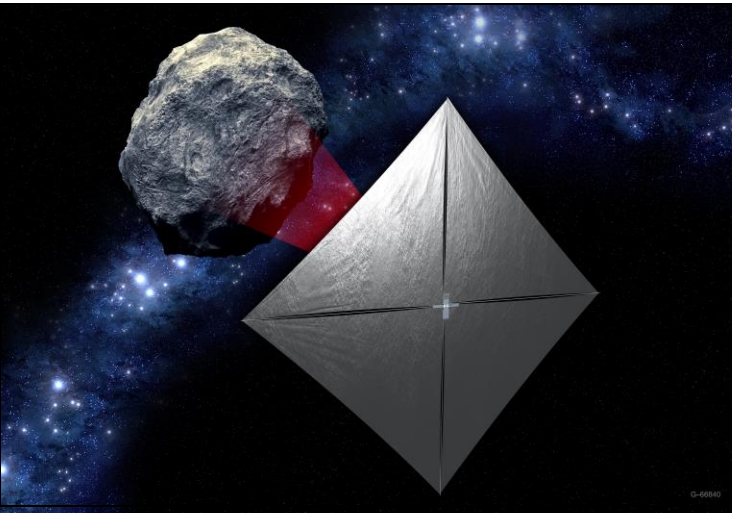
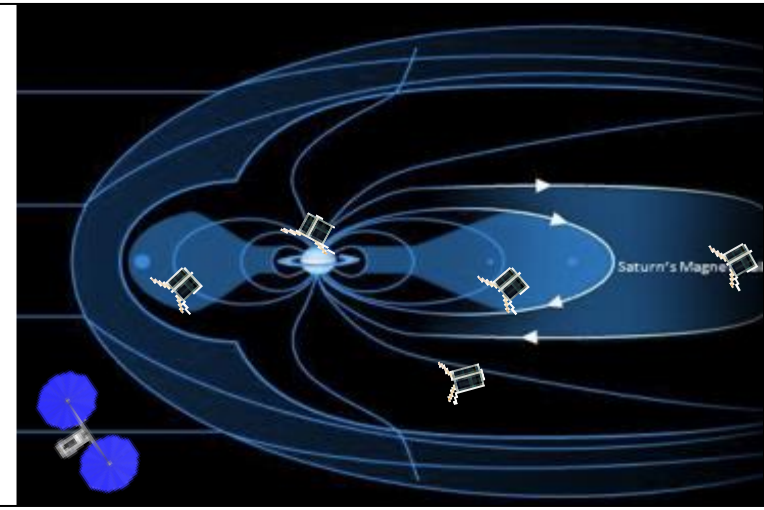




CubeSat for Planetary Science and Exploration

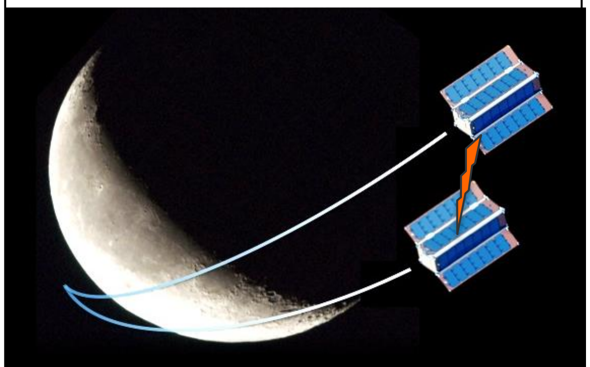
Breaking New Grounds

Julie Castillo-Rogez, Research Scientist
Jet Propulsion Laboratory

Jet Propulsion Laboratory
California Institute of Technology

Classes of Applications

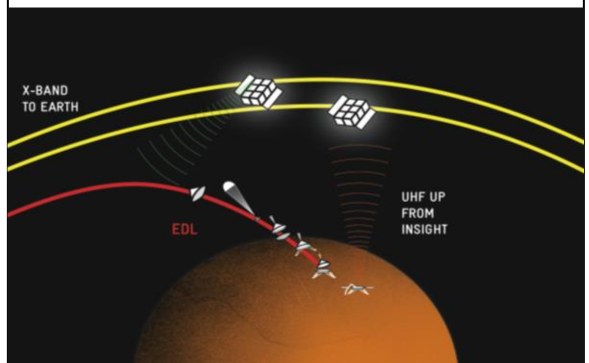
Technology Demos



INSPIRE (NASA/JPL

Use low-cost spacecraft for technology testing and validation in relevant environment

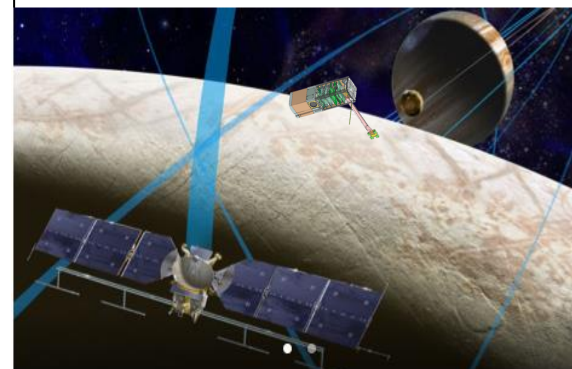
Engineering/Ops



MarCO (JPL)

For example telecom relays during critical operations for lander’s entry, descent, and landing; to support a Human crew at Mars; to facilitate teleoperations…

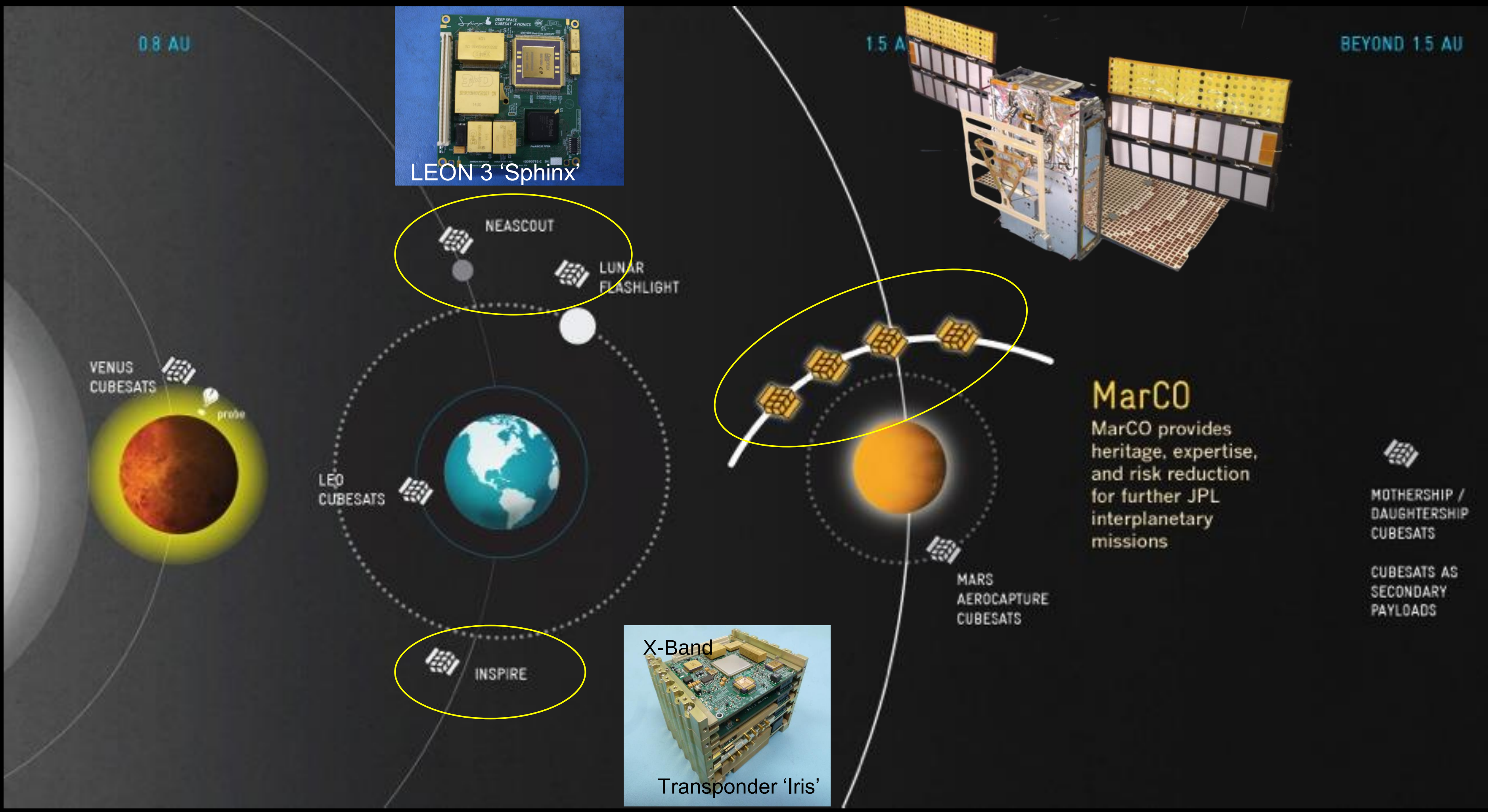
Science



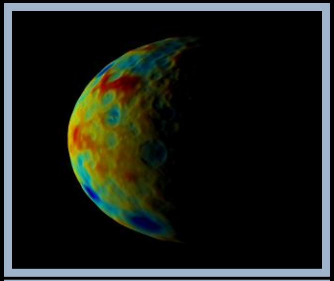
Europa CubeSats (NASA – Concepts)

CubeSats that carry primary science, reconnaissance, or opportunistic science investigations; by themselves or as daughtership

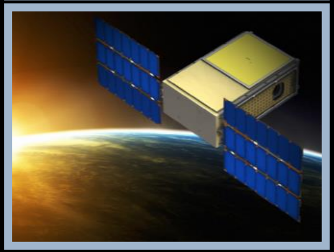
INSPIRE, MarCO, and EM-1 CubeSats as Stepping Stones to Deep Space



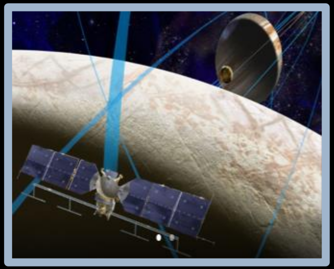
Outline



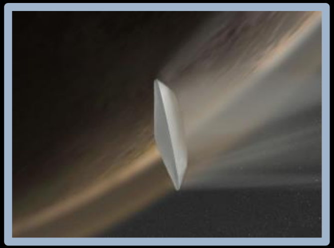
Science Pull for Planetary CubeSats



3U and 6U Planetary CubeSat Landscape

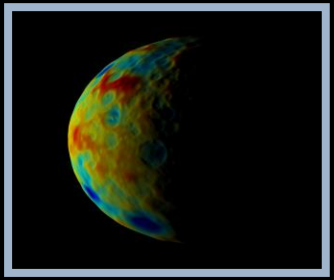


Visions for Future Voyages



Parting Thoughts

Outline

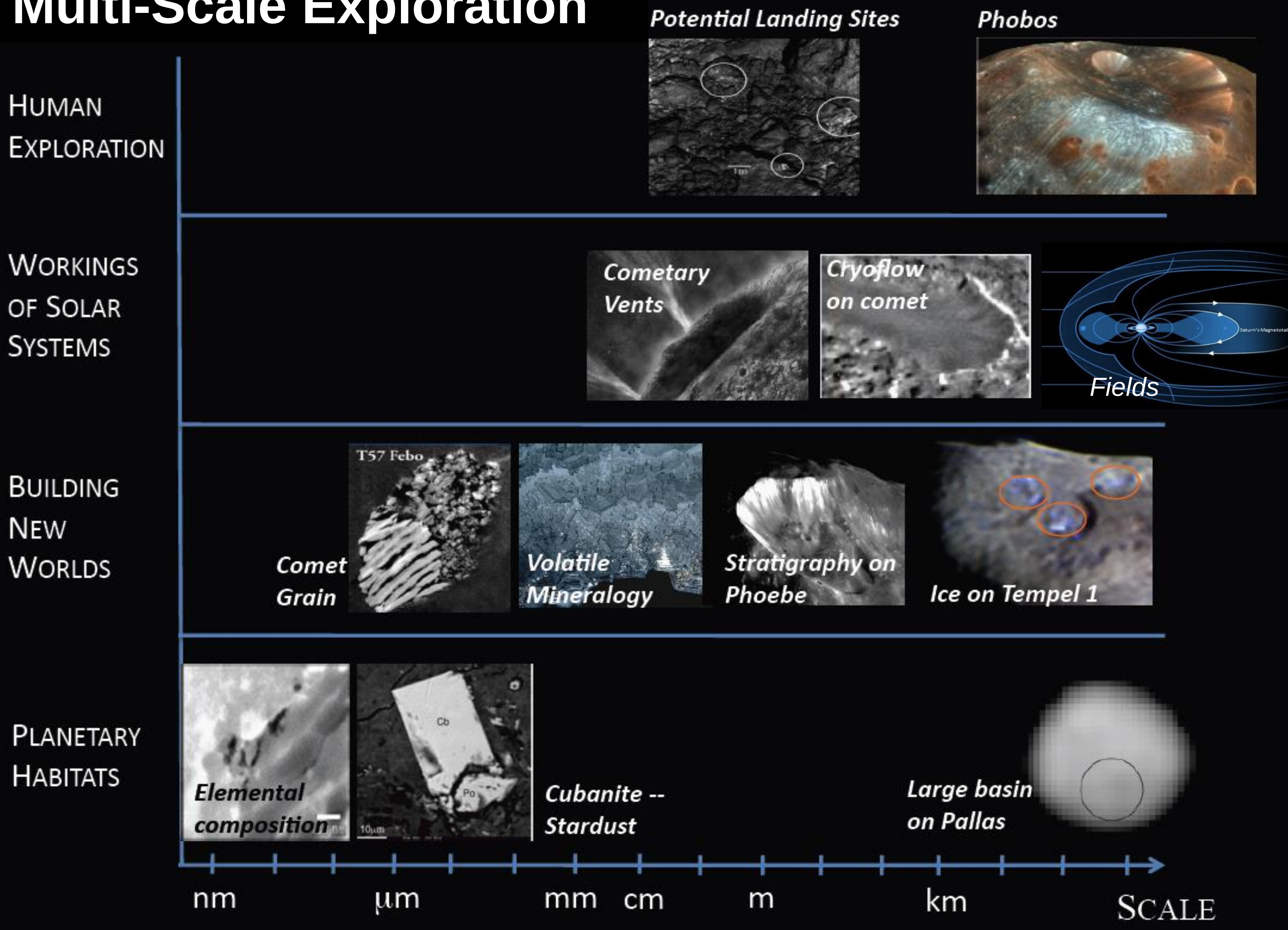


Science Pull for Planetary CubeSats

NASA Strategic Goals

PLANETARY SCIENCE Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.	1. Explore and observe the objects in the solar system to understand how they formed and evolve. 2. Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve. 3. Explore and find locations where life could have existed or could exist today. 4. Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere. 5. Identify and characterize objects in the solar system that pose threats to Earth, or offer resources for human exploration.	a. Building New Worlds—advance the understanding of solar system beginnings (1, 2) b. Planetary Habitats—search for the requirements for life (3, 4) c. Workings of Solar Systems—reveal planetary processes through time (1, 2, 5) **Planetary Science Decadal Survey Priorities**

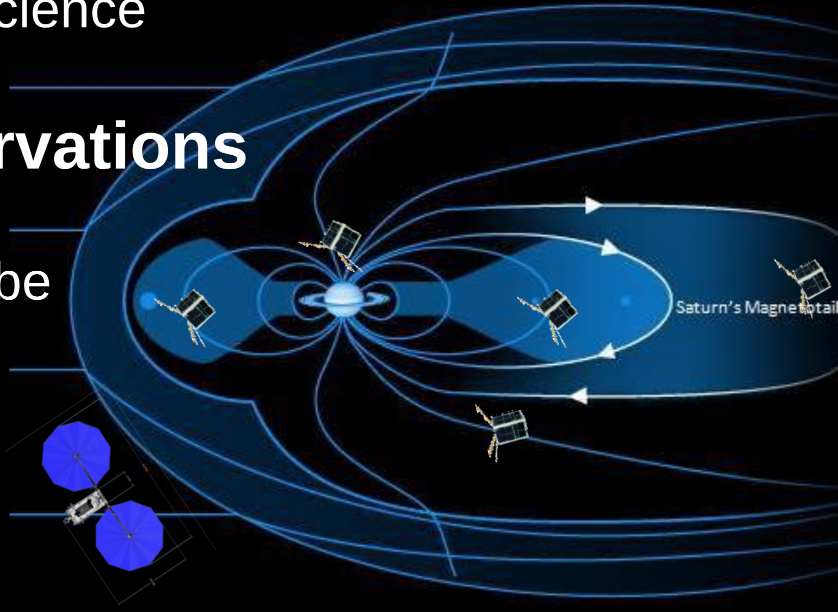
Multi-Scale Exploration



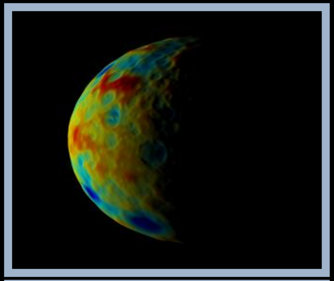
Science Pull for Planetary CubeSats

IAA Planetary CubeSat Study (2015)

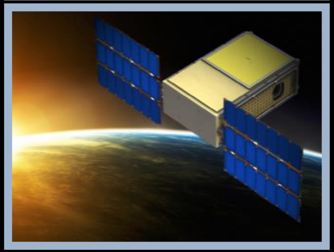
- **Science enablers**
  - Distributed measurements for dynamic processes
  - Impactor/observer architecture (cooperating assets)
- **Alternative low-cost architectures**
  - Fractionated payload for system science
- **High-risk, high-reward observations**
  - Access to unique vantage points
  - Risk assessment by sacrificial probe
- **Breaking new grounds**
  - Exploration of uncharted regions



Outline



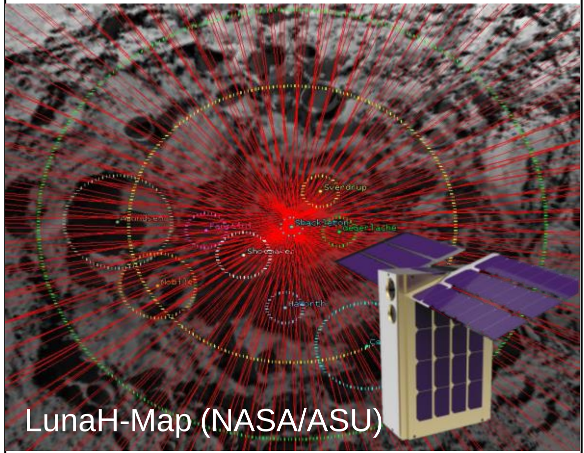
Science Pull for Planetary CubeSats



3U and 6U Planetary CubeSat Landscape

Science Applications

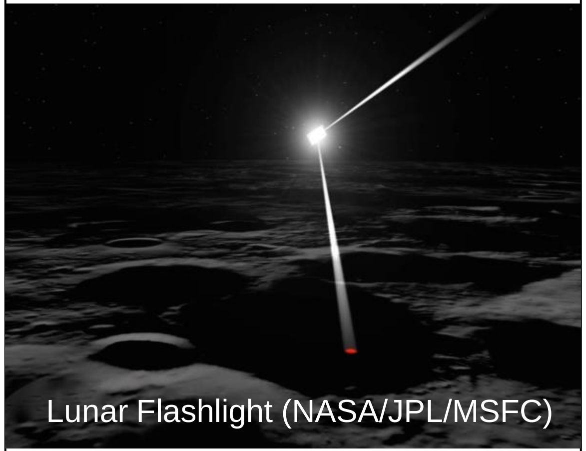
Decadal Science



LunaH-Map (NASA/ASU)

Addresses science tracing from Vision and Voyages' strategic questions (Origins, Habitability, Processes) e.g., LunaH-Map, AOSAT, Cu-Cape

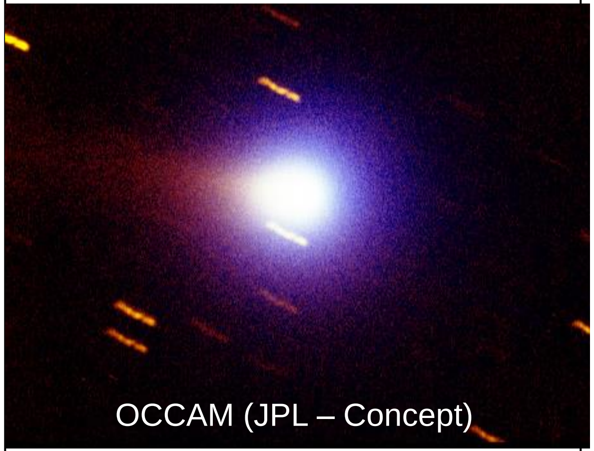
Reconnaissance



Lunar Flashlight (NASA/JPL/MSFC)

Strategic knowledge gap observations (e.g., BioSentinel, LF, NEAScout)
Reconnaissance prior to sampling and landing (e.g., comet sample return)

Pure Exploration



OCCAM (JPL – Concept)

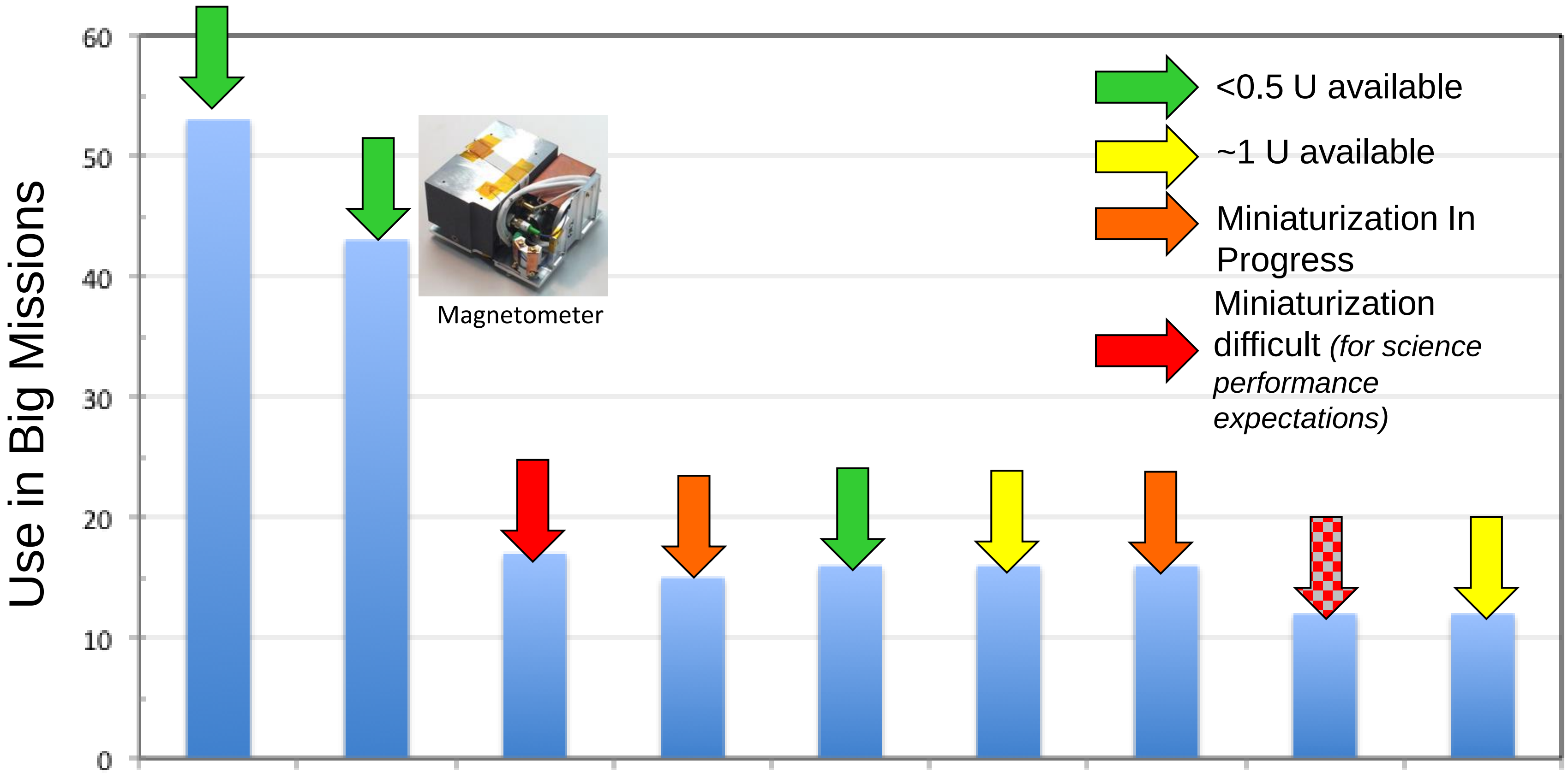
Pure science exploration of uncharted territories (e.g., Earth's Trojan clouds), close comet or NEA flyby

CubeSat-Based Measurements

that have been proposed so far

- Fields and particles
  - Distributed/simultaneous magnetic field measurements
  - Dust and gas/plume composition
  - Radiation
  - Plasma characterization
- Atmospheric Science
  - Distributed atmospheric measurements
  - Atmospheric composition (noble gases)
- Reconnaissance
  - High-risk site study and reconnaissance (eg caves, landing sites, etc.)
  - Object characterization
  - Water search
- In-Situ
  - Elemental, Isotopic & Mineralogical composition
  - Regolith mechanical properties
  - Surface dust dynamics

State of Small Instruments



Magnetometer

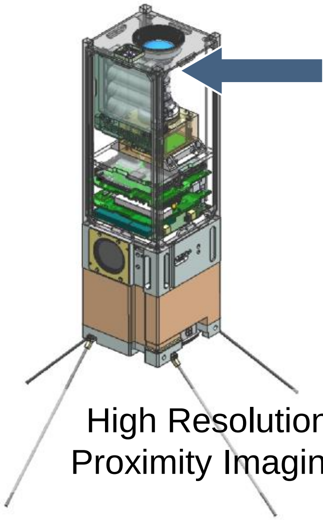
CSAC (atomic clock)

Philae's DIM (Dust Impact Monitor)

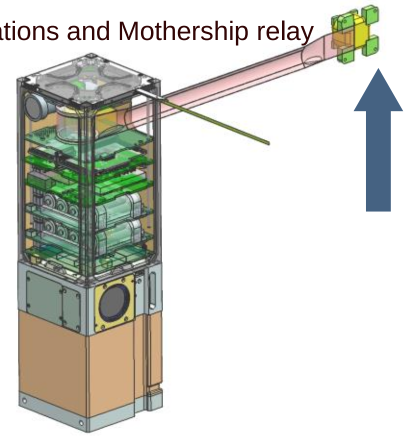
JPL's Technology Demonstration CubeSats via Discovery

Secondary Orbiter/Flyby Constellations

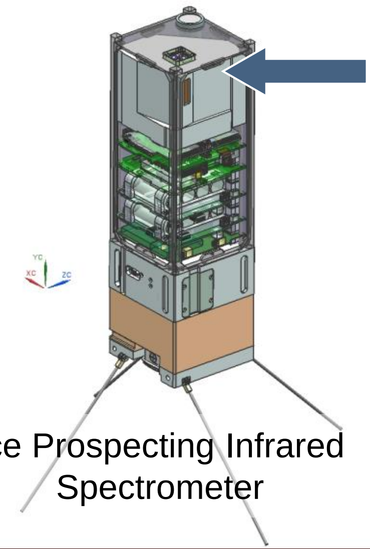
~48-72 hour operations with (semi-)autonomous operations and Mothership relay



High Resolution Proximity Imaging



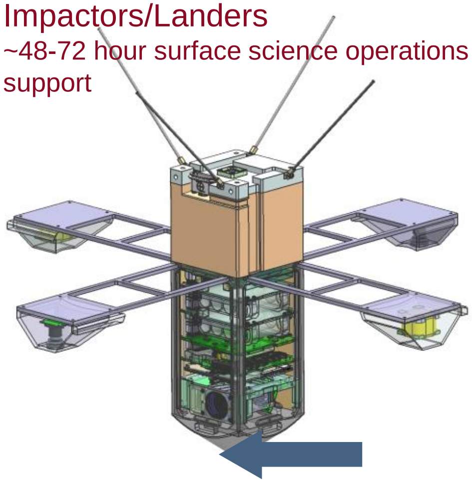
Distributed, Simultaneous Particles & Fields Measurements



Ice Prospecting Infrared Spectrometer

Impactors/Landers

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

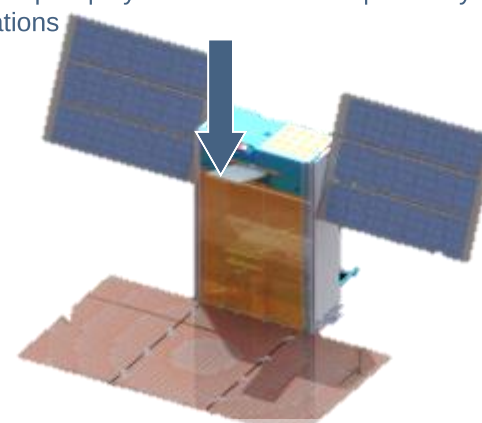


Asteroid/Comet Instrumented Surface Penetrator

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

Science has to Compete for Resources

Deep Space Environment Challenges

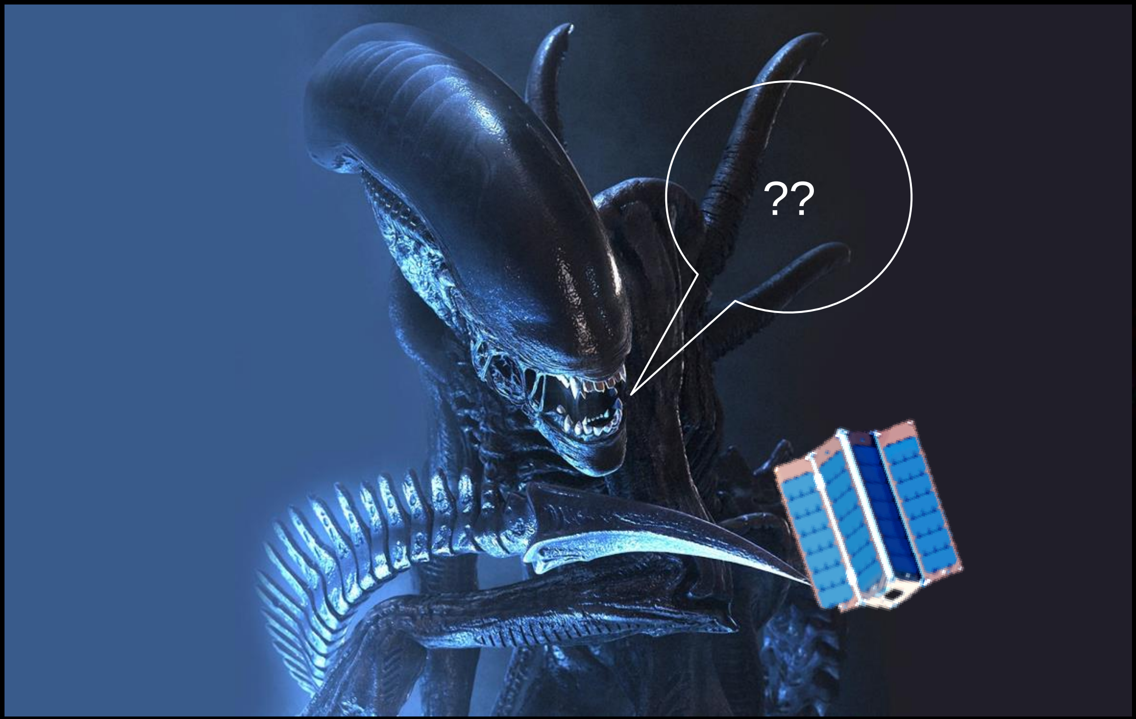
- Radiations require rad-hard subsystems and extra mass for shielding
- Limited power beyond 1 AU impacts operations and science return

➔ Instrument volume is limited to 0.5-1 U

- Small aperture/sampling drives integration time

➔ Long distance is severe limitation to science data retrieval

- Data rates beyond the Moon are between 0.5 and 8 kbps
- Long downlink times drive thermal issues

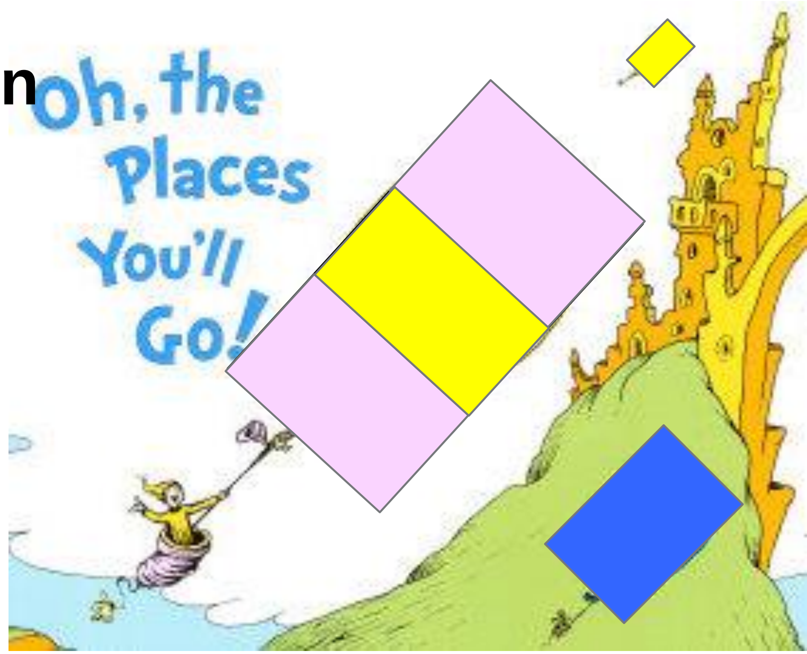


IN SPACE
NO ONE CAN HEAR
YOU SCREAM

ESPECIALLY
WHEN YOU HAVE A TINY ANTENNA

SCIENCE PERFORMANCE METRICS

Payload Sensitivity and Resolution
- Scales with instrument size



Delta-V - A few 100 m/s to km/s

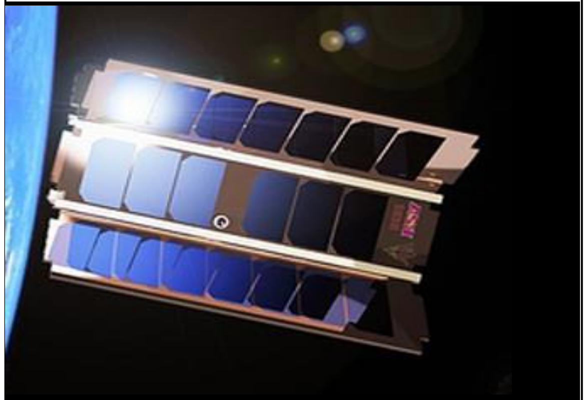
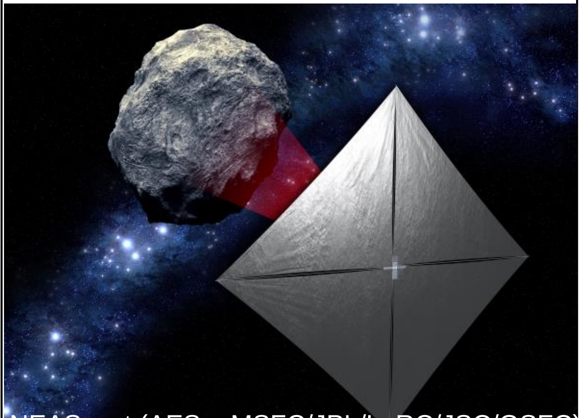
Pointing (control and stability)
Loose (fields), up to 7.2 arcsec accuracy, 1 arcsec stability in 1 sec.

Position Control – km-scale per radio-tracking; <100m with optical navigation

Data Volume - 10s Mb for fields/particles; 100s Mb for geology and chemistry

Mission Architectures (1/2)

Independent CubeSat

LEO Observatory	CubeSat at the Moon	And Beyond
 AOSAT (ASU)	 Lunar IceCube (MSU, GSFC)	 NEAScout (AES – MSFC/JPL/LaRC/JSC/GSFC)
e.g., low-cost, low-gravity laboratories, meteor observatories, continuous Jupiter photometry	e.g., Radiation monitoring, search for water, surface reconnaissance	e.g., physics, chemistry, and processes characterization for many objects
P/L · ΔV · Ptg · Pos · Data	P/L · ΔV · Ptg · Pos · Data	P/L · ΔV · Ptg · Pos · Data

Near Earth Asteroid Scout

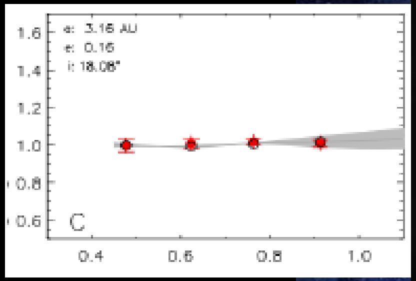
Marshall Space Flight Center/Jet Propulsion Lab/LaRC/JSC/GSFC/NASA

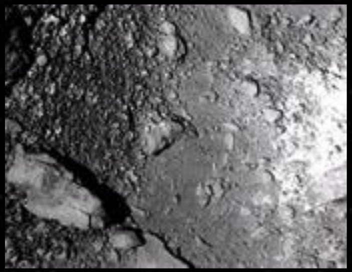
One of three 6U Cubesats sponsored by Advanced Exploration System, Joint Robotic Program to fly on SLS EM-1

GOALS

- Characterize one candidate NEA with an imager to address key Strategic Knowledge Gaps (SKGs)
- Demonstrates low cost capability for HEOMD for NEA detection and reconnaissance

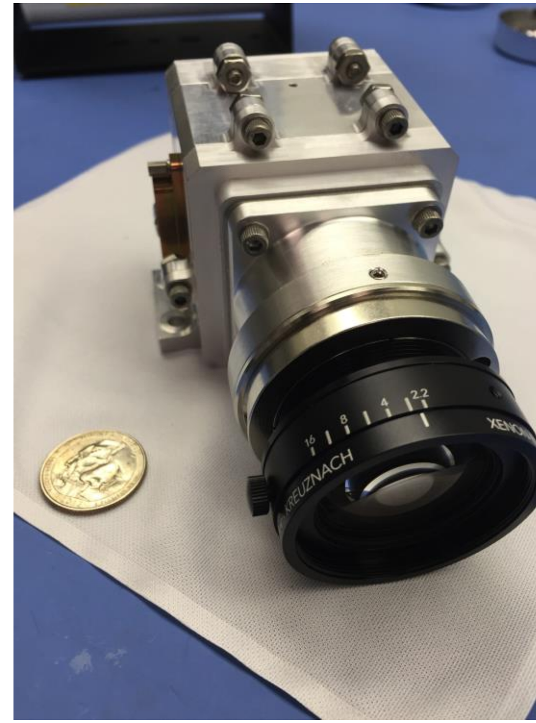
Measurements: *NEA volume, spectral type, spin and orbital properties, address key physical and regolith mechanical SKGs*





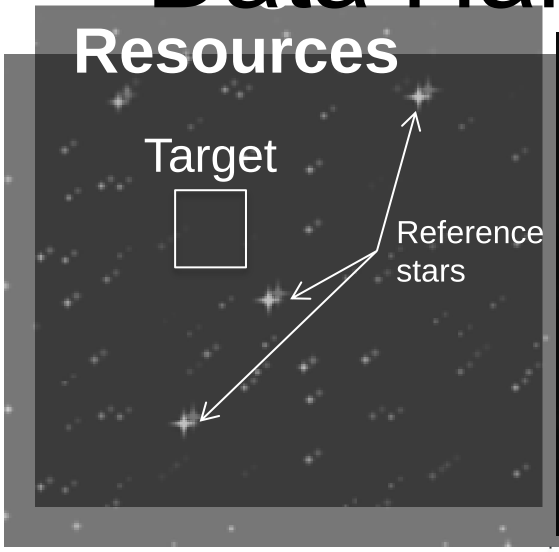
Science Performance of NEAS 6U

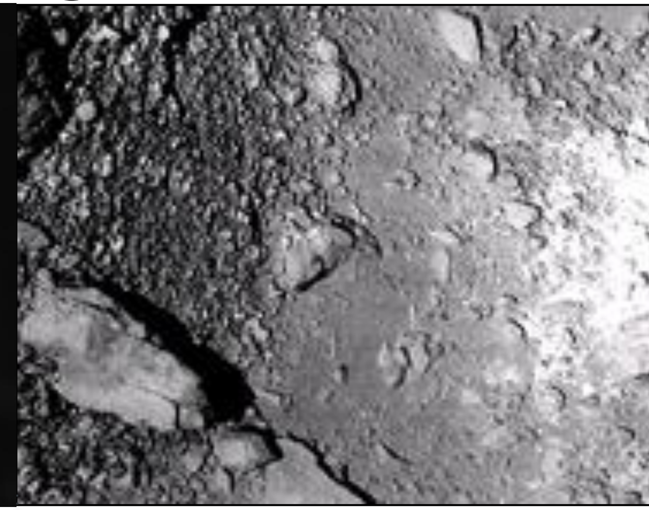
- Payload introduces IntelliCam
  - Meets resolution requirement of 10cm/pix at >500m distance
  - Meets sensitivity requirement to detect H=28 target at >10,000 km distance
- Pointing control/stability is met
  - Pointing knowledge is limited by current technology



- 0.5 to 1.7 km/s ΔV: Will definitely go places!!
  - Target pool is limited by camera aperture
- Biggest limitation is data volume vs power/thermal
  - Mitigated with operational strategies
  - Science software to increase data acquisition robustness

Data Handling with “Agile Science”





ACTIVITIES

Target Detection and approach with wide field imaging	Target Reconnaissance with medium field imaging	Close Proximity Imaging
Ephemeris determination	Shape, spin, and local environment	Local scale morphology, terrain properties, landing site survey

CHALLENGES

Downlink rate <1 kbps Large target position uncertainty	Short flyby time (<30 min) Uncertain environment	Short time at closest approach (<10 min.) Downlink rate <1 kbps past C/A

APPROACH

Autonomous sky scanning sequence
Image co-adding
subwindowing
Compression

Autonomous target pointing and **gain setting**
Thumbnails, triage, lossless compression, subwindowing

Mission Architectures (2/2)

Carrier/Relay

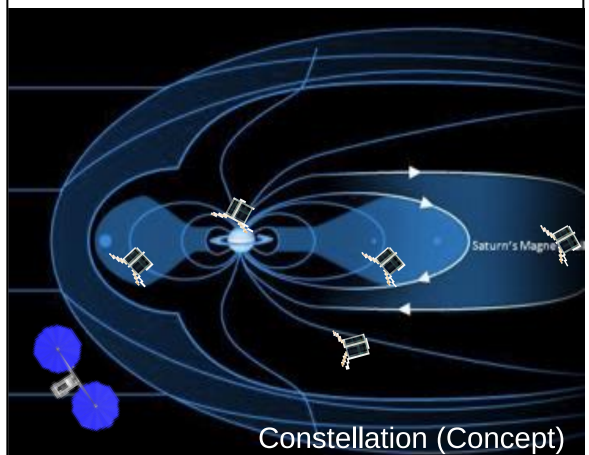
Mother-Daughter


Hayabusa-2 and MASCOT

Complementary vantage points; remote vs. in situ exploration; cooperation for motion planning, etc. *Can accommodate various form factors*

P/L	ΔV	Ptg	Pos	Data

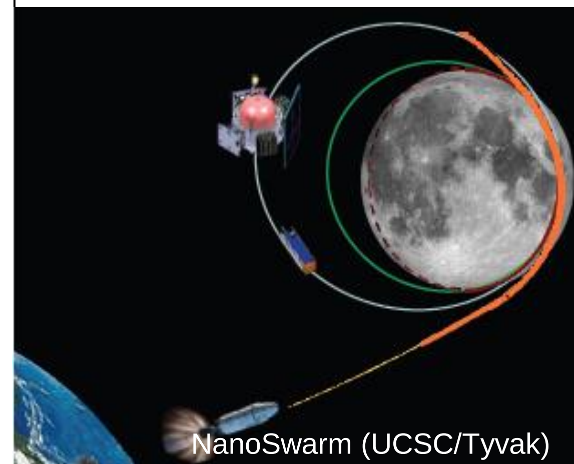
Fractionated Architectures


Constellation (Concept)

Distributed sensors for field, atmosphere, or system-wide exploration; constellation networks for event triangulation

P/L	ΔV	Ptg	Pos	Data

ESPA-Ring


NanoSwarm (UCSC/Tyvak)

Ring provides most of the ΔV and telecom relay; can reach asteroid main belt, potentially outer Solar system;

P/L	ΔV	Ptg	Pos	Data

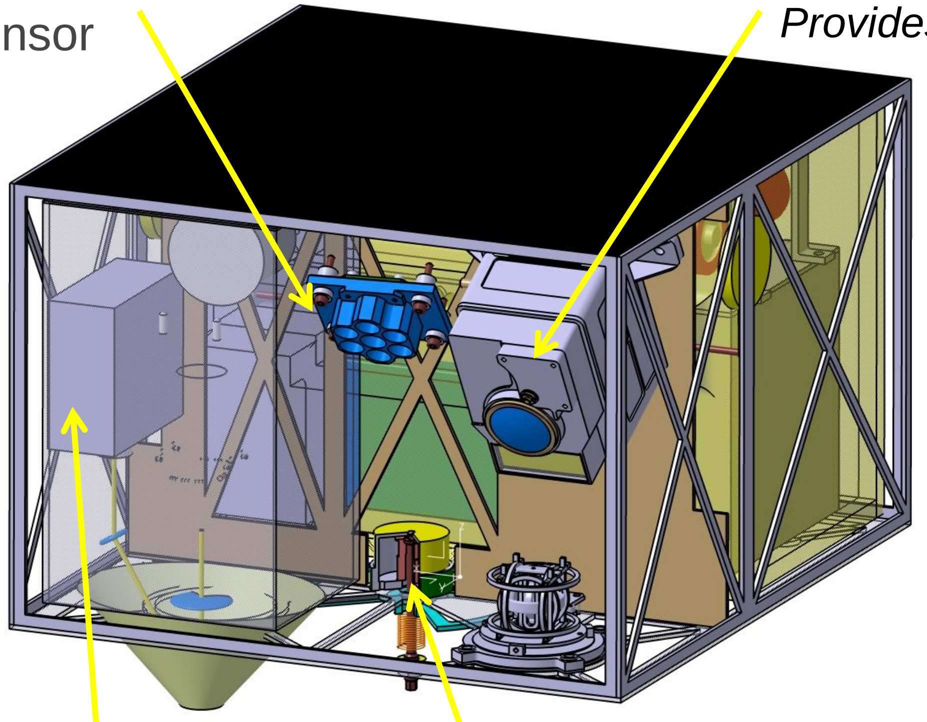
In Situ Exploration with MASCOT On Hayabusa-2

MASCOT's Science Performance

Mid-IR thermal sensor

Wide Angle Camera

Provides geological context



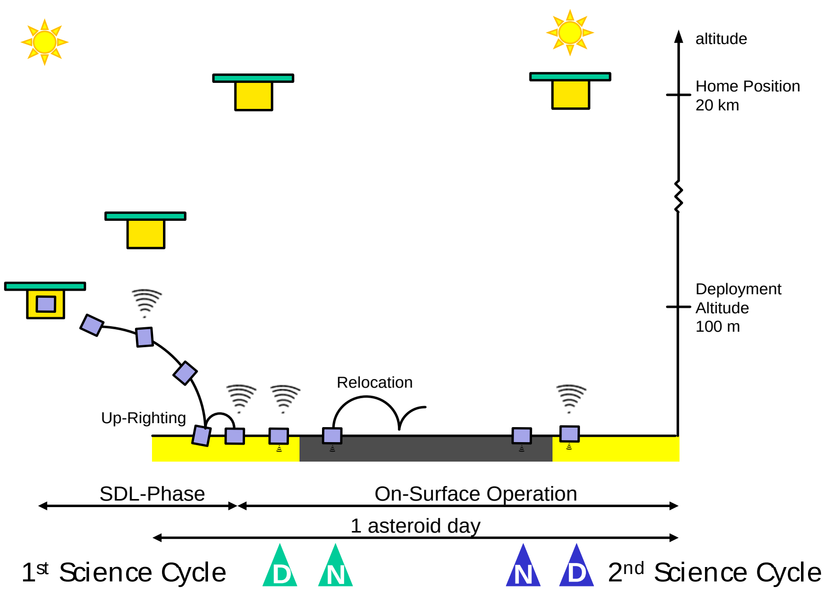
- ~10 kg incl. 3 kg payload
- Includes hopping mechanism
- Lifetime of ~15 hr
- Data relay to mothership

3-axis fluxgate Magnetometer

Remnant mag field

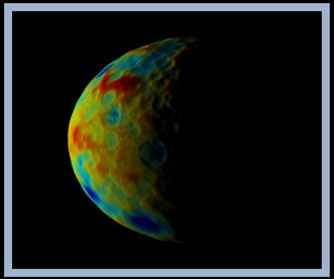
Imaging Spectrometer

Regolith mineralogy at μ-scale

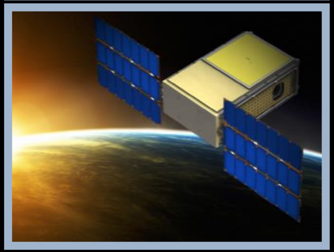


Limited lifetime but efficient operational timeline – will meet focused but important objectives to characterize NEO surface

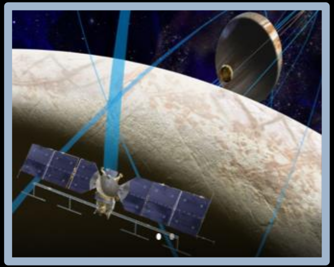
Outline



Science Pull for Planetary CubeSats

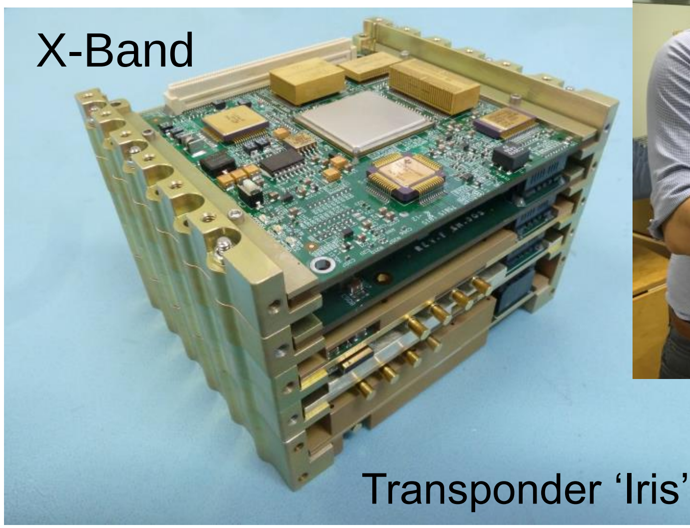


3U and 6U Planetary CubeSat Landscape

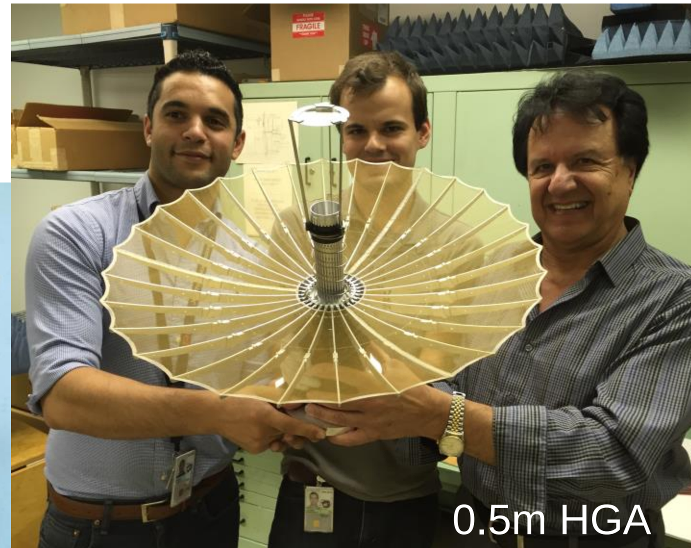


Visions for Future Voyages

New Deep Space Tailored CubeSat Subsystems



X-Band Transponder 'Iris'



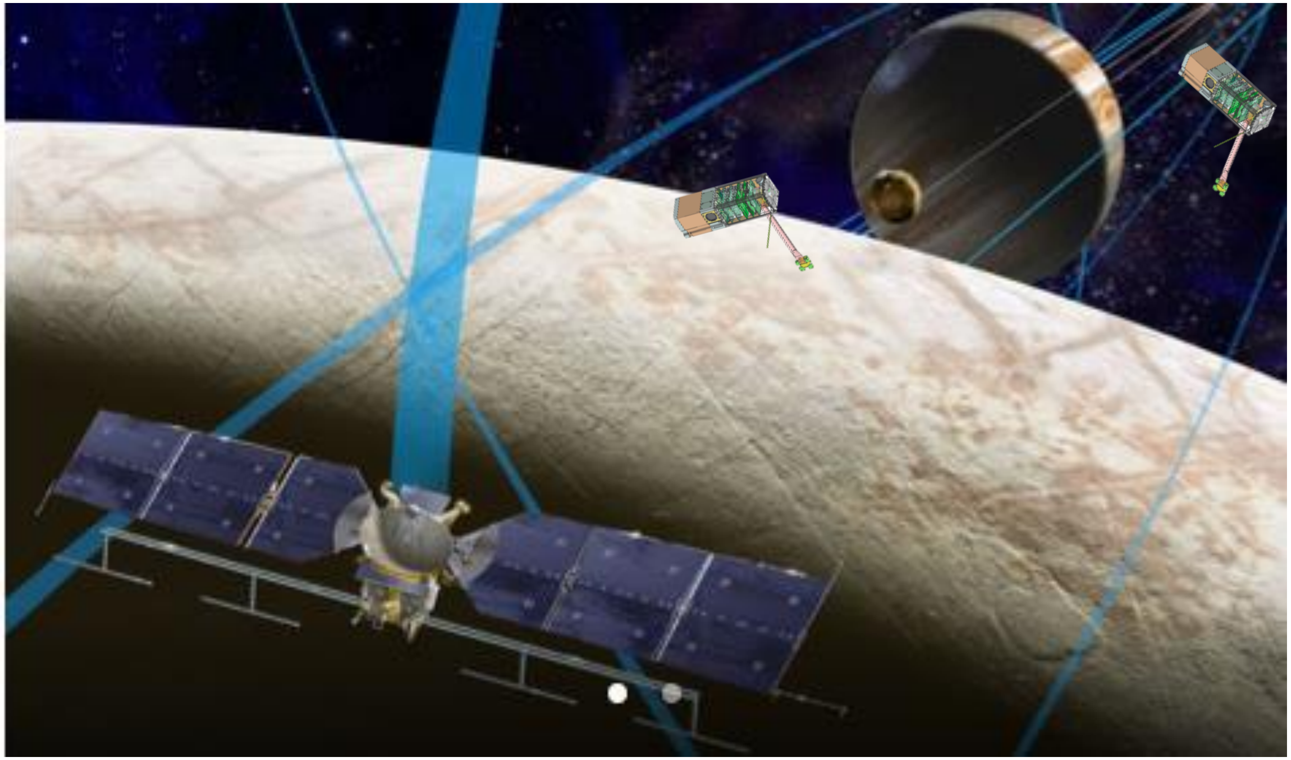
0.5m HGA

LEON 3 Computer 'Sphinx'

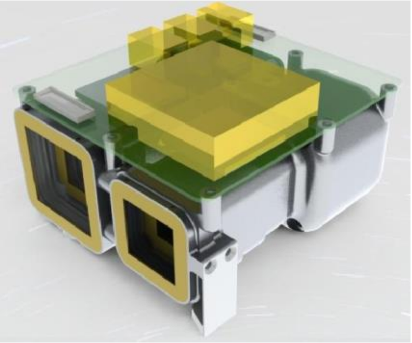
Hybrid Propulsion

Characterizing Europa's Deep Ocean

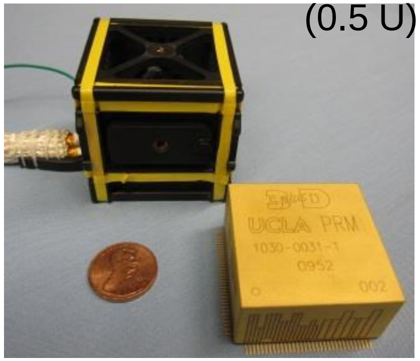
Distributed Magnetometer Network at Europa



Particle detector (0.5 U)



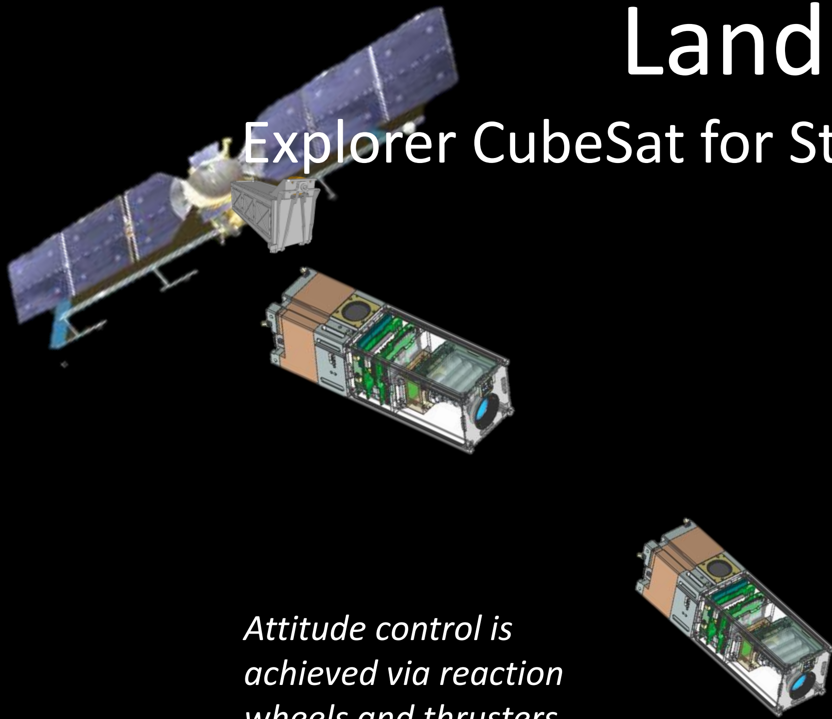
Flux gate magnetometer (0.5 U)

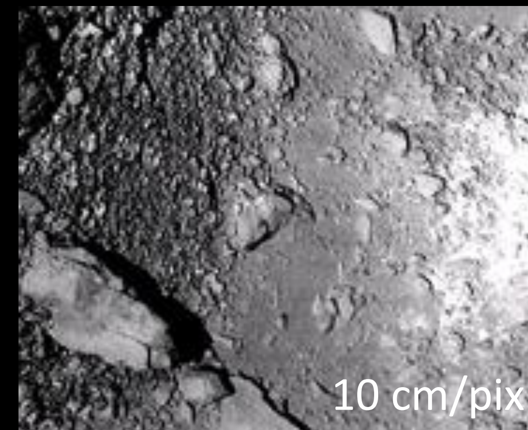


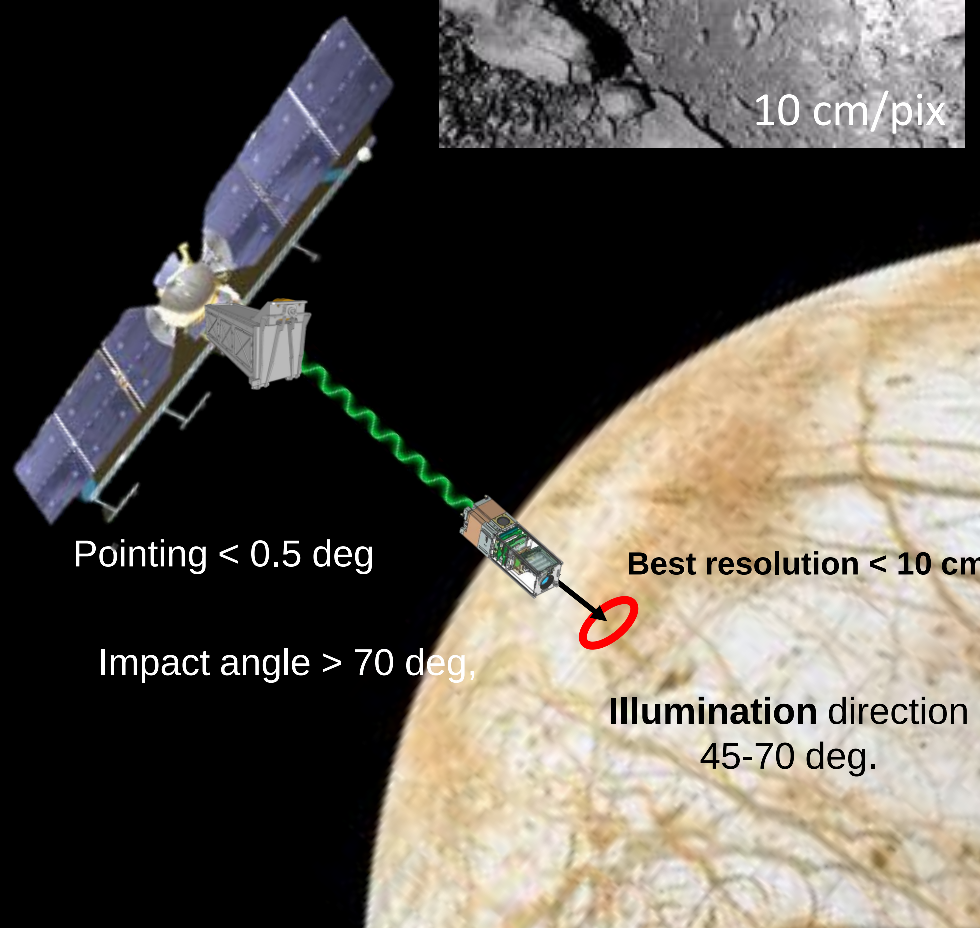
- Based on INSPIRE's design upgraded with electronics vault – fits in 3 U
- Life time requirement is < 48 hours
- Particle detector is combined with magnetometer and provides additional shielding

Landing Site Reconnaissance

Explorer CubeSat for Student Involvement in Travels to Europa



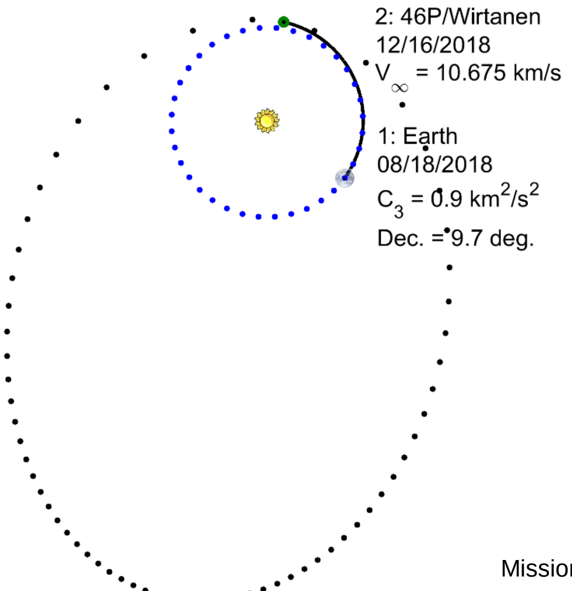


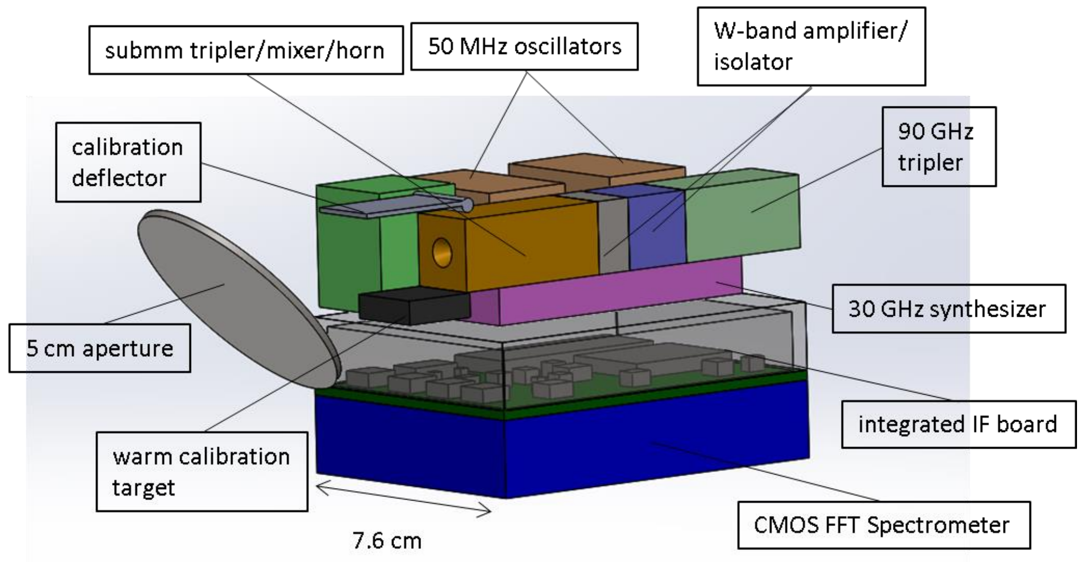


- "Ranger-Style" probe relays images down to 1 km to the surface
- Based on INSPIRE's design upgraded with electronics vault – fits in 3 U
- Life time requirement is < 10 hours

Comet Volatile Isotopic Composition for Origin Science

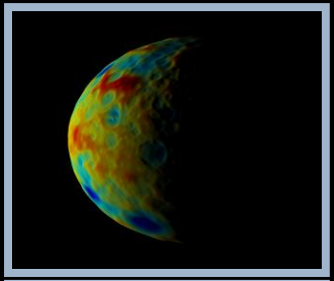
To obtain a high-precision oxygen isotopic measurement from a Jupiter-family comet



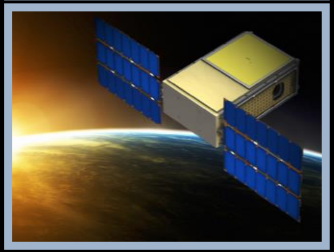


- WISPER uses a millimeter wave spectrometer (cf. MIRO)
- Mission would fly by <1000 km from Wirtanen
- Performance requirement exceeded by ~50%

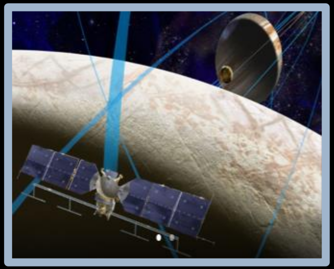
Outline



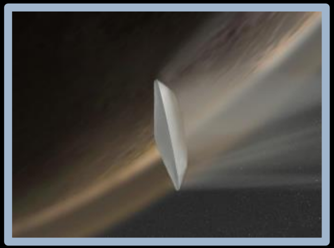
Science Pull for Planetary CubeSats



3U and 6U Planetary CubeSat Landscape



Visions for Future Voyages

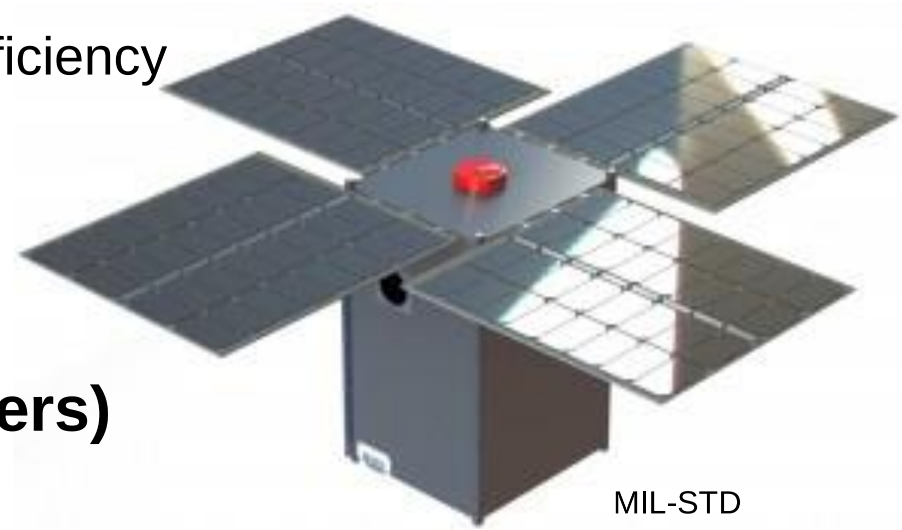


Parting Thoughts

Can I Have Another U (or 6?)

Doubling the Volume Offers Major Advantages

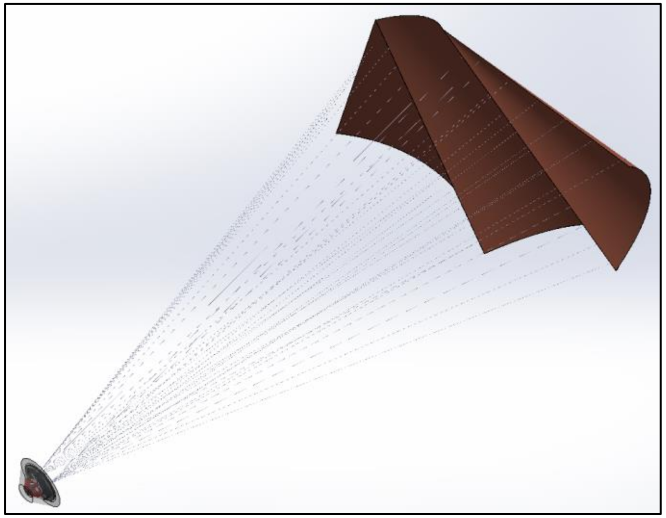
- **Increase antenna size**
  - E.g., combine MarCO's reflectarray with NEAS avionics
- **Increase ΔV**
  - Pack more propellant, more efficiency
- **Add another instrument**
  - On top of camera
- **Increase lifetime (nanolanders)**
- **Selected redundancy**
  - Backup reaction wheels
  - Redundancy on key avionic components (e.g., computer)

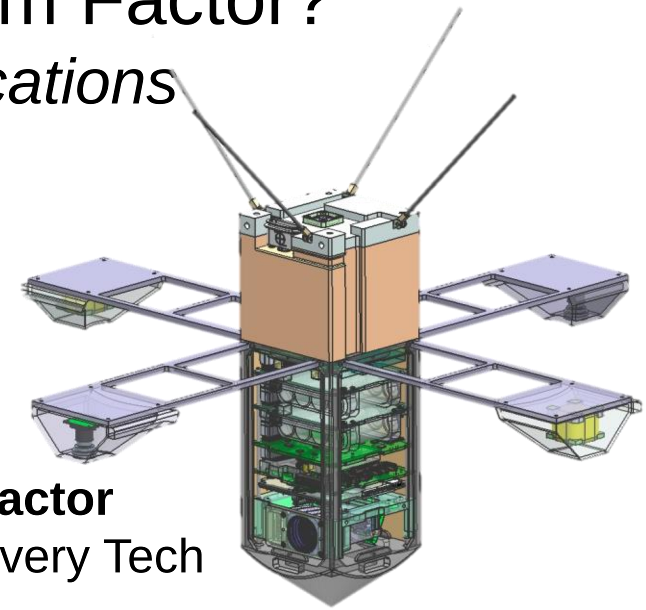


MIL-STD

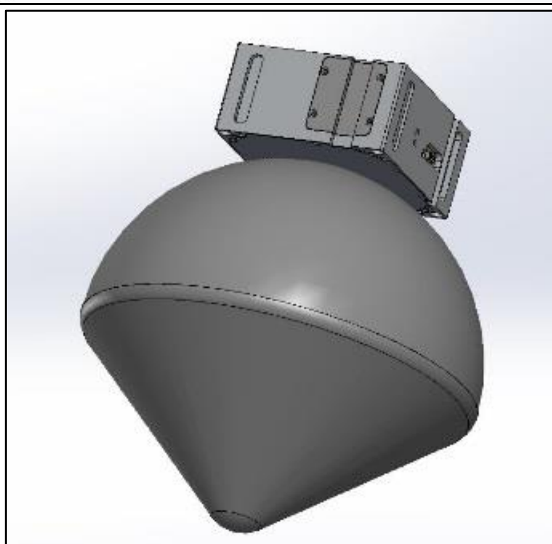
Can I Have a Different Form Factor?

Tailoring to specific applications

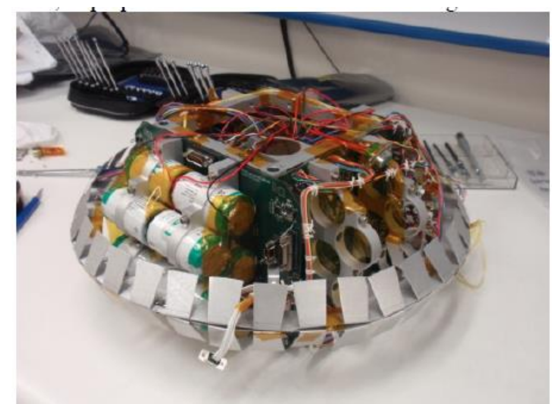




Comet Impactor
(ASU/JPL Discovery Tech Demo)



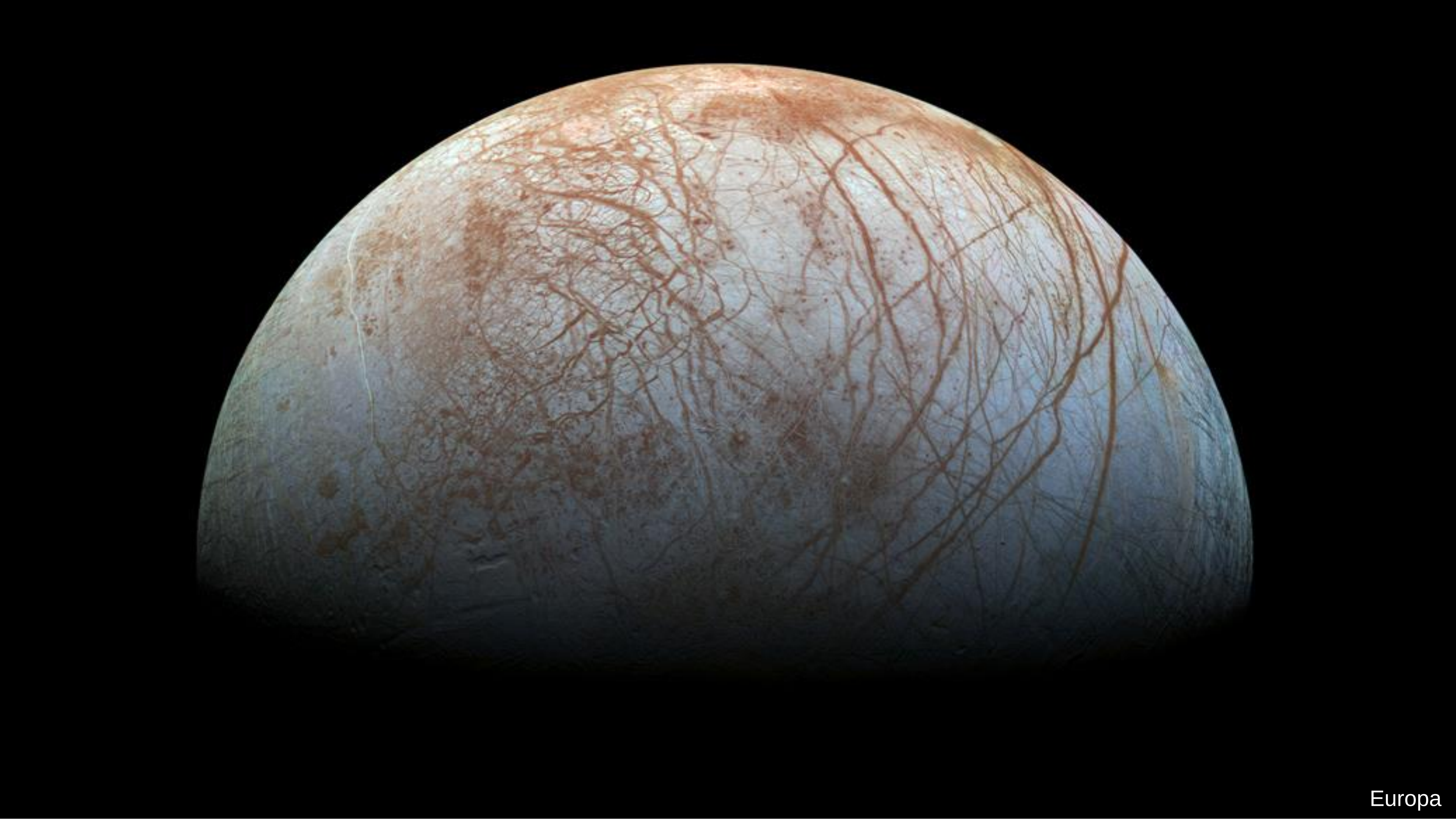
Atmospheric Probe
(MarsDrop, JPL)



Small Body Hoppers
(Hedgehog, Stanford/MIT/JPL; POGO, APL)

Considerations

- We’re almost there!
    - Advances promoted by AES and internal R&TD programs are bringing CubeSats to the next level
- CubeSats have the potential to enable novel architectures for decadal-class science
    - Space is hard – Deep space CubeSats *are not cheap*
    - Going places takes time – Operations for deep space CubeSats *should be* expensive
- **Cost/Risk posture will determine success**


Europa

Nanosats provide an opportunity for (relatively) low cost focused science and technology investigations

Jet Propulsion Laboratory
California Institute of Technology