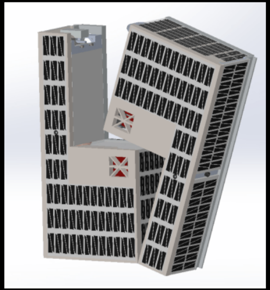
- NASA’s Cube Quest Challenge is offering a total of $5M in prizes to demonstrate new technologies for CubeSat propulsion and deep space communications.

- The competition includes the Lunar Derby (entering lunar orbit and communicating with Earth) and the Deep Space Derby (communicating from the most distant heliocentric orbit). Three finalists have been selected for flight on EM-1.

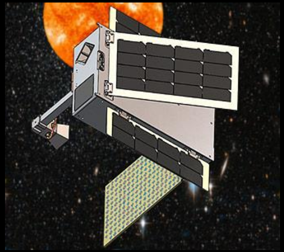
- Cislunar Explorers (Cornell University): Competing in the Lunar Derby. Uses water electrolysis propulsion system for lunar orbit insertion. Splits into two rotating L-shaped spacecraft after deployment.

- University of Colorado Boulder’s Earth Escape Explorer (CU-E3): Competing in the Deep Space Derby. Attempting to communicate with Earth from a distance of 27 million kilometers using a planar deployable antenna array.

- Team Miles (Fluid and Reason LLC): Competing in the Deep Space Derby. Attempting to communicate with Earth from a distance of 96 million kilometers using a software defined S-band radio.



Cislunar Explorers



CU-E3

Team Miles

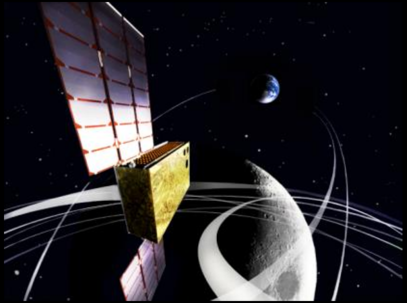
International CubeSats

NASA will launch three CubeSats contributed by international partners on EM-1.

- Equilibrium Lunar-Earth Point 6U Spacecraft (EQUULEUS) - JAXA, University of Tokyo: Imaging helium ions in the Earth's plasmasphere using an extreme ultraviolet camera. Demonstrating low-energy trajectory control techniques in multiple lunar flybys.

- Outstanding Moon Exploration Technologies Demonstrated by Nano Semi-Hard Impactor (OMOTENASHI) - JAXA, University of Tokyo: Demonstrating the technology for landing a 1-kilogram nano-lander on the Moon using a small solid rocket motor and airbag.

- ArgoMoon - ASI: Conducting proximity operations around the SLS upper stage, and imaging the release of the other EM-1 CubeSats.

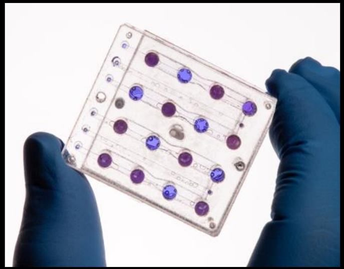


EQUULEUS

OMOTENASHI

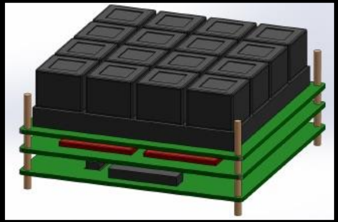
ArgoMoon

EM-1 CubeSat Instrument Technology

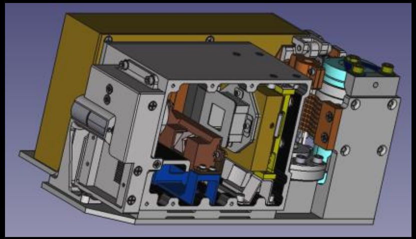


Microfluidics array integrating sample wells, valves, optical detectors, and heaters will monitor DNA repair in yeast exposed to deep space radiation (BioSentinel)

Laser reflectance spectrometer uses four 40W laser diodes transmitting at different wavelengths to detect water in permanently shadowed craters (Lunar Flashlight)

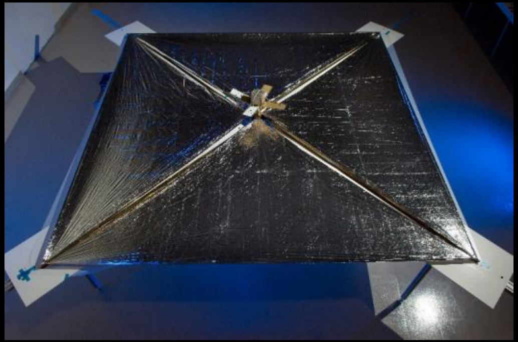


Compact neutron/gamma ray detector can sense hydrogen 1 meter below the surface (LunaH-Map)

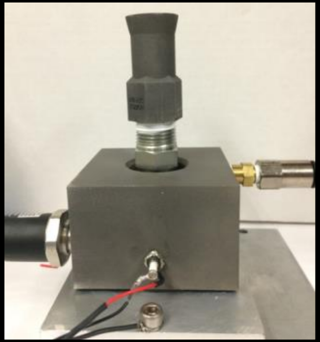


Broad InfraRed Compact High Resolution Exploration Spectrometer (BIRCHES) with a wavelength range of 1 to 4 microns can detect water in its liquid, ice, and vapor forms. (Lunar IceCube)

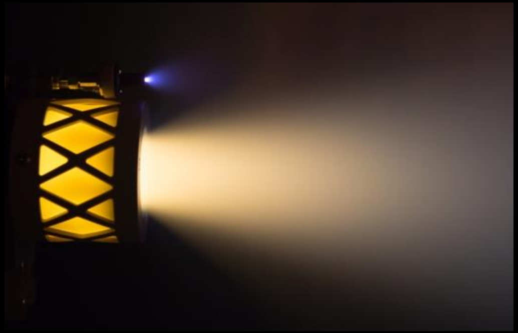
EM-1 CubeSat Propulsion Technology



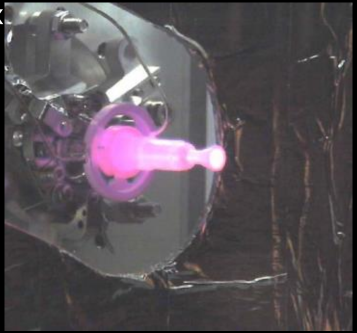
86 m^2 solar sail with rollable metallic booms and active mass translator for CG control. (NEA Scout)



Water electrolysis thruster produces hydrogen and oxygen for combustion (Cislunar Ex

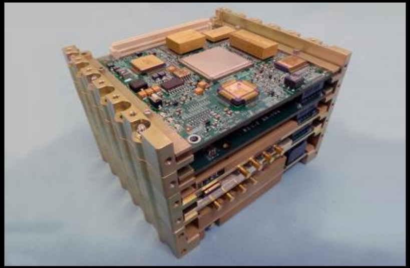


Busek BIT-3 75 W ion thruster uses solid iodine propellant.
(Lunar IceCube, LunaH-Map)

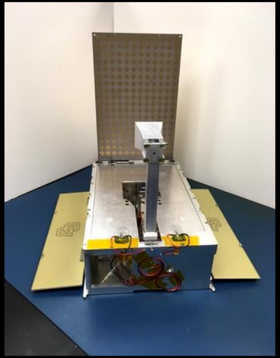


ECAPS 100 milliNewton thruster for lunar orbit insertion uses green LMP-103S monopropellant (Lunar Flashlight)

EM-1 CubeSat Communications Technology



4-Watt Iris radio developed by JPL will ensure commonality in spacecraft communications and reduce cost. Used on 8 EM-1 CubeSats.



Deployable planar antenna array for deep space communication (CU-E3)

Upgrading Morehead State University’s 21-meter antenna for communicating with EM-1 CubeSats. Implementing Disruption Tolerant Networking protocols.

Summary

- EM-1 CubeSats will address a broad range of exploration, science, technology demonstration, and international partnership objectives:
  - Prospecting for lunar resources (4)
  - Investigating space weather and the biological effects of deep space radiation (2)
  - Scouting near-Earth asteroids (1)
  - Demonstrating deep space communications (3)
  - International partnerships (3)

- EM-1 CubeSats will advance many innovative CubeSat technologies for instruments, communications, and propulsion.

- These diminutive explorers will revolutionize deep space exploration by enabling more affordable and more frequent missions to new destinations.

- NASA plans to launch CubeSats on every SLS flight, so the future possibilities are limitless.

The NRC Achieving Science Goals With CubeSats Study

NASA (57 Missions / 80 CubeSats) and NSF (15 Missions / 24 CubeSats) [2015]

	Funding Program	CubeSat Missions Launched	CubeSat Missions Planned	Launch Years
NASA	Heliophysics	MinXSS	CeREs, CuSP, ELFIN-STAR,[a] HeDI, SORTIE, TBEx	2015-2018+
	Earth Science	GRIFEX, IPEX, MCubed/COVE (2)	CIRAS, CIRiS, CubeRRT, HARP, IceCube, LMPC, MiRaTa, RainCube, RAVAN, TEMPEST-D	2011-2018+
	Planetary Science	O/OREOS	INSPIRE (2), LunaH-Map, MarCO (2), Q-PACE Technology Development Only: DAVID, HALO, MMO	2010-2018+
	Astrophysics		HaloSat	2018
	Advanced Exploration Systems and Human Exploration and Operations	GeneSat, PharmaSat, SporeSat (2)	BioSentinel, EcAMSat, Lunar Flashlight, Lunar IceCube, NEA Scout, Skyfire	2006-2018+
	Space Technology	EDSN (8),[b] NODeS (2), OCSD-A, PhoneSat (5)	CPOD (2), CSUNSat-1, ISARA, iSAT, OCSD (2)	2013-2017
	Centers (Internal)			2008-2018+
	Ames Research Center	PreSat,[c] TechEdSat (3)	KickSat	
	ARC and Marshall Space Flight Center	NanoSail-D (2)		
	Goddard Space Flight Center		CANYVAL-X, Dellingr, ESCAPE, RBLE	
	Jet Propulsion Laboratory	LMRST, RACE[d]	ASTERIA, MITEE	
	Kennedy Space Center		Cryocube, StangSat	
	NASA IV&V Facility		STF-1	
NSF	National Science Foundation	CADRE, CSSWE, CINEMA-1, DICE (2), ExoCube, FIREBIRD (4), Firefly, RAX (2)	ELFIN, ISX, IT-SPINS, LAICE, OPAL, QBUS/QB50 (4), TRYAD (2)	2010-2018+

a) ELFIN is now jointly funded by NASA/NSF as ELFIN-STAR, b) Super-Strypi launch failure, c) Falcon-1 launch failure, d) Antares launch failure