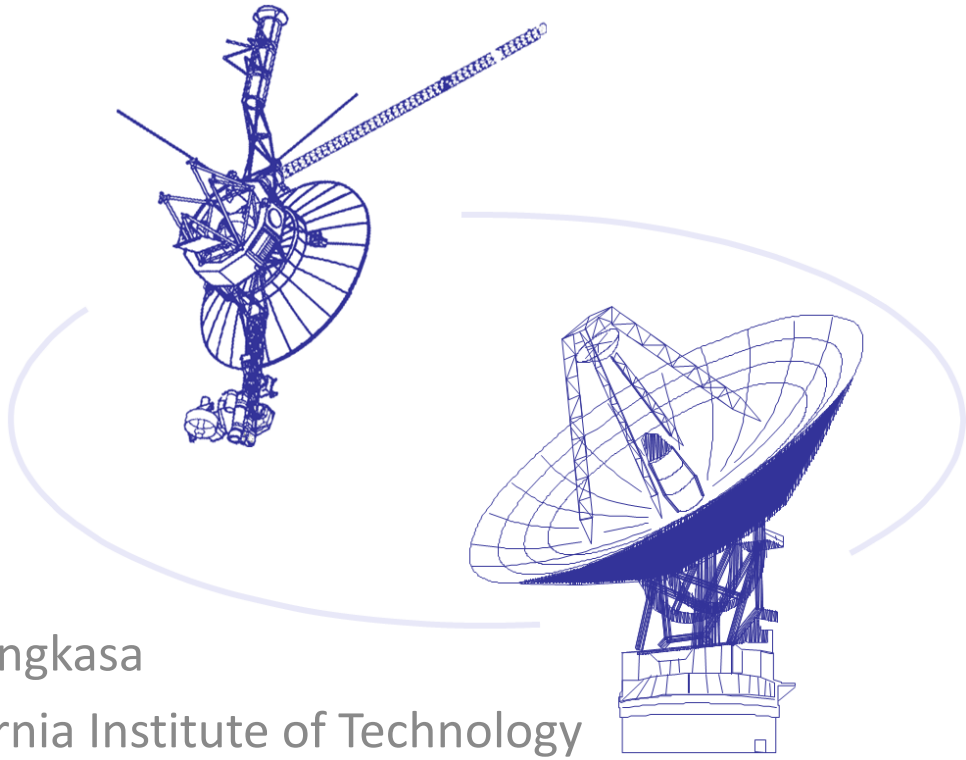
First CubeSat Missions with Deep-Space Telecommunication and Navigation

8th European CubeSat Symposium
London, United Kingdom
7-9 September 2016



M. Michael Kobayashi and Krisjani S. Angkasa
Jet Propulsion Laboratory at the California Institute of Technology

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Outline

- CubeSats for science
- Deep-space telecom challenges
- Purveyors of deep-space CubeSat Missions
- Iris Deep-Space Transponder and Antennas
- NASA SLS EM-1 Secondary Payloads
- Future enhancements

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Achieving Science with CubeSats

- National Academies committee on achieving science goals with CubeSats (Zurbuchen, et.al.) tasked to
  - Develop a brief summary overview of the status, capability, availability, and accomplishments
  - Recommend any potential near-term investments
  - Identify a set of sample priority science goals

Achieving Science with CubeSats: Thinking Inside the Box

ISBN 978-0-309-44263-3

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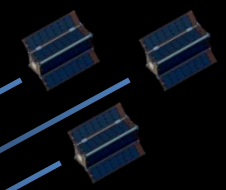
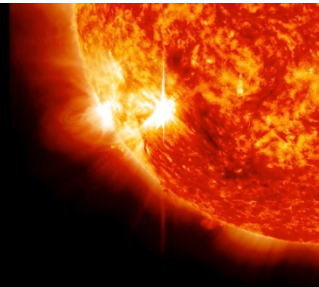
CubeSats CAN do High-Value Science

Lunar Investigations:

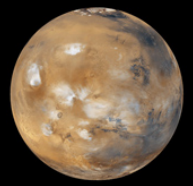
- Magnetic swirls on lunar surface
- Permanently shadowed craters





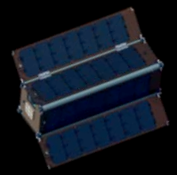
Heliophysics:

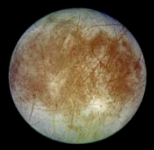
- Mapping space weather with a constellation of CubeSats



Interplanetary Explorations:

- Imaging Phobos and other moons
- Proximity ops for elemental and mineralogy measurements





Supplemental Science:

- Probes for atmospheric study
- Unique vantage point reconnaissance of flagship missions

**IMAGES NOT TO SCALE*

Image credit: NASA

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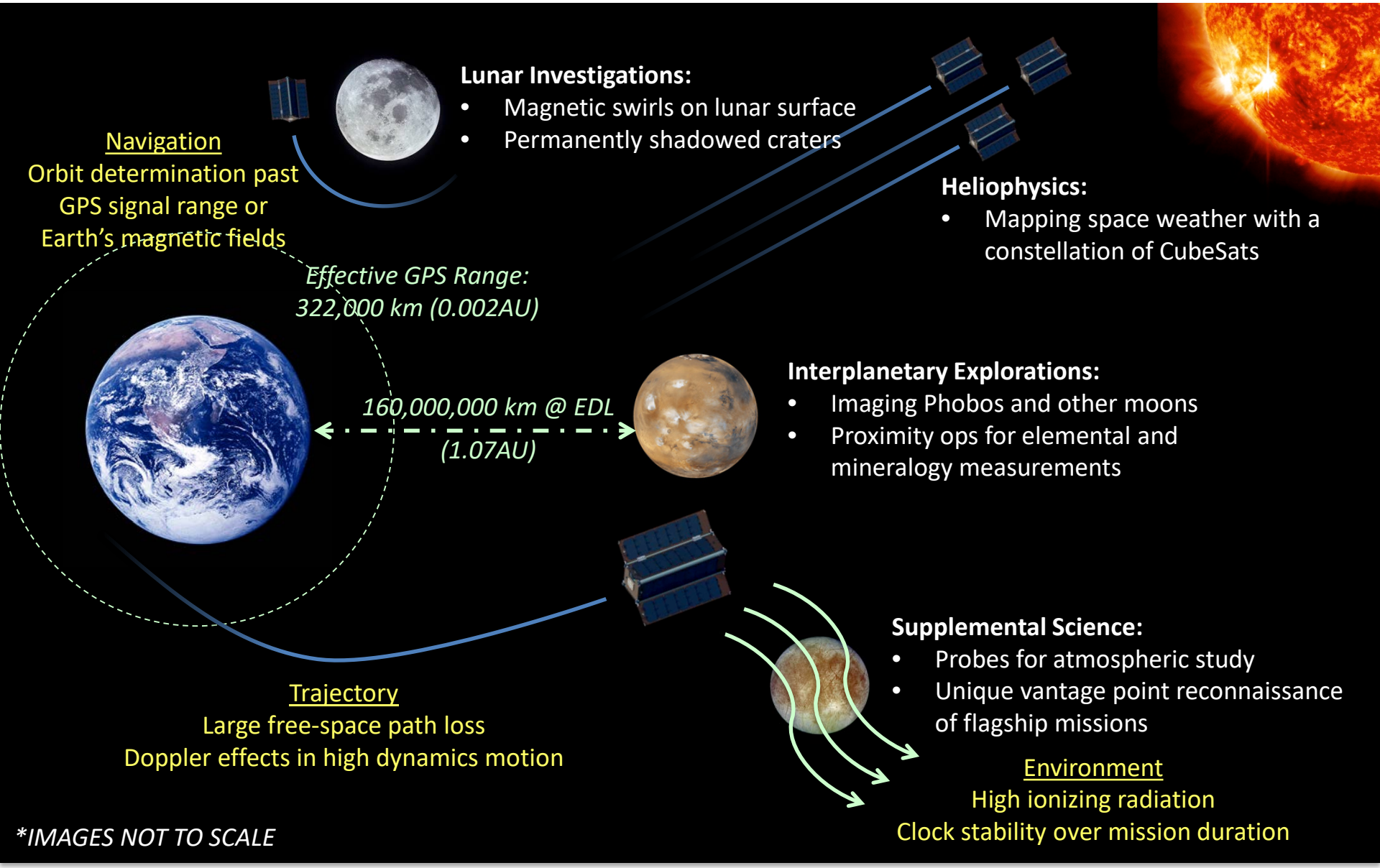
Telecom Challenges in Deep Space



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NASA's Deep Space Network

- DSN Functions
  - Receipt of spacecraft telemetry
  - Transmission of spacecraft command
  - Radiometric tracking (Ranging, Doppler)
  - Very Long Baseline Interferometry (VLBI)
  - Delta-Differential One-Way Ranging (DDOR)
  - Radio Science and Radio Astronomy
  - Interface to Ground Data System (GDS)

Quick uplink comparison at 1.0AU

	MSU* 21m dish		DSN 34m	
Xmtr Power	2	kW	20	kW
Gain	62	dBi	67	dBi
EIRP	125	dBm	140	dBm
Path Loss	273	dB	273	dB
S/C Rx Ant Gain	7.0	dBi	7.0	dBi
Rx Tot Power	-142	dBm	-127	dBm

**** Morehead State University in Kentucky, USA***

Receiver sensitivity difficult to achieve on COTS radios

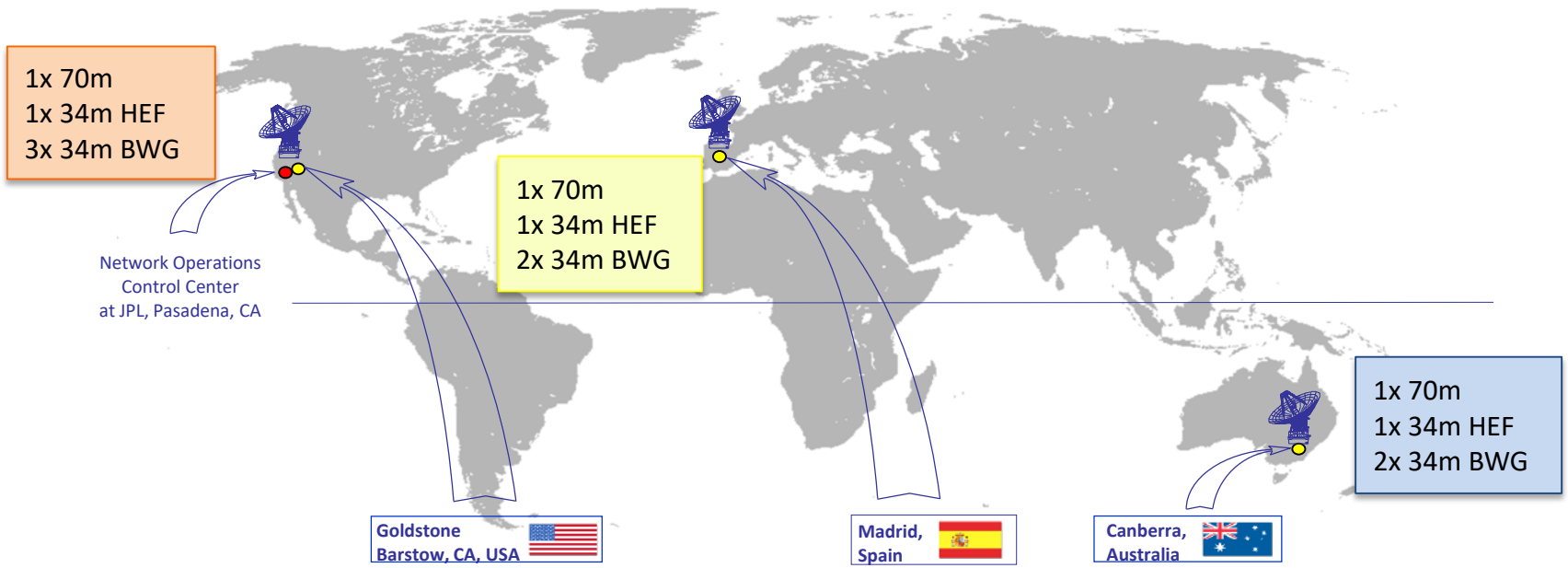

Image credit: NASA/DSN

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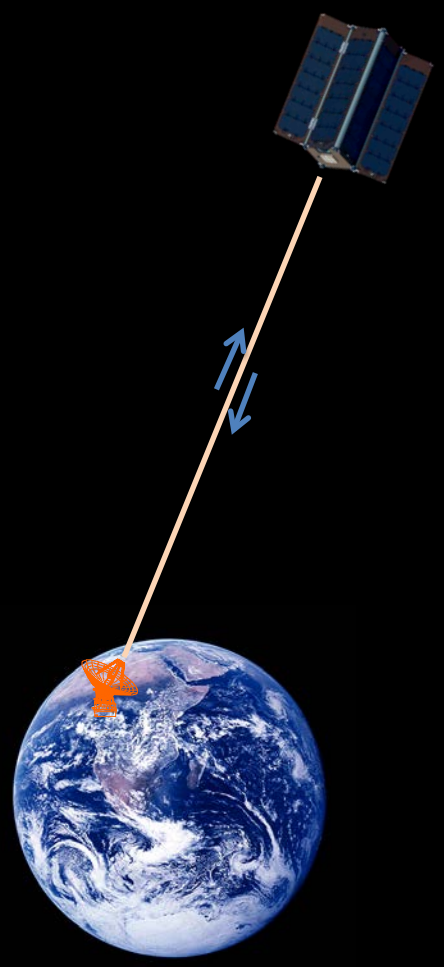
Radiometric Tracking Techniques



<u>Ranging</u>

Observable: One-way transit time of ranging signals

$$\rho = t_g c$$

ρ = topocentric range
t_g = one-way transit time
c = speed of light

Image credit: NASA/DSN

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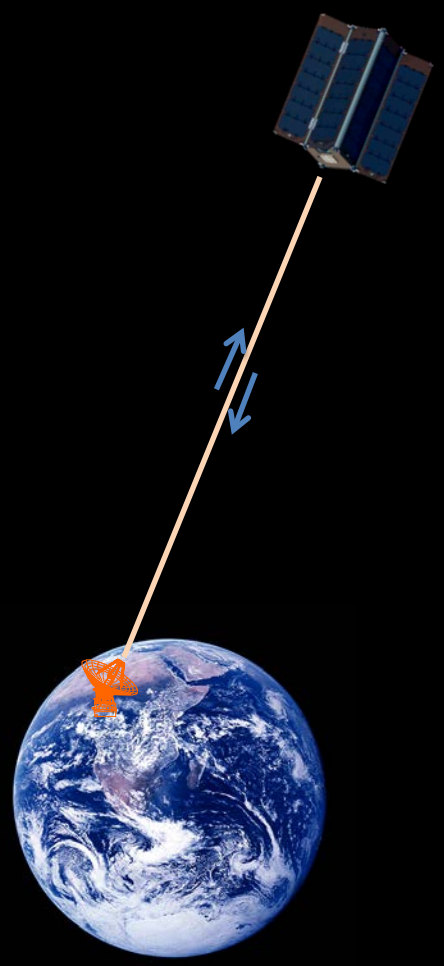
Radiometric Tracking Techniques



<u>Ranging</u>

Observable: One-way transit time of ranging signals

$$\rho = t_g c$$

ρ = topocentric range
t_g = one-way transit time
c = speed of light

<u>Doppler Tracking</u>

Observable: Frequency shift of received signal

$$f_R = \left(1 - \boxed{\frac{\dot{\rho}}{c}}\right) f_T$$

ρ' = topocentric range rate
f_R = received frequency
f_T = transmitted frequency
c = speed of light

Doppler Frequency Shift

Image credit: NASA/DSN

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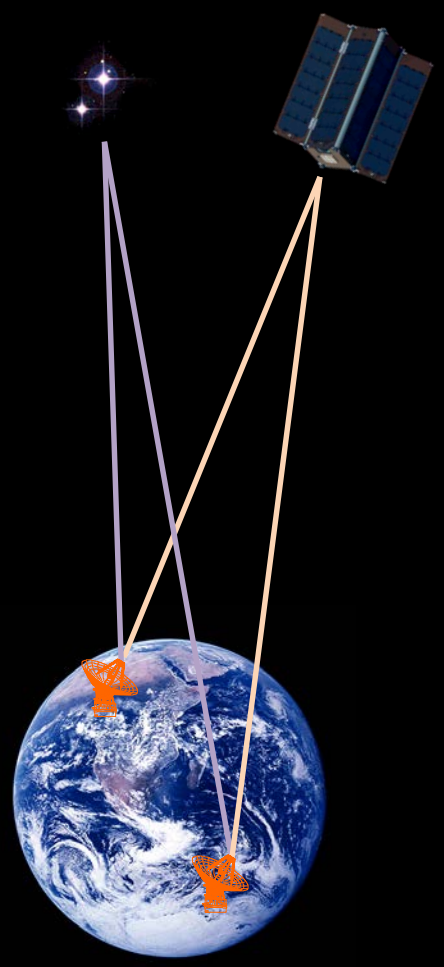
Radiometric Tracking Techniques



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$$f_R = \left(1 - \boxed{\frac{\dot{\rho}}{c}}\right) f_T$$

ρ' = topocentric range rate
f_R = received frequency
f_T = transmitted frequency
c = speed of light

Doppler Frequency Shift

<u>Very Long Baseline Interferometry (VLBI) Tracking also known as Delta-Differential One-Way Range (DDOR)</u>

Observable: Differential angular location to a reference location

$$\Delta\rho = t_g c = B \sin\theta$$

Θ = angle b/w wave front and baseline
B = baseline distance
t_g = wave front arrival time difference
c = speed of light

Image credit: NASA/DSN

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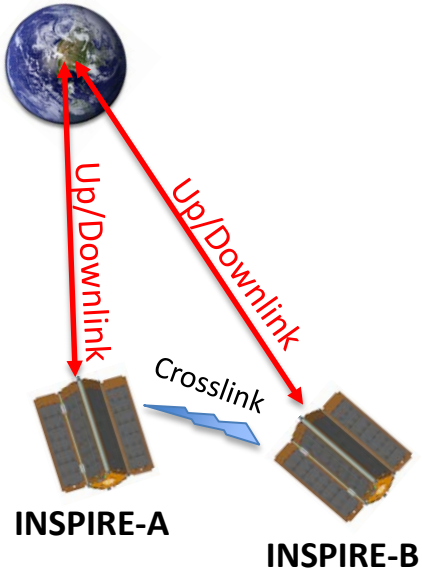
Purveyors of Deep-Space CubeSats

INSPIRE *Interplanetary Nano Spacecraft Pathfinder in a Relevant Environment*

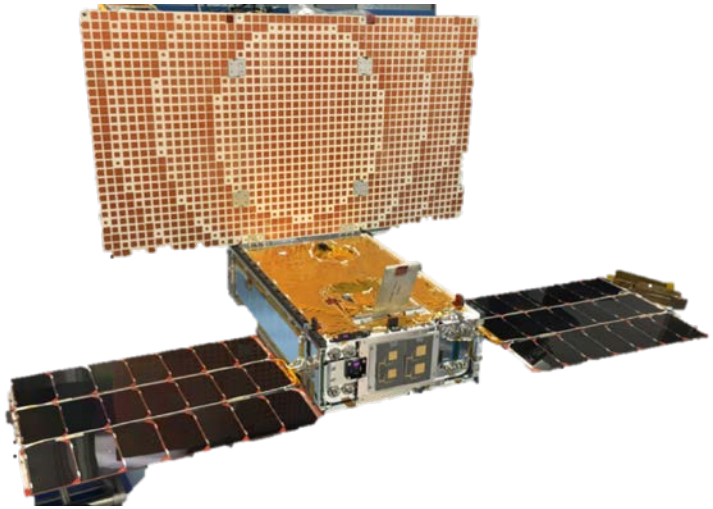
INSPIRE-A INSPIRE-B

INSPIRE Mission Concept

Provide reduced size/cost components to enable a new class of interplanetary explorers

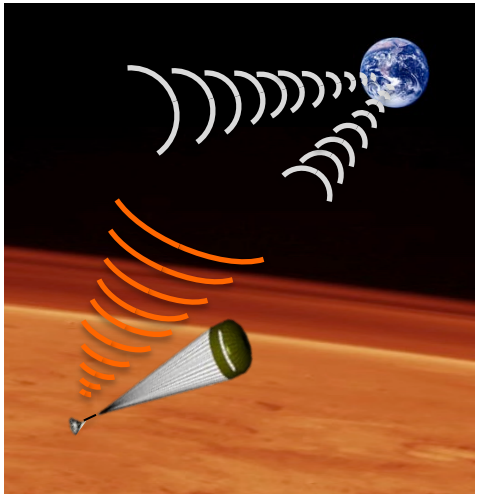


MarCO *Mars Cube One (alongside NASA's InSight Mission)*



MarCO Mission Concept

Provide real-time bent-pipe relay communications during InSight's Entry-Descent-Landing into Mars



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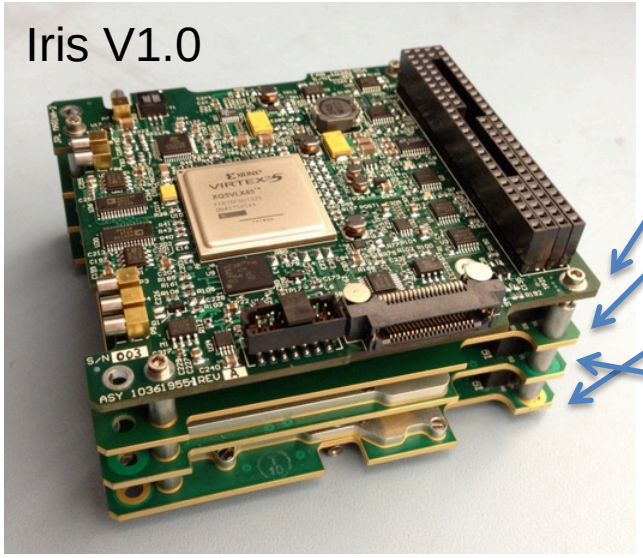
Iris Deep-Space Transponder

- CubeSat/SmallSat compatible deep-space transponder
- ~0.5U volume (100.5 x 101.0 x 56.0 mm; transponder only)
- DSN-compatible X-band uplink/downlink (7.2GHz/8.4GHz)
- Provides deep-space navigational support (Doppler, Ranging, DDOR)
- Modular hardware design for other frequency bands (UHF, S-band, Ka-band)
- Software Defined Radio with embedded Leon3-FT softcore processor
- Radiation tolerant to 15krads TID, 5krads ELDRS

Delivered 2 FM units to INSPIRE

Delivered 3 FM units to MarCO



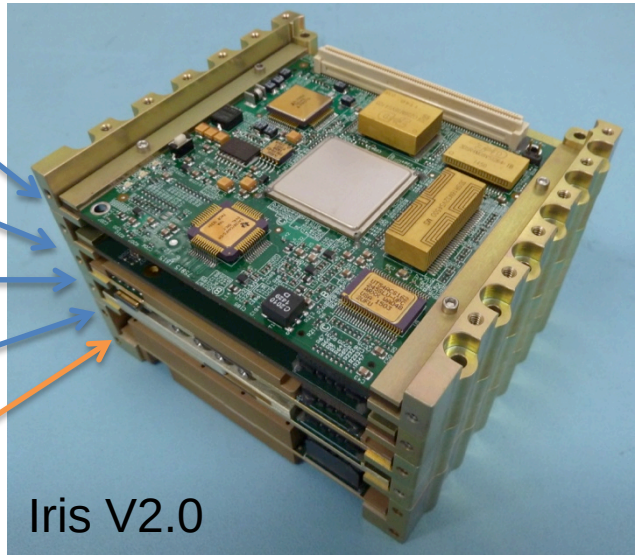
Digital Processor

Power Converter

X-Band Exciter

X-Band Receiver

UHF Receiver



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Key Specifications Table

Iris Specification	Units	Iris V1.0 for INSPIRE	Iris V2.0 for MarCO	Iris V2.1 for SLS EM-1
Digital Processor		Xilinx Virtex-5	Xilinx Virtex-6	Xilinx Virtex-6
Mass	grams	450 (no chassis)	1210 (w/ UHF-Rx)	<1000 (X/X-only)
Volume	U	0.46	0.77 (w/ UHF-Rx)	0.56
Bus Input Voltage	Vdc	6.4 – 8.4	10.5 – 12.3	9.0 – 28.0
DC Power*	W	13.0	30.0	30.0
RF Output Power*	W	0.15	5.0	5.0
Receiver Noise Figure	dB	5.0 – 6.0	3.5	3.5
Receiver Sensitivity	dBm	-135 @ 70Hz LBW	-139 @ 70Hz LBW	-151 @ 20Hz LBW
Uplink Data Rate†	bps	1,000	62.5 & 1,000	62.5 – 8,000
Downlink Data Rate†	bps	62.5 – 64,000	62.5 & 1,000 & 8,000	62.5 – 256,000
Telemetry Encoding		Conv & Reed Solomon	Turbo-1/6 only	Conv, Reed Solomon, Turbo 1/2, 1/3, 1/6
Navigational Support		Doppler, SRA	Doppler, SRA, DDOR	Doppler, SRA, DDOR
UHF Return Link Rate	bps	N/A	8,000	N/A
Radiation Tolerance	krads	N/A	15.0 TID	15.0 TID [TBC]
S/C Interface		1 MHz SPI	1 MHz SPI	1 MHz SPI

* Nominal at ambient
† Subject to link margin

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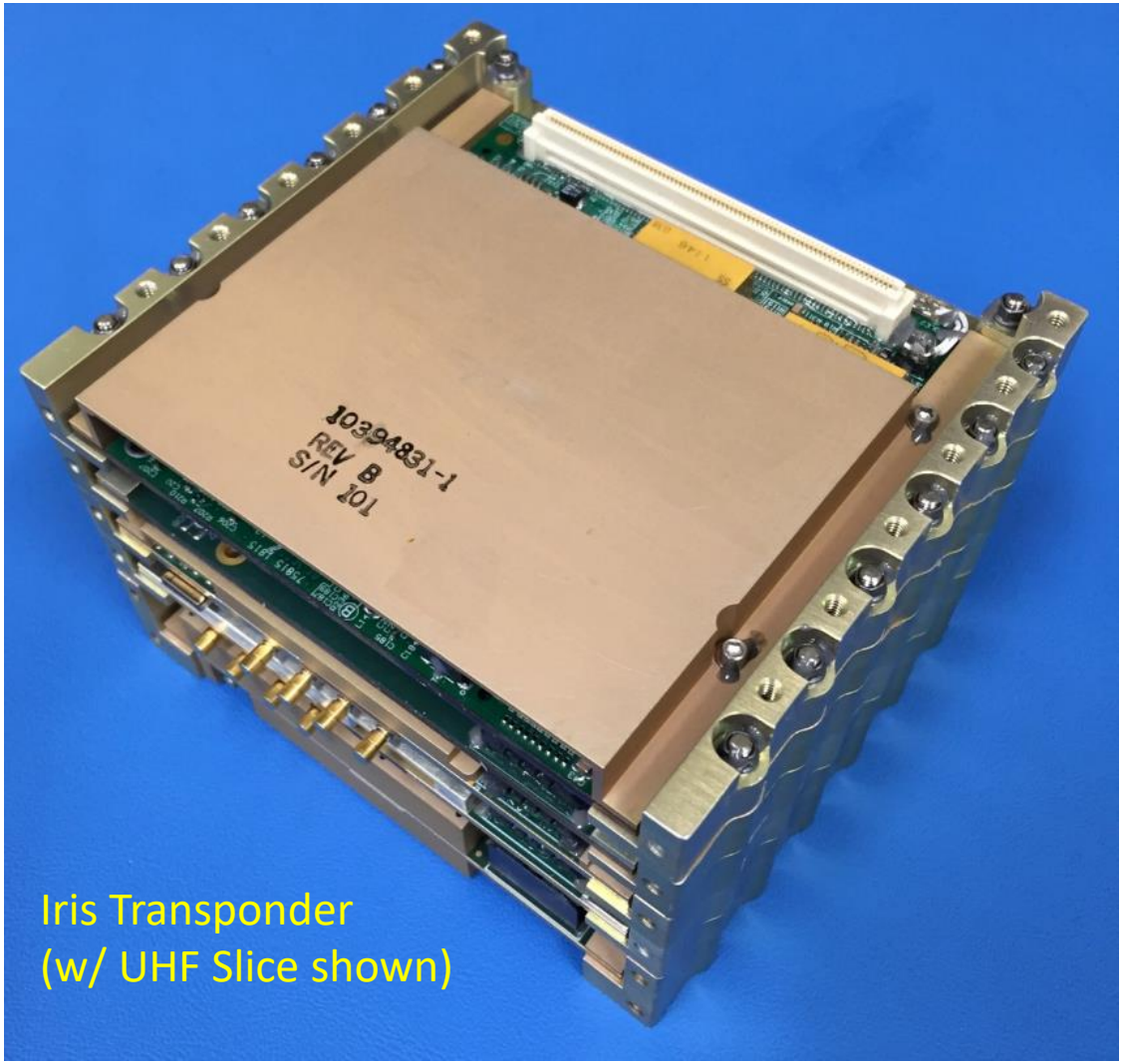
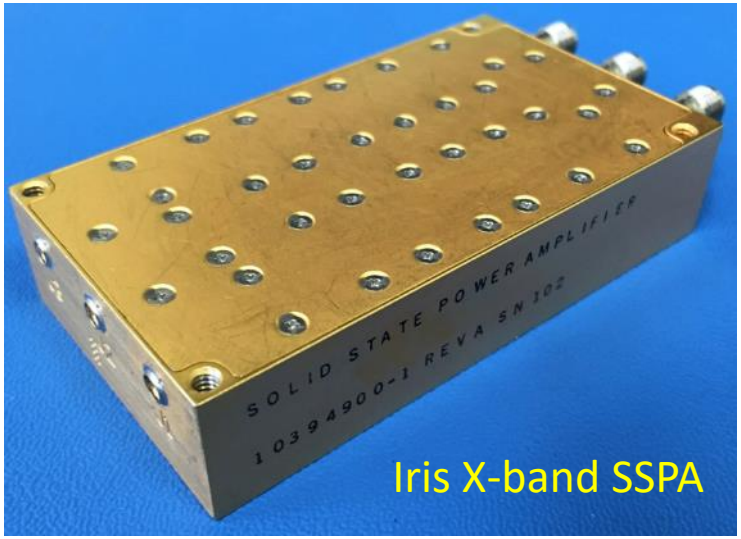
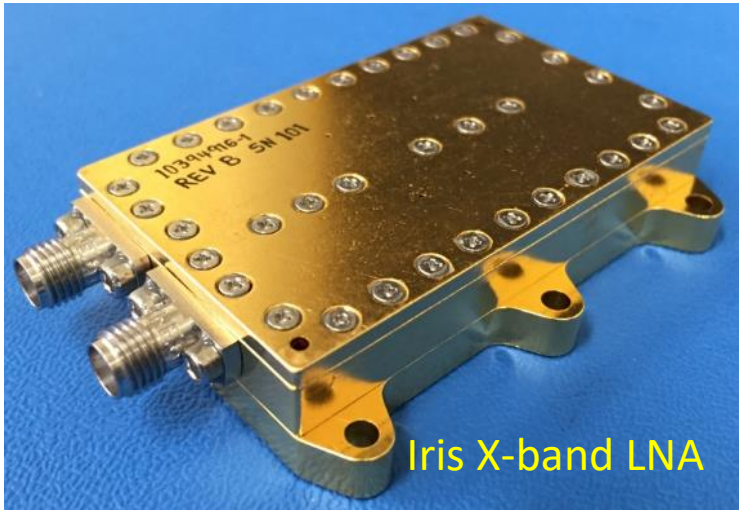
Iris V2 for MarCO Photos



Iris Transponder
(w/ UHF Slice shown)



Iris X-band SSPA



Iris X-band LNA

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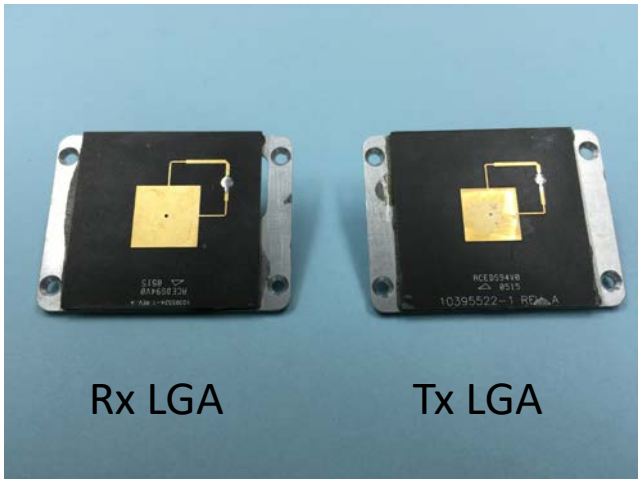
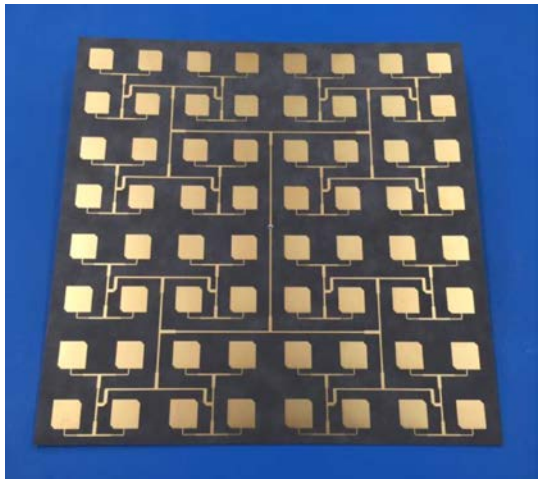
CubeSat X-Band Antennas

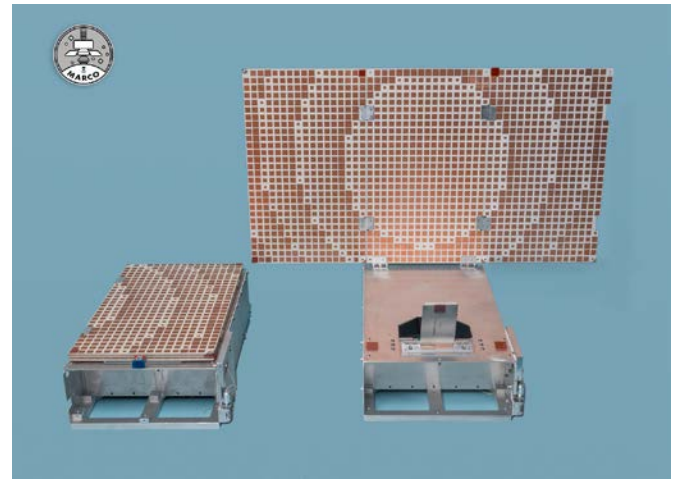
LGA (Single Patch)



Tx MGA (8x8 Patch)



Tx HGA (Reflectarray)



Property	Units	Rx LGA	Tx LGA	Tx MGA	Tx HGA
Frequency	MHz	7145 – 7190	8400 – 8450	8400 – 8450	8400 – 8450
Boresight Gain	dBi	+7.0	+7.6	+23.4	+28.4
Beamwidth (-3dB)		74°	74°	9.5°	4.1° (Az), 7.1° (El)
Sidelobe Level	dB	--	--	< -11.5	< -19.0
XPD	dB	> 5dB b/w ±90°	> 5dB b/w ±90°	> 18	> 17
Polarization		RHCP	RHCP	RHCP	RHCP
Return Loss	dB	≥ 20	≥ 20	≥ 15	≥ 13 (feed)
Mass	gram	15	15	250	1100

Image credit: N. Chahat, JPL

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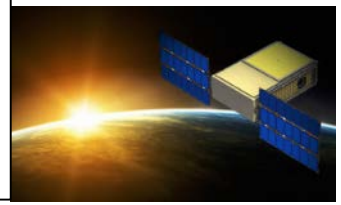
Iris on SLS EM-1 Secondary Payloads

Space Launch System (SLS) Exploration Mission 1 (EM-1)

Use **yeast** to detect, measure & compare the **impact of deep space radiation on living organism** over long durations beyond low-Earth orbit.

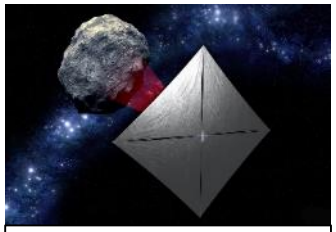
BioSentinel, *AMES*



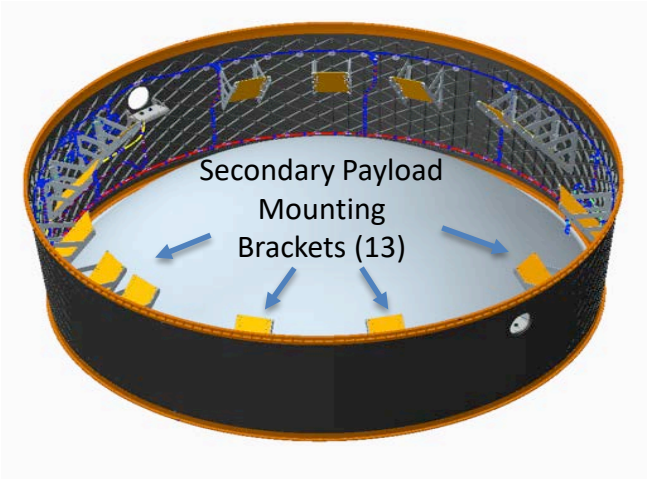
LunaH-Map, *ASU*

Map **hydrogen rich craters** near the lunar south pole, tracking depth & distribution of compounds like **water**.

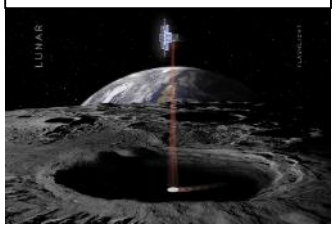
NEA Scout, *MSFC*



Proof-of-concept of a **solar sail** CubeSat capable of **encountering near-Earth asteroids (NEA)**.



Map the concentration of **exposed water ice** within the permanently shadowed regions of the **lunar south pole**.

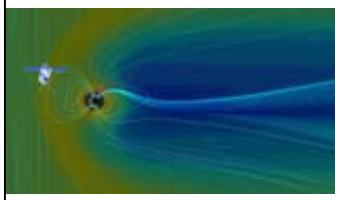


Lunar Flashlight Concept, *JPL*

Investigate the distribution of **water in ice, liquid, and vapor forms** in a low-perigee lunar orbit.

Lunar IceCube, *MSU*

Study the dynamic particles and magnetic fields that stream from the **Sun** and as a proof of concept for the feasibility of a **network of stations** to track **space weather**.



CuSP concept, *SWRI*

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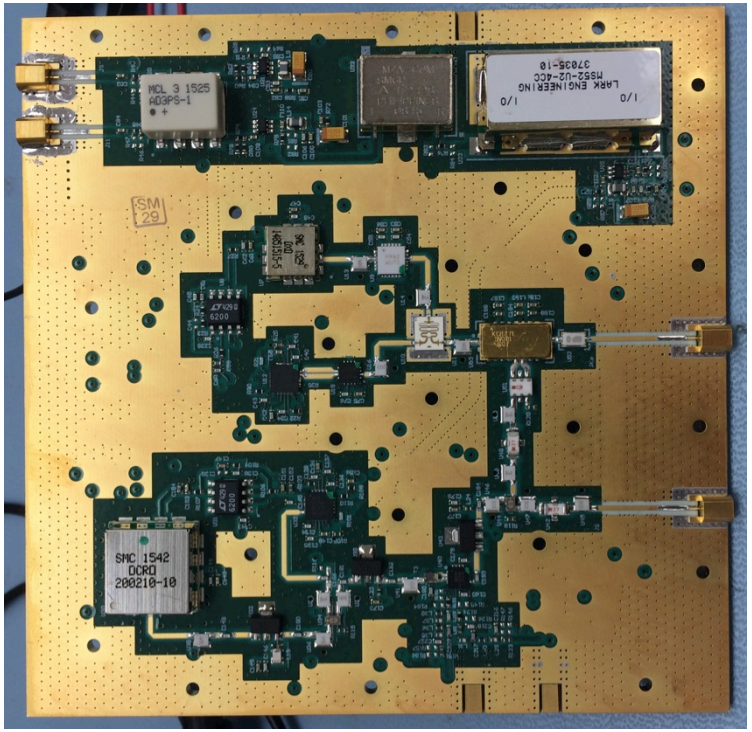
Future Enhanced Iris Capabilities

- Higher downlink rates beyond 2Mbps
- Low-Density Parity-Check (LDCP) code
- SpaceWire interface for high-rate data transfers to S/C C&DH unit
- Pseudonoise (PN) Regenerative Ranging for improved ranging SNR
- Reliable space-link protocols (CCSDS Prox-1 protocol)
- Delay/Disruption Tolerant Networking
- Other frequency bands (UHF, S, Ka)



<u>TRL-4 S-/Ka-band exciter</u>
S-band RF output: 0dBm
S-band phase noise: -95 dBc/Hz
Ka-band RF output: -13dBm
Ka-band phase noise: -74 dBc/Hz
Power: 4.7W

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Conclusion

- Upcoming launch of SLS EM-1 secondary payloads are at the frontier for CubeSats achieving high-value science.

- NASA's Deep Space Network functions for overcoming the challenges of deep-space telecom and navigation.

- Iris Deep-Space Transponder with radiometric tracking support for orbit determination of CubeSats.

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