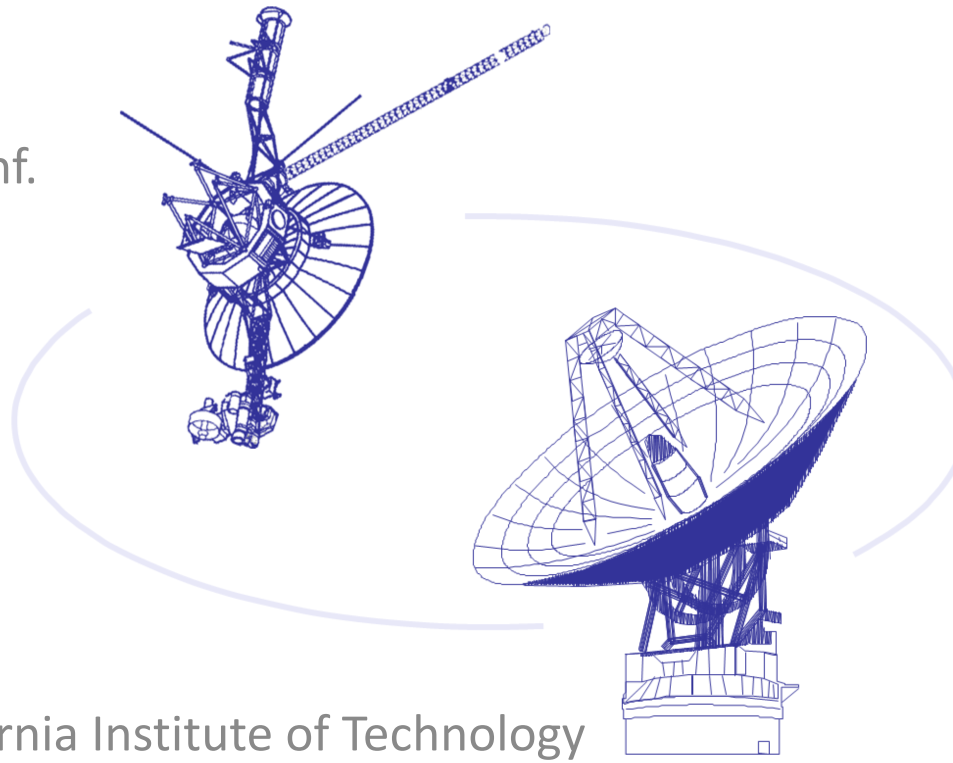
CubeSat Telecom System Needs for Deep-Space Missions

2017 Interplanetary Small Satellite Conf.
San Jose, California, USA
1-2 May 2017



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CL#17-1703

Outline

- Deep-Space telecom needs
- Survey of CubeSat communication systems
- Overcoming large distances
- Navigation in deep space
- Iris Deep-Space Transponder
- Iris hardware design description
- Software Defined Radio heritage
- Comparison of deep-space transponders
- Planned deep-space CubeSat missions
- Future enhancements

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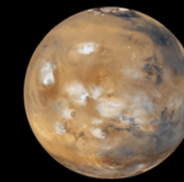
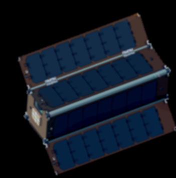
Deep-Space Telecom Needs

<u>Trajectory</u>
Large free-space path loss
Spacecraft dynamics effects



<u>Navigation</u>
Outside GPS signal range
No Earth’s magnetic fields



<u>Environment</u>
High ionizing radiation
Clock stability over mission duration

**IMAGES NOT TO SCALE*

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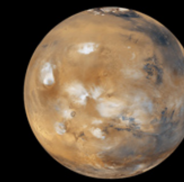
Image credit: NASA

Deep-Space Telecom Needs

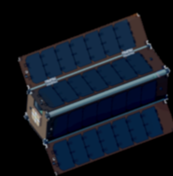


<u>Trajectory</u>
Large free-space path loss
Spacecraft dynamics effects

→ Large aperture antennas
Low receiver sensitivity

<u>Navigation</u>
Outside GPS signal range
No Earth's magnetic fields

→ Radiometric Navigation Techniques



<u>Environment</u>
High ionizing radiation
Clock stability over mission duration

← Space-grade parts
Coherent Transponder

An equally capable <u>ground station</u> to support deep-space exploration needs is required.

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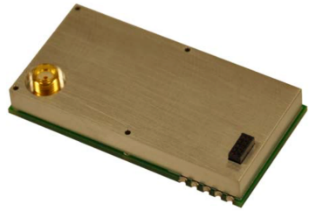
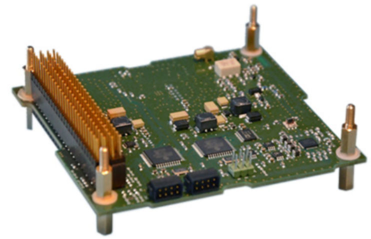
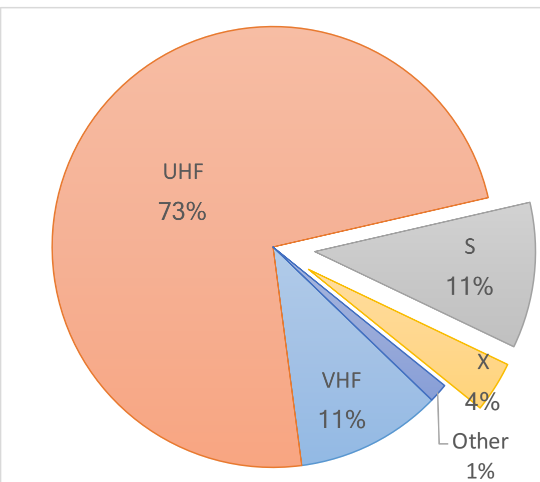
Image credit: NASA

Survey of CubeSat Telecom Systems

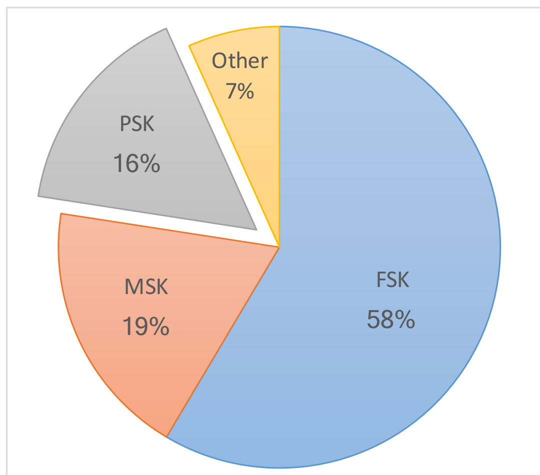
	 AstroDev Li-1	 ISIS TRXUV	 GomSpace AX100	 Freewave FGRM
Bands	VHF/UHF	VHF/UHF	VHF/UHF	S-band
Mod	FSK/GMSK	BPSK	FSK/MSK/GFSK/GMSK	GFSK
Rates (baud)	9600	1200 – 9600	100 – 115,200	115,200 – 153,600

Frequency Bands



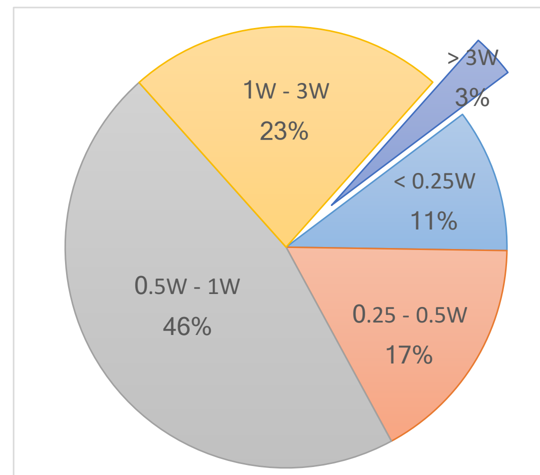
Deep-space frequency band limited to S, X, and Ka

Modulation Schemes



PSK highly recommended by CCSDS for deep-space use

RF Output Power



Higher power for farther distances necessary

* Data Source: B. Klofas, CubeSat Communications System Table, Version 13, 16 Aug 2016.
Survey of 215 CubeSats

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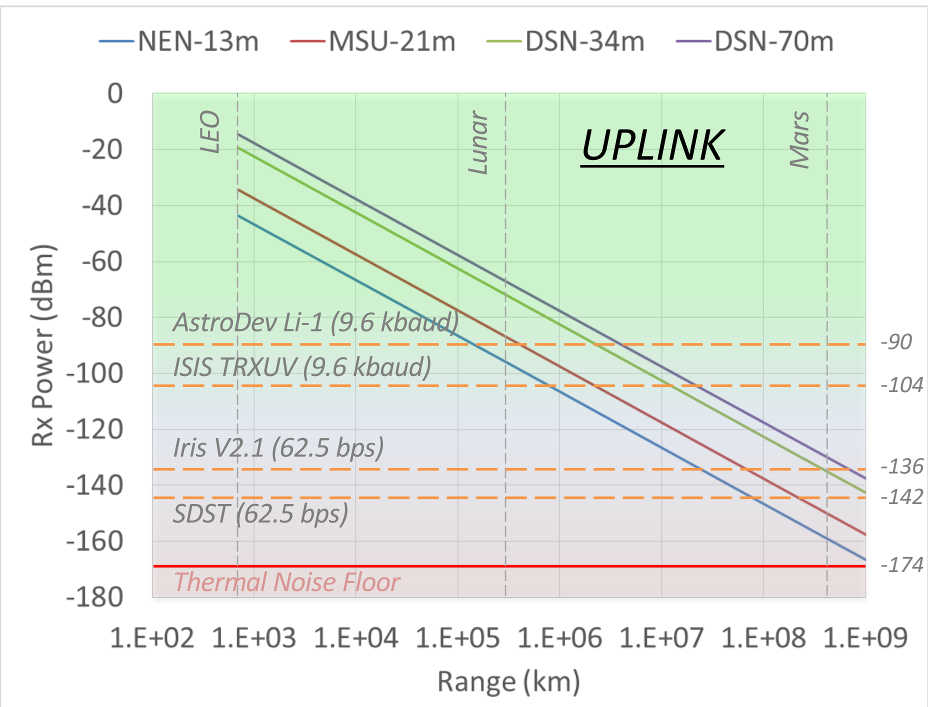
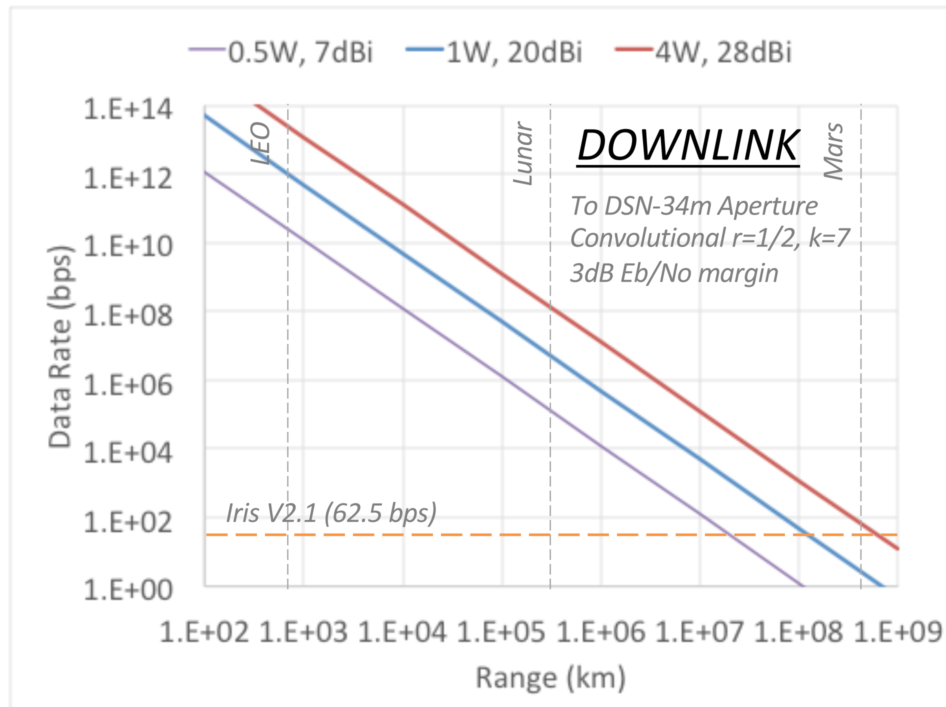
Overcoming Large Distances





*2kW assumed for EIRP calculation

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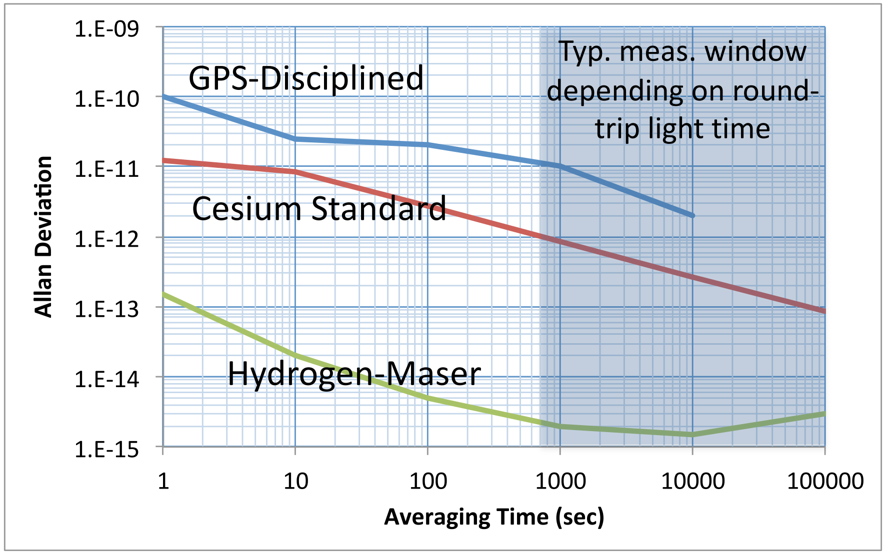
Navigation in Deep Space

- Support radiometric navigation (ranging, Doppler track, VLBI) for orbit determination
  - A carefully characterized Coherent Radio Transponder is necessary for turn-around ranging on the S/C
  - Transmitter with special DOR tones for VLBI support (note: need two Earth stations to support)
  - Earth Station equipped with navigation processing tools
- Stable reference clock for reduced navigational error
  - Detect milli-Hertz variations within GHz signals.
  - Long integration times with low frequency drift
    - Stability required over round-trip light time (ranging)
    - VLBI tracking times 8-12 hours.
- Overcome S/C dynamic effects
  - Configurable carrier tracking loops for varying dynamics
  - Pre-emphasis Doppler compensation from Earth station

$$20\log_{10}\left(\frac{f_{link}}{f_{ref}}\right)$$



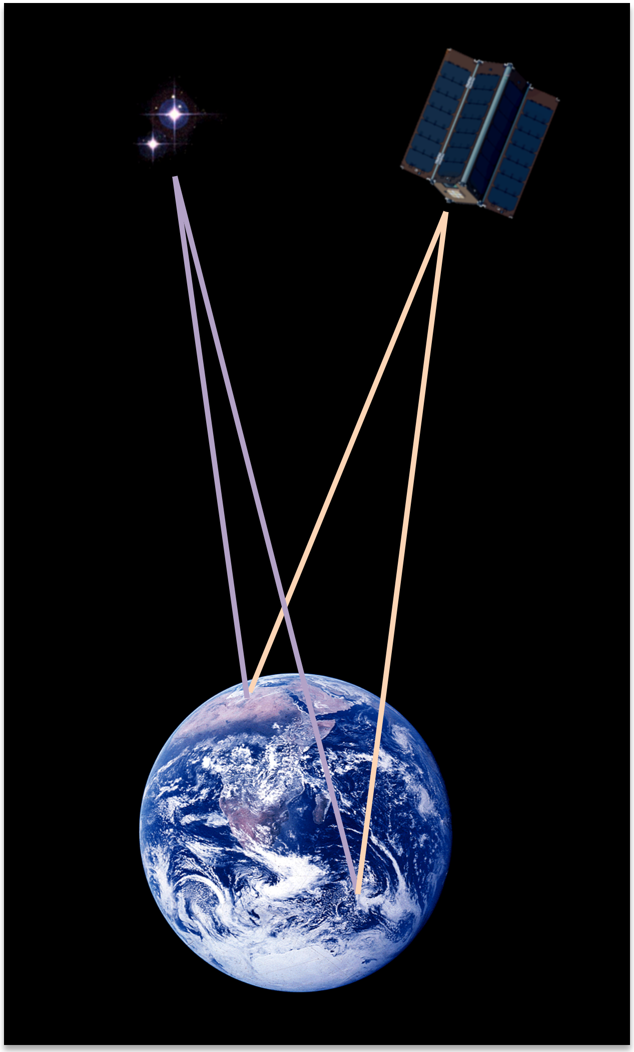


Image credit: NASA/DSN

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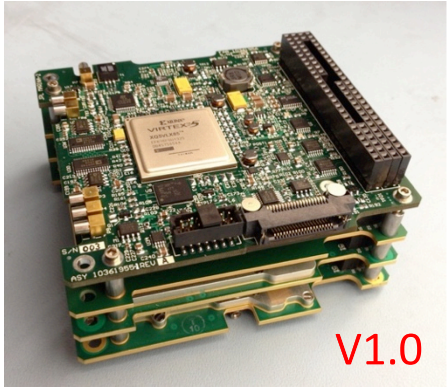
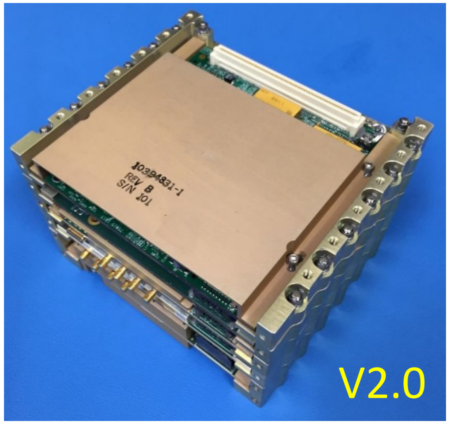
Iris Deep-Space Transponder

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



Iris Specification	Units	Iris V1.0 for INSPIRE	Iris V2.0 for MarCO	Iris V2.1 for SLS EM-1
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	35.0	33.7
RF Output Power*	W	0.15	3.3	3.8
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
Radiation Tolerance	krads	N/A	15.0 TID	23.0 TID
S/C Interface		1 MHz SPI	1 MHz SPI	1 MHz SPI



* Nominal at ambient

† Subject to link margin

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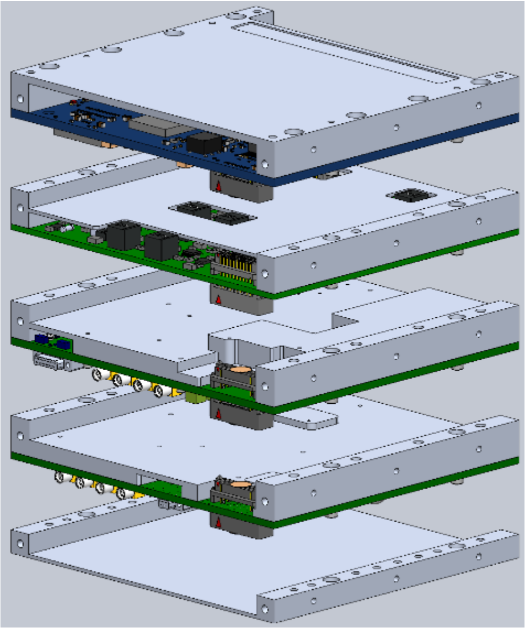
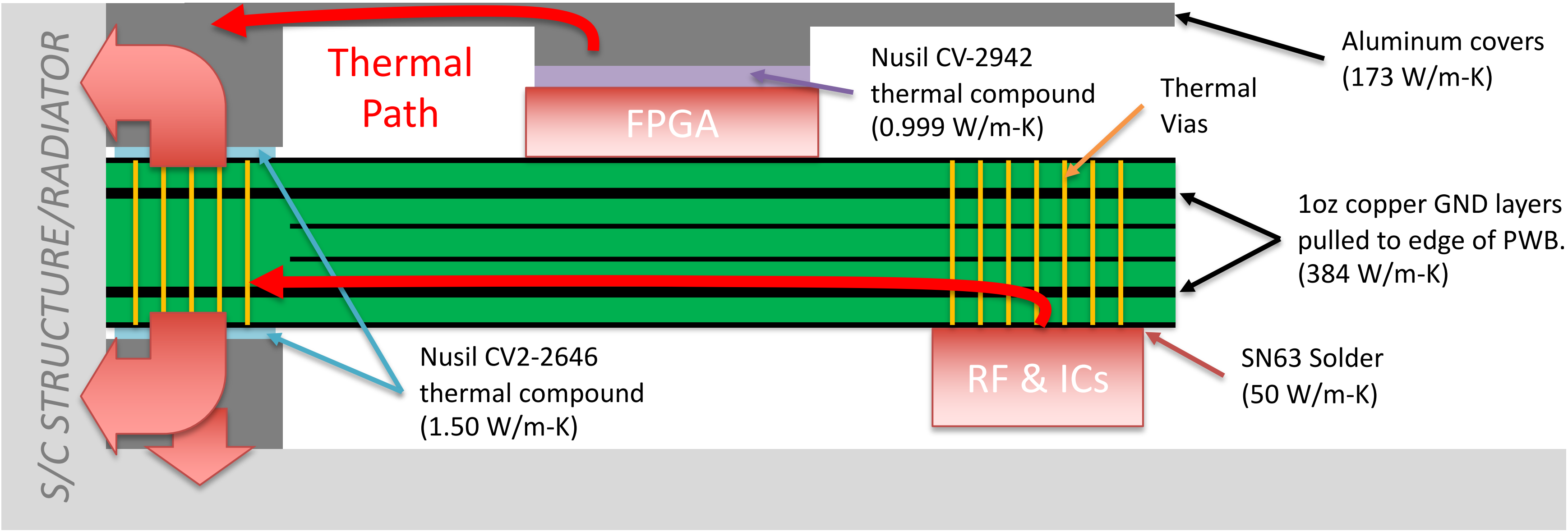
Hardware Design Considerations

- Modular hardware built of slice elements
  - NASA-STD-4009 (Space Telecom Radio System) guidelines
  - Slices are interconnected with stacking connectors
  - RF modules are generic to allow future designs with other frequency bands (UHF, S, Ka)
- Radiation tolerant up to 23 krads; no destructive SEL.
- EMI covers/shields to minimize radiated emissions
- Emphasized efficient thermal design





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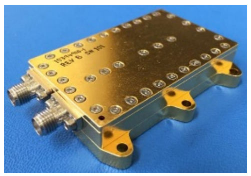
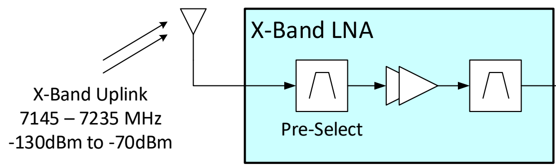
Top-Level Block Diagram

Iris LNA

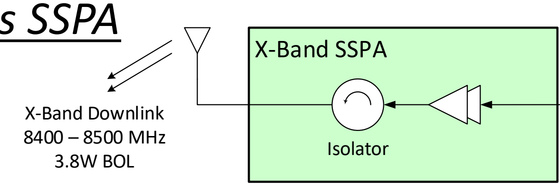


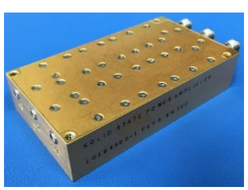
Modular MIC assembly

- Reduce noise figure by shortening cable length from antenna
- Separate gain cavities between LNA and Rx (risk of oscillations)



Iris SSPA

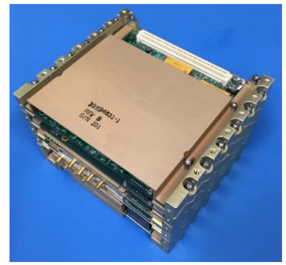


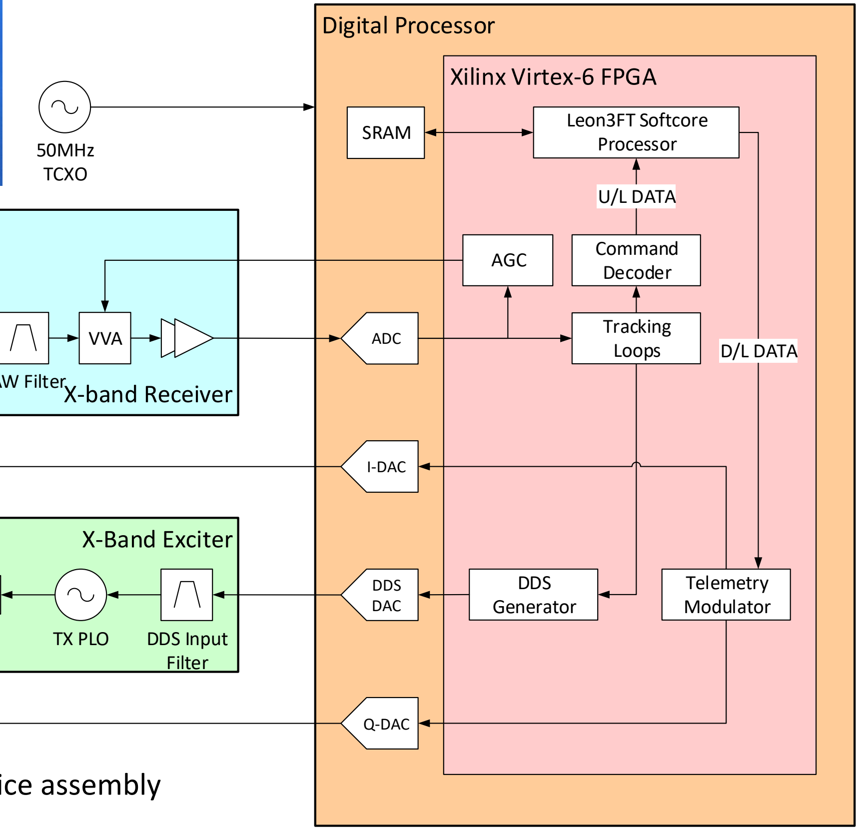
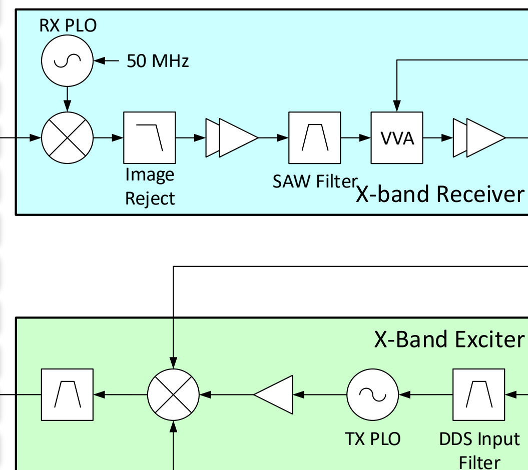


Modular MIC assembly

- Provide superior heat dissipation path to structure/radiator
- Chip-and-wire assy to reduce losses for higher efficiency

Iris Transponder Stack



Modular stacked-slice assembly

- Superheterodyne receiver with single-downconversion stage to 112.5 MHz IF
- Digitally closed tracking loops (carrier, subcarrier, symbol)
- Direct Digital Synthesis (DDS) reference for downlink carrier Doppler tracking
- Baseband telemetry modulated direct at X-band
- Embedded softcore processor (Leon3-FT) for configuration and protocol mgmt

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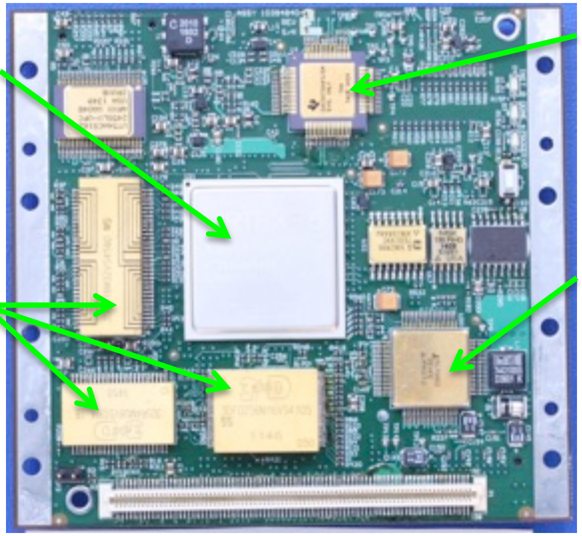
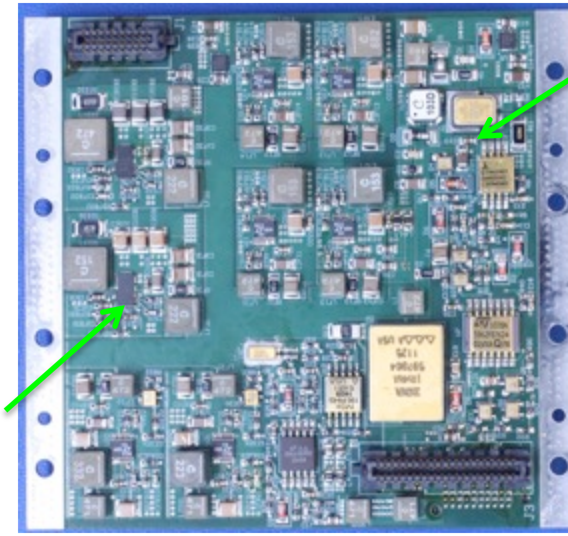
Iris Hardware Photos

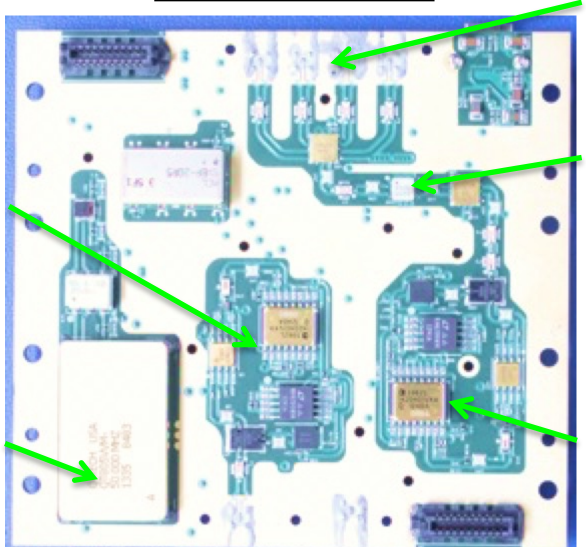
Digital Processor



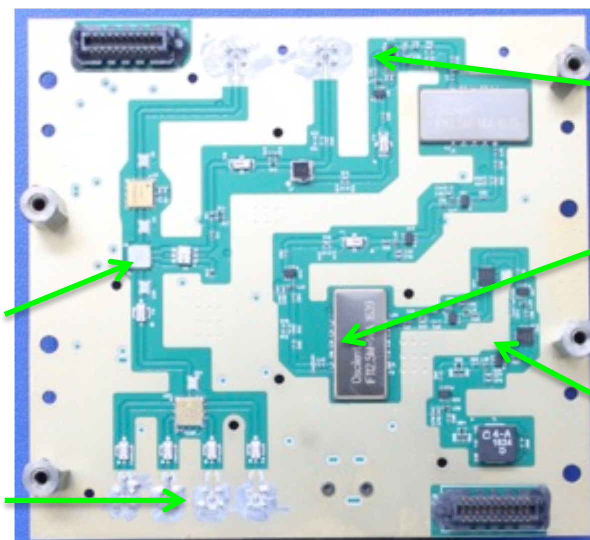
Power Supply



X-band Exciter



X-band Receiver



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Software Defined Radios

- Leading the pathway to **“smart radios”**
  - Reconfigurable to adapt to mission-specific needs
  - Platform for rapid technology infusion
    - Delay/Disruption Tolerant Networking
    - Pseudo-noise (PN) Regenerative Ranging
    - Advanced higher-order modulation schemes
    - State-of-the-art Forward Error Correction algorithms

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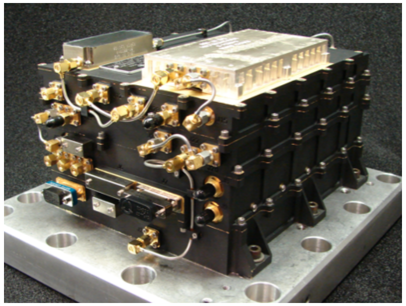
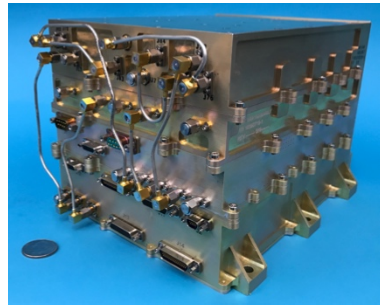
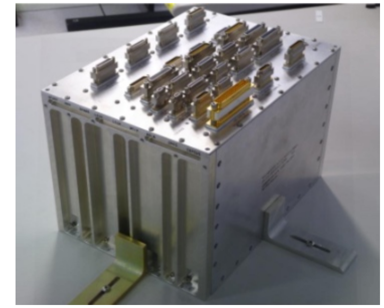
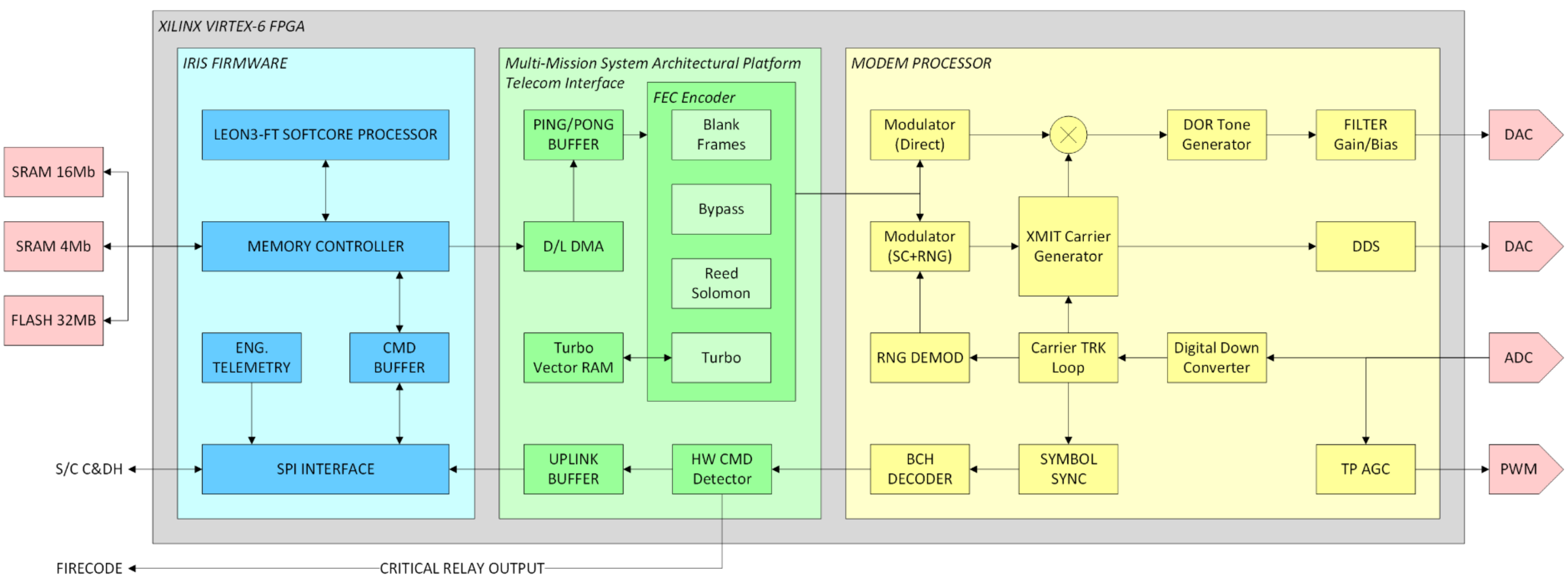
Software Defined Radio Heritage Pieces







Electra Proximity Radio	**Universal Space Transponder**	**Multi-Mission Sys. Architectural Platform**
Automatic Gain Control algorithm	Coherent transponder algorithm	Reed-Solomon encoder
Carrier/Subcarrier tracking loops	Sequential ranging demodulator	Turbo 1/2, 1/3, 1/6 encoder
Phase Shift Key modem	Delta-DOR tone generator	Hardware Command Detector
Early/Late symbol synchronizer	BCH uplink decoder	Error Detection and Correction



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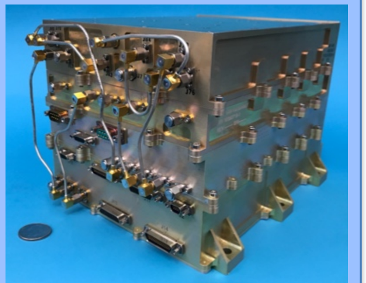
Deep-Space Transponder Comparisons

Reconfigurable

Iris (JPL)

Mass: 1.0 kg

UST (JPL)



Mass: 4.5 kg†

One-Time Programmable

SDST (GD)

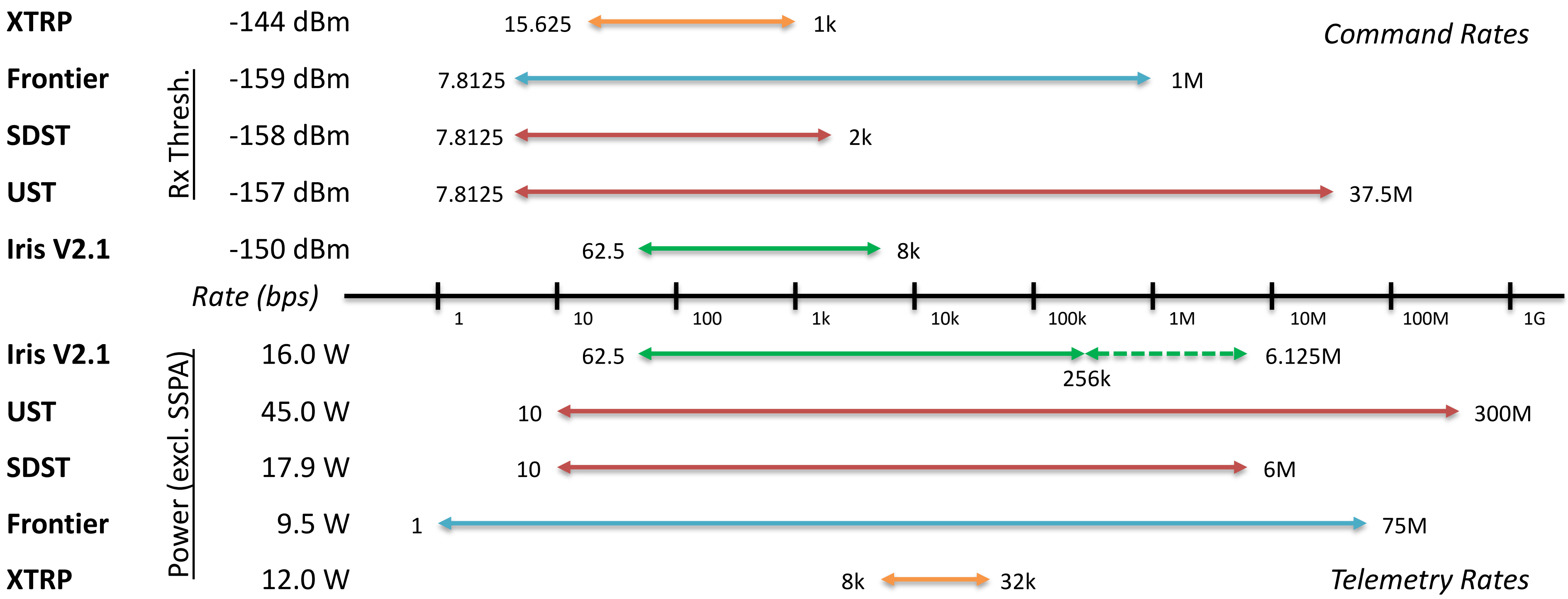
Mass: 3.3 kg

Frontier (APL)

Mass: 2.3 kg

XTRP (JAXA)

Mass: 1.2 kg



† Dual Channel Version

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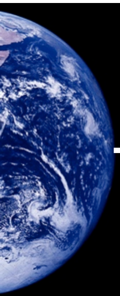
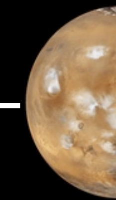
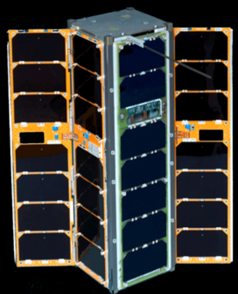
Planned Deep-Space CubeSat Missions



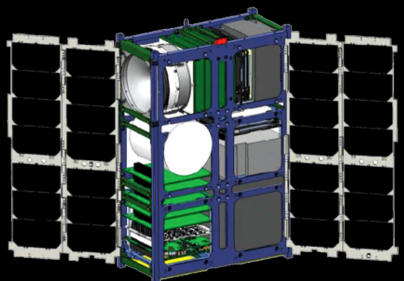
1.5 Mkm	15 Mkm	84 Mkm	110 Mkm	160 Mkm
0.01 AU	0.10 AU	0.56 AU	0.74 AU	1.07 AU





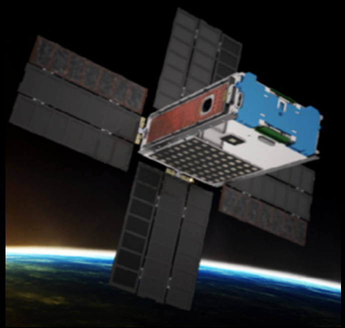
INSPIRE, *JPL*

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



CuSP, *SwRI*

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.

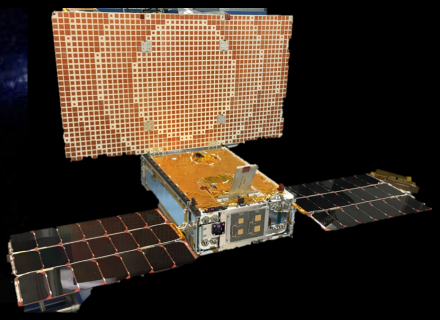


BioSentinel, *AMES*

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

NEA Scout, *MSFC*

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



MarCO, *JPL*

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

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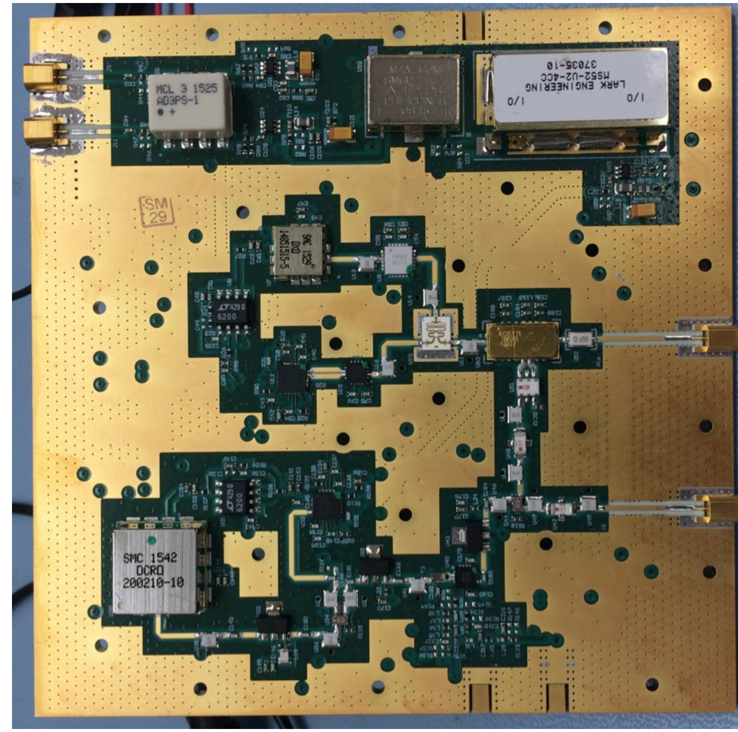
Future Enhanced Iris Capabilities

- 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

- Iris Deep-Space Transponder with radiometric tracking support for orbit determination of CubeSats.
- NASA's Deep Space Network functions for overcoming the challenges of deep-space telecom and navigation.
- Software defined radios as "smart radios" to enable rapid technology infusion.

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