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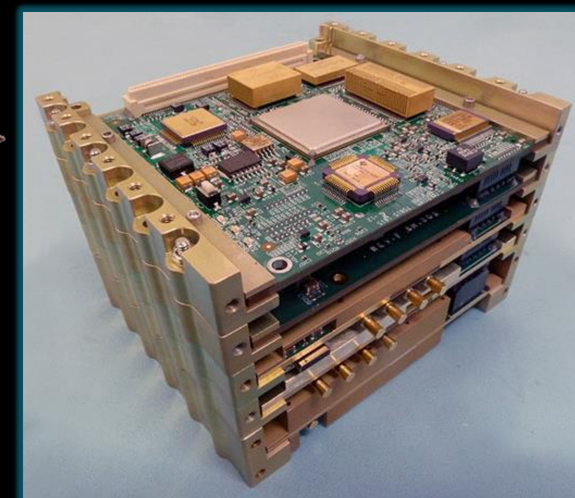
Iris Deep-Space Transponder for Artemis-1 Payloads

Inter-Planetary Small Satellite Conference

Pasadena, California

11-12 May 2020



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Outline

- History of Iris
  - V 1.0 (INSPIRE Version), V 2.0 (MarCO Version), & V 2.1 (Artemis -1 “formerly EM-1” Version)
- V 2.2 (Enhanced version of V 2.1 that also is available to Artemis-1 CubeSat Missions)
- High Level Design Description: HW, SW, and available modes
- Performance Testing at DSN Testing Facility DTF-21
  - Over-the-Air Programmability
  - Pseudo-Noise (PN) Delta DOR & PN Regenerative Ranging
  - Higher Downlink & Uplink data rates
  - QPSK and OQPSK
- Missions used/using Iris
  - MarCOs, and Artemis-1 (formerly EM-1)
- Future Enhancements that are considered for Lunar Communication and navigation applications

What is in the name Iris (Ιρις)

The Iris: an Illuminated Souvenir (1852),
upload.wikimedia.org/wikipedia/commons/4/49/1852_Iris_Illuminated_Souvenir.png.
Public Domain

- Not an acronym
- Iris – a goddess associated with communication, messages, the rainbow and new endeavors
- “Little Sister” to Electra
  - Electra is a JPL SDR UHF Relay Radio.
- Cousin of Cassandra (Cassy)
  - Ground Support Equipment (GSE) that is used for testing Iris

Iris Transponder Evolution History

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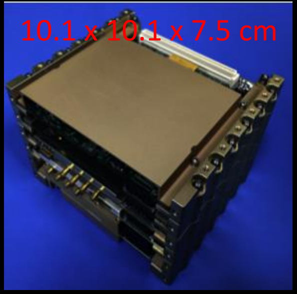
- **<u>Iris V1.0</u>**: To extend CubeSat/SmallSat deep space capability, JPL introduced the Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) mission[1], coupled with the first-generation of Iris deep-space transponder[2]. Modular Design (4-slices)

- **<u>Iris V2.0</u>**: The radio was further developed, matured, and in 2018 successfully flown onboard Mars Cube One (MarCO), to support InSight's Mars Entry, Descent, and Landing (EDL)[3]. Five slices (including an UHF receive slice).

- **<u>Iris V2.1</u>**: The latest version of Iris includes design updates that support Artemis-1 CubeSats missions[4].

Iris V1.0 Stack



Iris V2.0 Stack

Iris V2.1 Stack

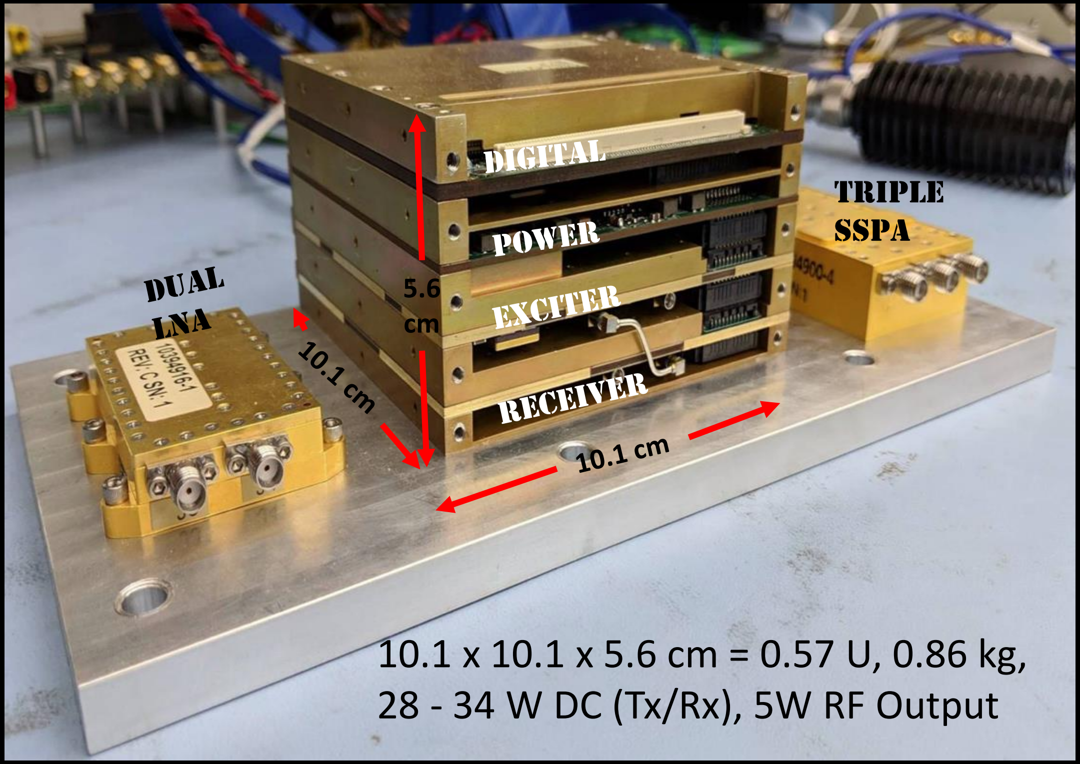
Specification	Units	
Downlink frequencies	MHz	8400-8600
Uplnk frequencies	MHz	7146-7235
Turn-around ratio		880/749
Downlink symbol rates	sps	62.5-6.25 M
Uplink data rates	bps	62.5-8000
Modulation waveforms		PCM/PSK/PM w/subcarrier
		PCM/PM w/biphase-L, BPSK
Telemetry encoding		Turbo (1/2, 1/3, 1/6)
Receiver noise figure (NF)	dB	3.5
Carrier tracking threshold	dBm	-151 @ 20-Hz LBW
RF output power	Watts	> 3.8
Navigation		Nonregenerative ranging
		Delta-DOR, Doppler
Transmit phase noise		
(one-way noncoherent)	dBc/Hz	≤ -20 @ 1-100 Hz
		≤ -60 @ 100-100,000 Hz
Oscillator stability	ppm	0.001 @ Δt = 1 sec
Mass	k	≤ 1.0
Volume	U	0.56 (excl. SSPA/LNA)
Power consumption	Watts	12.0 Rx-only
		33.7 Full Tx/Rx
Sapcecraft bus interace		1-MHz SPI
Bus voltage range	V	9-28
Allowable flight temperatures	degC	-20 to +50
Dynamics		14.1 grms random vibe
Radiation tolarenace (total ionizing doze)		> 23.0 krad
Radiation tolerance (single event latch-up)		> 37 MeV-cm2/mg

Iris V2.1 Key Specifications[4]

[1] A. Klesh et al., "INSPIRE: Interplanetary NanoSpacecraft Pathfinder In Relevant Environment," in *AIAA SPACE Conf. and Expo.*, San Diego, CA, 2013.
[2] C. B. Duncan et al., "Iris Transponder – Communications and Navigation for Deep Space", in *Small Satellite Conf.*, Logan, UT, 2014.
[3] A. Klesh et al., "MarCO: Early Operations of the First CubeSats to Mars," in *Small Satellite Conf.*, Logan, UT, 2018.
[4] M. M. Kobayashi et al., "Iris Deep-Space Transponder for SLS EM-1 CubeSat Secondary Payloads", IEEE Aerospace and Electronic Systems Magazine, Volume 34, Issue 9, pp 34-44, September 1, 2019.

Artemis-1 Iris (V2.1)

- The only small deep space transponder that is compatible with the NASA standard deep space signal and protocol stack.
- Four slices:
  - Digital: Virtex 6 (Defense-grade) with embedded CPU (SPARC V8: LEON3-FT softcore) running at 50 MHz
  - Power Supply Board
  - X-Band Exciter
  - X-Band Receiver
- 1 MHz SPI Interface
- 2-ch LNA: 7 x 4.8 x 1.3 = 44 cc
- 3-ch SSPA: 8.7 x 4.3 x 1.8 = 68 cc
- Receiver Noise Figure: 3.5 dB
- 62.5 bps to 6 Mbps (uncoded), CCSDS Deep Space
- Doppler, Seq. Ranging, Delta DOR
- Radiation Tolerance: 23 krads TID
- Licensed to Space Dynamics Laboratory (SDL) for manufacturing and sale.



V 2.1 is shown here for a reference. Missions that are interested in updating from V 2.1 to V 2.2 need to update the new FW/SW on the ground in order to have the Over-the-Air Programmability capability built-in.

Iris Generational Specification Summary

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Iris Specification	Units	Iris V1.0 INSPIRE Version	Iris V2.0 MarCO Version	Iris V2.1 Artemis-1 Version
Digital Processor		Xilinx Virtex-5 (commercial-grade)	Xilinx Virtex-6 (Industrial-grade)	Xilinx Virtex-6 (defense-grade)
Embedded CPU		N/A	SPARC-Based Leon3-FT Softcore	SPARC-Based Leon3-FT Softcore
No. Of Slices		4	5	4
Mass (excl. SSPA/LNA)	grams	450	1200	860
Volume (excl. SSPA/LNA)	U	0.46	0.77	0.56
Memory		32 Mbit NOR-Flash 128 Mbit Phase-Change Memory chip for the SPI interface	32 Mbit NOR-Flash 16 Mbit SRAM 4 Mbit EDAC SRAM	32 Mbit NOR-Flash 16 Mbit SRAM 4 Mbit EDAC SRAM
S/C Interface		1 MHz SPI±	1 MHz SPI	1 MHz SPI
Bus Power Interface	Vdc	6.4 - 8.4	10.5 – 12.3	9.0 – 28.0
DC Power	W	13.0	30.0 (including 5-W SSPA)	30.0 (including 5-W SSPA)
RF Output Power	W	1.0§	5.0	5.0
Receiver Noise Figure	dB	5.0 – 6.0	3.5	3.5
Receiver Sensitivity	dBm	-135 @ 70 Hz LBW	-139 @ 70 Hz LBW	-151 @ 20 Hz LBW
Downlink Frequencies	MHz	8400 - 8500	8400 - 8500	8400 - 8500
Uplink Frequencies	MHz	7145 - 7235	7145 - 7235	7145 - 7235
Turn-around Ratio		880/749	880/749	880/749
Uplink Date Rates	bps	1,000	62.5 & 1,000	62.5 - 8,000
Downlink Data Rates	bps	62.5 - 64,000	62.5 & 1,000 & 8,000	62.5 - 256,000
UHF Receive Freq	MHz	N/A	390 - 405	N/A
UHF Rertun Link Rate	bps	N/A	8,000	N/A
Modulations Waveforms		PCM/PSK/PM w/ subcarrier PCM/PM w/ biphase-L, BPSK	PCM/PSK/PM w/ subcarrier PCM/PM w/ biphase-L, BPSK	PCM/PSK/PM w/ subcarrier PCM/PM w/ biphase-L, BPSK
Telemetry Encoding		Conv & Reed Solomon	Turbo 1/6	Conv & Reed Solomon Turbo ½, 1/3, 1/6
Navigational Support		Doppler, SR*	Doppler, SR, DDOR†	Doppler, SR, DDOR
Radiation Tolerance	krads	N/A	15.0 TID‡	23.0 TID

±SPI: Serial Peripheral Interface bus
§ For the INSPIRE mission, the PA was backed off to 0.2 W to save power
* SR: Sequential Ranging
†DDOR: Delta Differential One-way Ranging
‡TID: Total Ionizing Dose

High Level Hardware Overview

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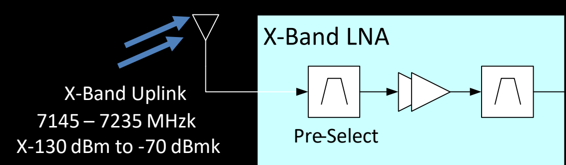
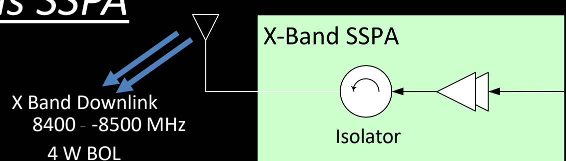
Iris LNA

Modular MIC assembly

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



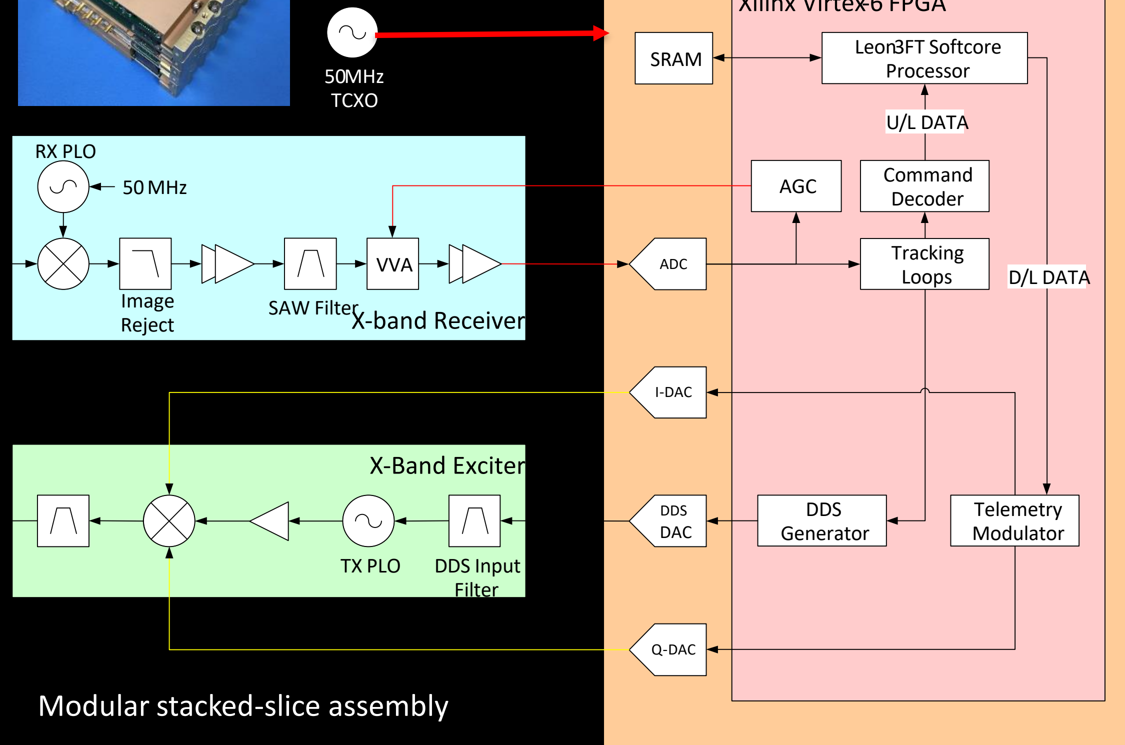
Iris SSPA



Modular MIC assembly

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

Iris Transponder Stack

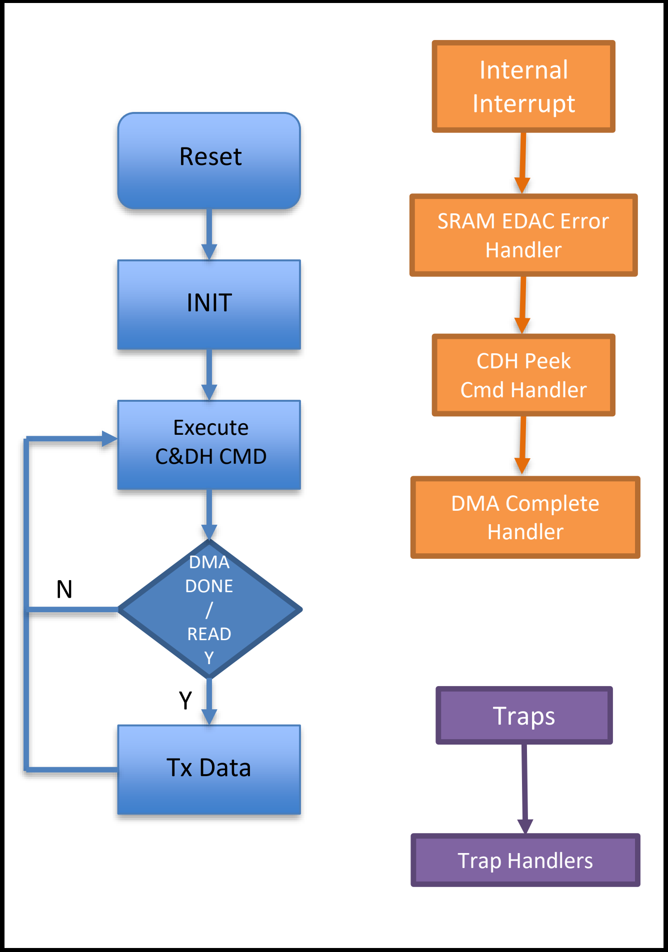


Modular stacked-slice assembly

- 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

Software Specs / Architecture

- Single-threaded using SPARC V8 instruction set, targeted for LEON3-FT soft core processor
- SRAM: 2 MB total
  - Program size:
    - Text: 99.7 kB
    - Data: 2.9 kB
- Running at 50 MHz



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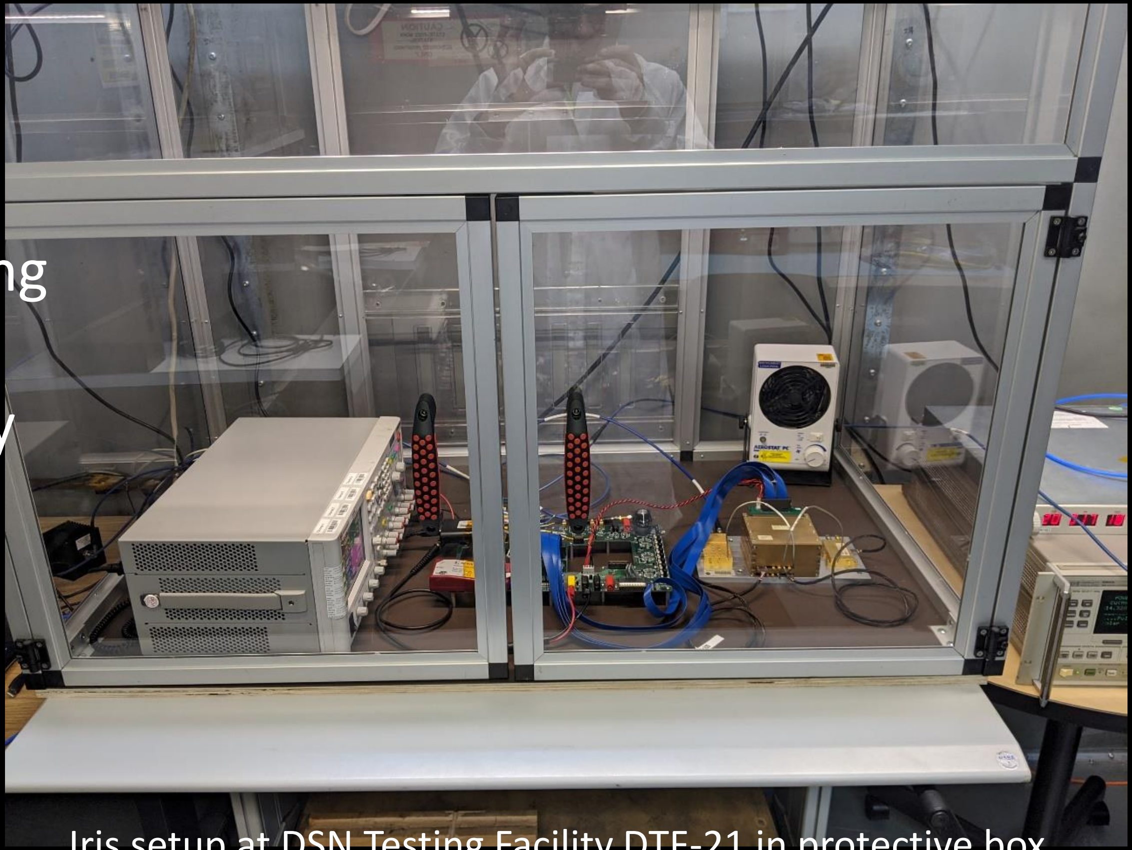
Available Modes and Some Configuration Parameters

Mode	Receiver	Transmitter	Ranging	DDOR	Coherency
X-Band Receive-Only	LNA, 62.5 bps, PCM/PSK/PM 16 kHz sine	--	--	--	--
X-Band Transmit-Only	--	SSPA, 62.5 bps, PCM/BPSK/PM 25 kHz square	*Off*	*Off*	*Off*
X-Band Transmit/Receive	LNA, 62.5 bps, PCM/PSK/PM 16 kHz sine	SSPA, 62.5 bps, PCM/BPSK/PM 25 kHz square	*Off*	*Off*	*On*
Ranging – No Data	LNA, 62.5 bps, PCM/PSK/PM 16 kHz sine	SSPA	*On*	*Off*	*On*
DDOR – No Data	--	SSPA	*Off*	*On*	*Off*
Other Modes	Additional commands may be used to configure the Iris into modes not defined above. *For example, if Ranging with Data is desired, command Iris to Tx/Rx mode, and then send a command to enable ranging.*				

Configuration Parameter	Available Settings
Uplink Data Rate	62.5, 125, 250, 500, 1000, 2000, 4000, 8000 bps
Downlink Data Rate	62.5, 125, 250, 500, 1000, 2000, 4000, 8000, 16000, 32000, 64000, 128000, 256000 bps
Downlink Data Encoding	Turbo 1/2, Turbo 1/3, Turbo 1/6
AOS Frame Length	8920 or 1784 bits
Exciter Mod Index	Subcarrier: 0 to 138 degrees Direct carrier: 0 to 135 degrees
Other parameters include subcarrier frequency, coherency, antenna selection, etc.	

Overview of Iris V 2.2 Features

- Over-the-Air Programmability
- PN Delta DOR
- PN Regenerative Ranging
- SCID Filter Functionality
- High Rate Uplink
- High Rate Downlink
- QPSK



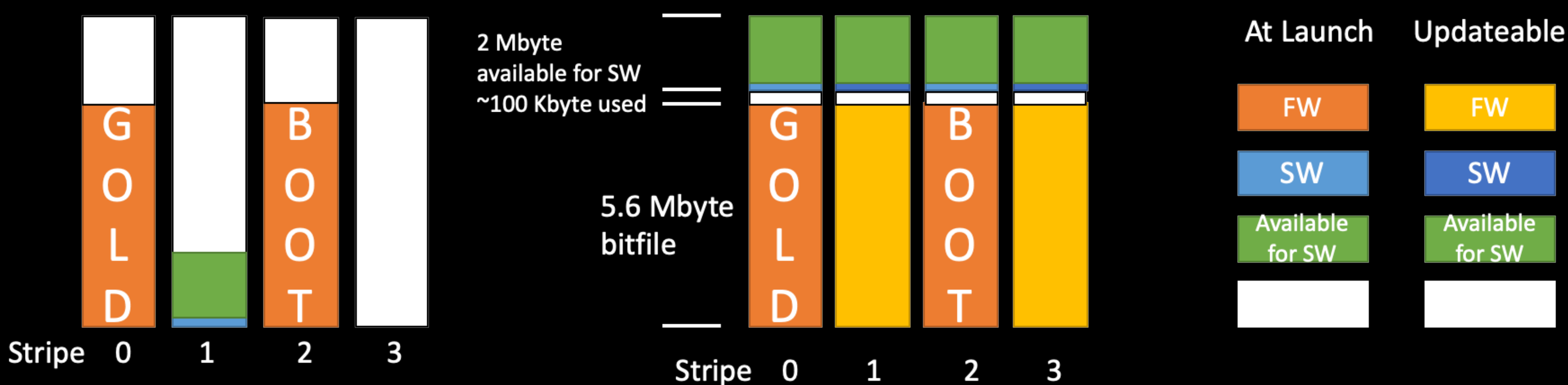
Iris setup at DSN Testing Facility DTF-21 in protective box (January 2020)

Missions that are interested in updating from V 2.1 to V 2.2 need to update the new FW/SW on the ground in order to have the Over-the-Air Programmability capability built-in.

Over The Air Update (OTAU) Summary

- OTAU Process Demonstrated – Driven by C&DH
  - Upload new image (via Iris) to C&DH
    - Iris never holds the complete image except in flash due to memory limitations
  - Erase Target Flash Stripe 1 or 3
  - Move image from C&DH to target stripe over SPI
  - Checksum image on stripe
  - Warm boot to target stripe
    - Iris always cold boots to stripe 2
    - Iris always falls back to stripe 0 on any boot failure

Artemis-1 Delivered | With OTAU

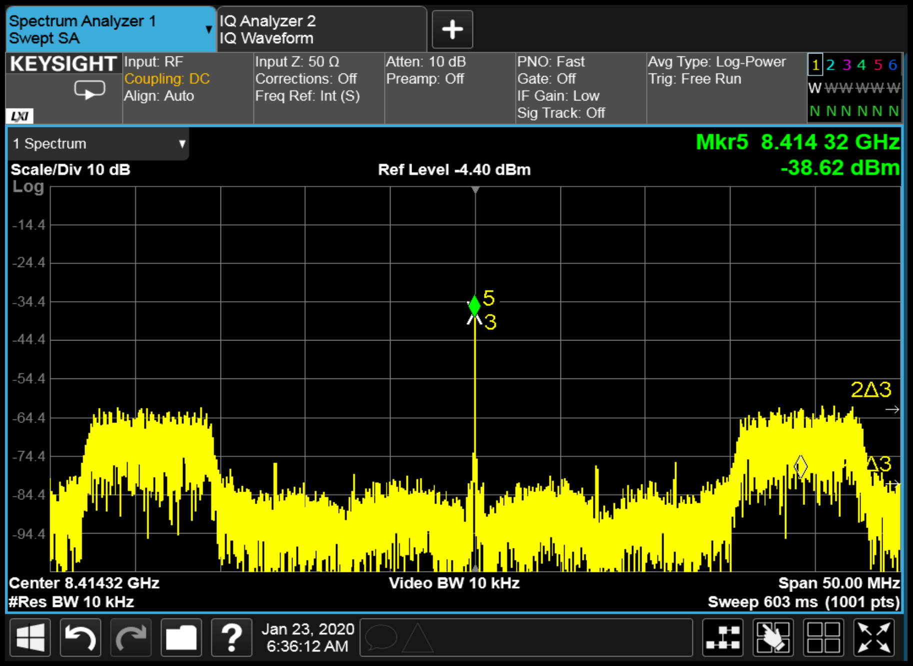


Missions that are interested in updating from V 2.1 to V 2.2 need to update the new FW/SW on the ground in order to have the Over-the-Air Programmability capability built-in.

Pseudo-Noise (PN) Delta DOR[1] Tests

- Improve ΔDOR measurement accuracy by replacing sinusoidal tones with a spread spectrum signal.
- Improved ΔDOR accuracy is needed for missions with tight targeting requirements such as Mars sample return missions and deep space manned missions.
- PN Delta DOR transmissions with the three different Gold Code were captured by Open Loop Recording (OLR) in DTF-21 and found to be working as intended in post processing.

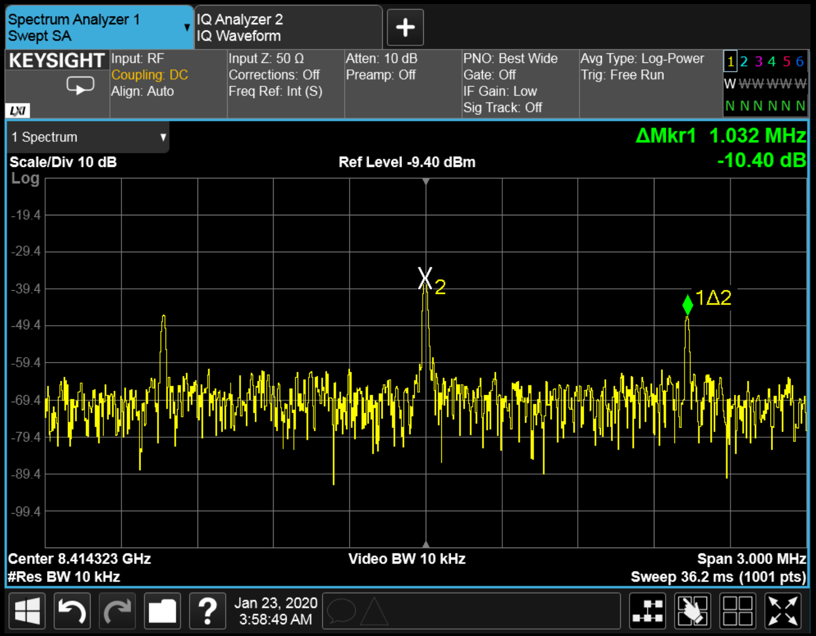
[1] Z. Towfic, C. Volk, J. Border, T. Voss, and M. Shihabi, "Improved Signals for Differential One-way Range," IEEE Aerospace and Electronics Systems Magazine, Volume 35, Issue 3, pp 70-79, March 2020.



PN DDOR spectrum

PN Regenerative Ranging[2]

- The ability to do ranging while also doing telecom.
- More efficient in the use of link power than is the current approach, nonregenerative ranging
- Primary advantage over classical sequential ranging is orders of magnitude improvement in ranging SNR threshold.
- The New Horizons mission to Pluto with extremely large propagation loss, and the BepiColombo mission with ultra-high navigation precision requirements had to use regenerative ranging
- The improved ranging SNR can also equate to system trades for reduced transmit power, reduced ranging modulation index, or smaller antenna aperture, all of which are of prime interest to SmallSats.

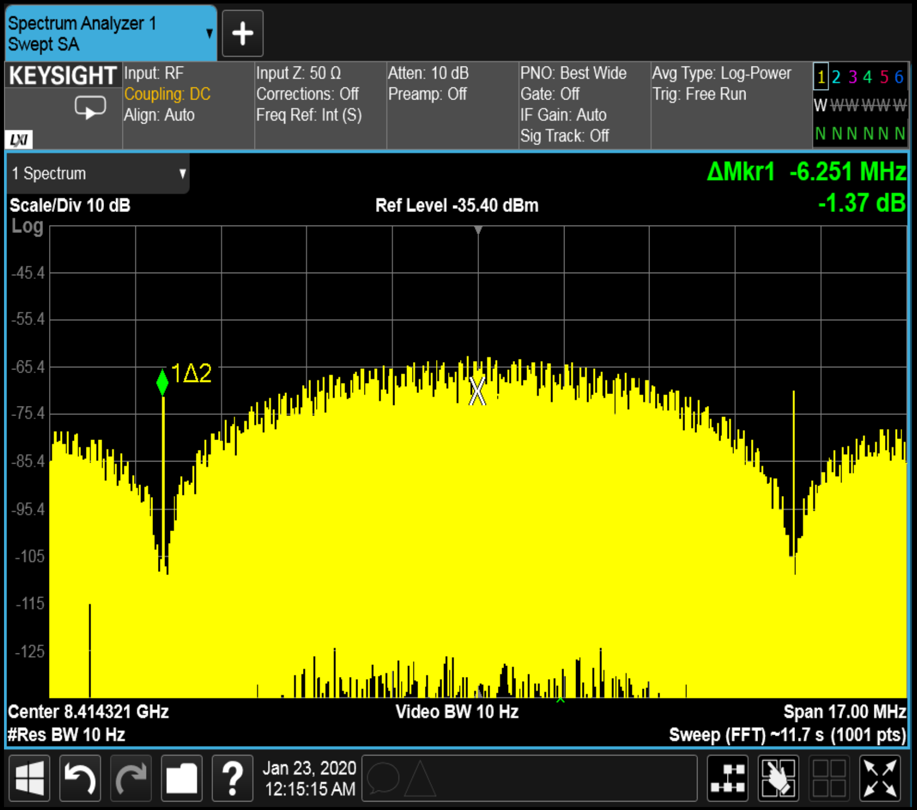


Regenerative Ranging spectrum (DTF-21)

[2] K. Angkasa et al., "Regenerative Ranging for JPL Software-Defined Radios", IEEE Aerospace and Electronic Systems Magazine, Volume 34, Issue 9, pp 46-55, September 1, 2019.

Downlink Telemetry Tests

- Verified the maximum symbol rate on Iris at 6.25 Msps for Turbo 1/2, 1/3 and 1/6.
- QPSK is working currently when coupled with convolutional code rate = ½
  - Need additional work to have QPSK working with the other coding schemes.
- Gathered the threshold data at each downlink configuration

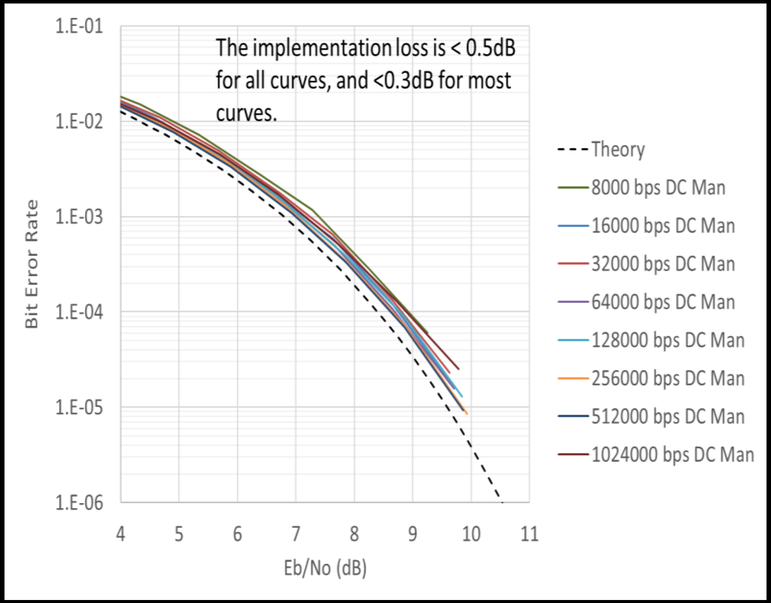


6.25 Msps spectrum

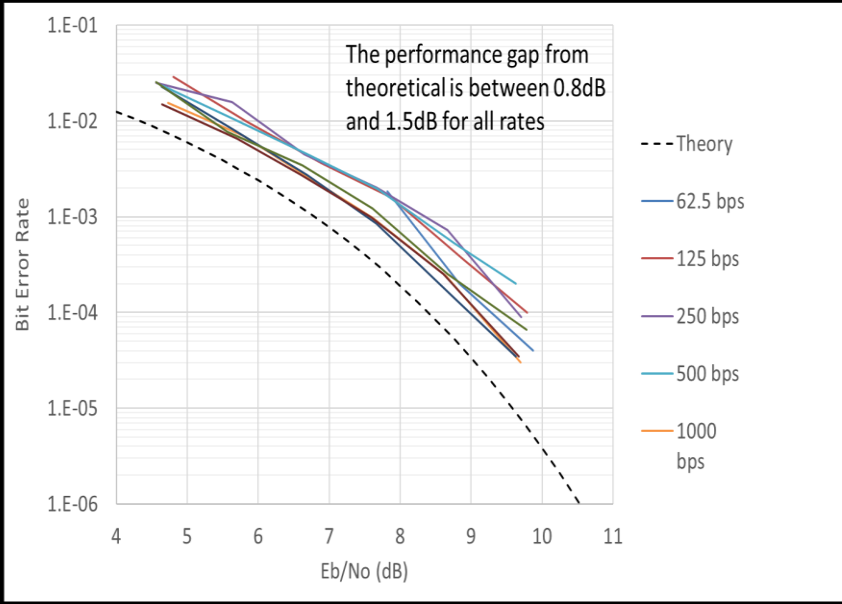
Uplink Performance

- Carrier Tracking Threshold from -146 to -155 dBm depending on LBW
- Command threshold for 62.5 bps at -141 dBm (DTF-21)
- Demonstrated up to 1 Mbps with the direct carrier mode.
- Added a spacecraft identification (SCID) Filter
  - Demonstrated at DTF-21 that when SCID filter is enabled, only the correct SCID message was received, then when disabled, both messages make it through.

Direct-Carrier Residual Carrier Mode Uplink Results

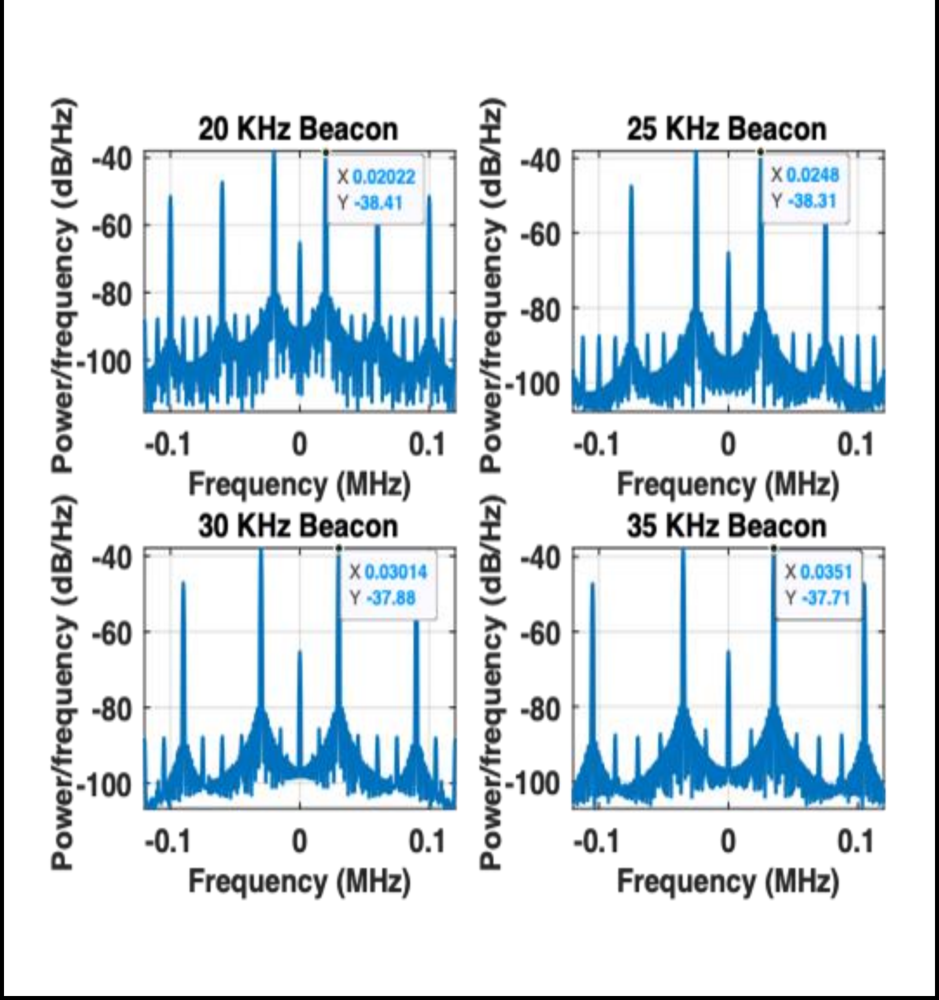


Subcarrier Mode Uplink Results



Beacon Mode

- Iris can generate Beacon Tones using pokes command
- Below are a demonstration of 4 beacons for 20, 25, 30, 35 KHz
- These are generated in the Squarewave Subcarrier Mode (and fully suppressed carrier)
- Need to convert the pokes commands into software (C&DH) commands for use in flight operation.



MarCO Mission Overview (2018)

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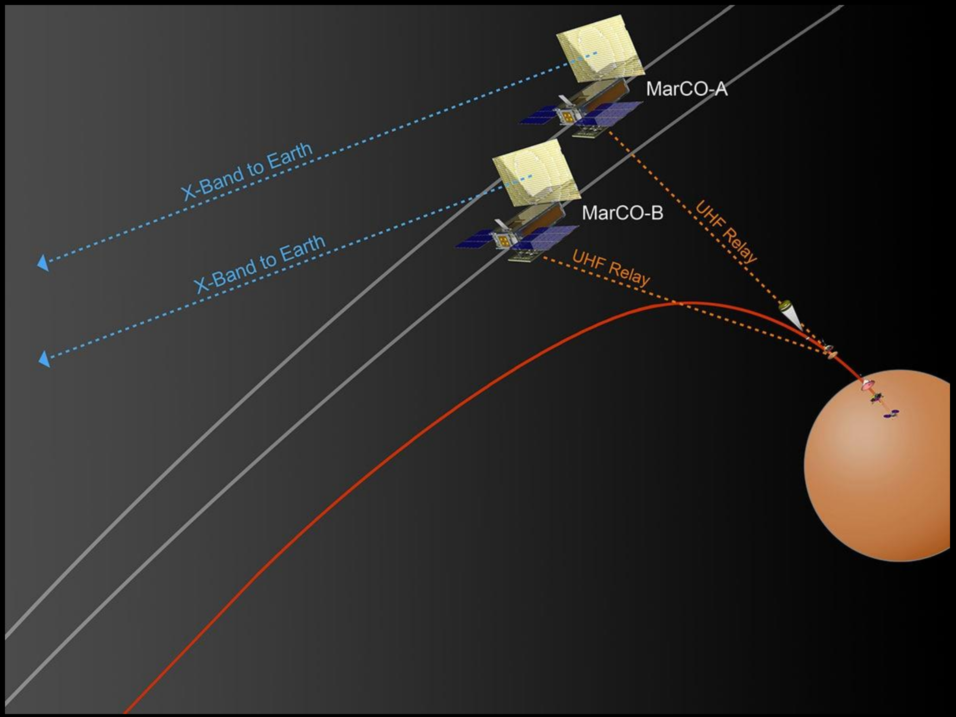
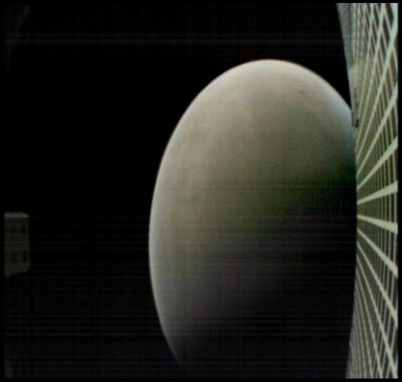
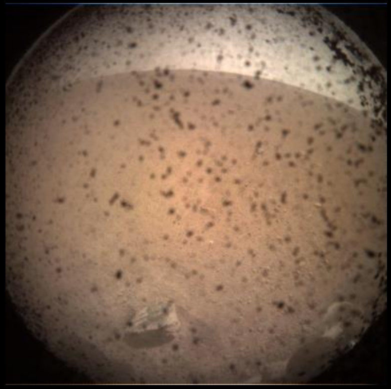
- Provided "real-time" data relay during EDL of InSight to Mars
- Bent-pipe:
  - UHF receive of EDL data
  - X-band transmit Direct-to-Earth
- Two MarCOs for redundancy
- First deep space CubeSats
- MarCOs launched with InSight but traveled independently to Mars
- Successfully completed EDL with zero data loss
- MarCO enabled quick reception of InSight's first image on Mars (on the right)
  - Also, an image of Mars & the reflect array HGA with the feed showing (on the left).

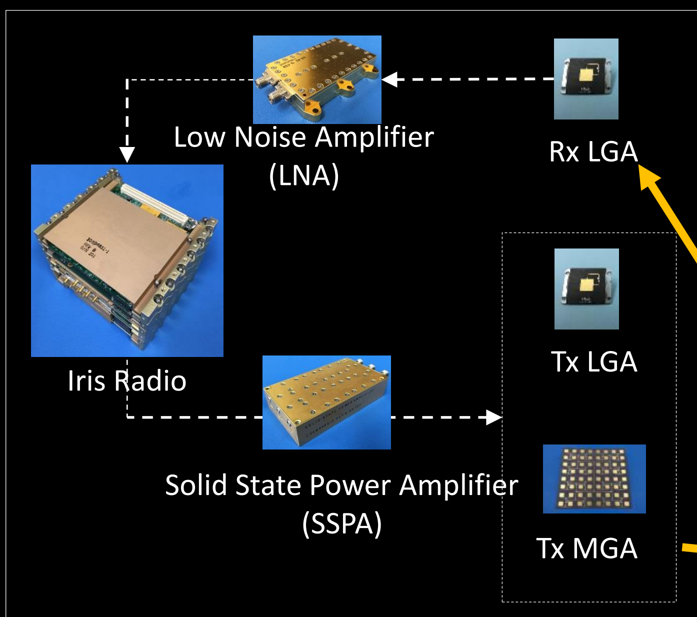






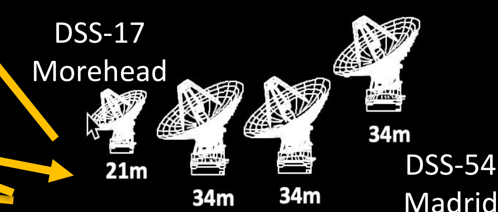
6 Artmeis-1 CubeSats Using Iris (2020~)

- 7 Artemis-1 CubeSats have baselined to use Iris for basic telecom & navigations.
  - For the 6 NASA missions, JPL managed the contract with SDL
  - ArgoMoon Iris was purchased directly by Agotec from SDL.
- They share common Telecom Hardware (Iris Radio, LNA/SSPA, Rx/Tx antennas) with different science goals & target destinations.

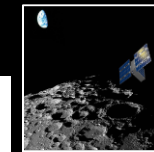


Artemis-1 CubeSat Telecom Hardware Using Iris

Mission Name	Target Destination	Max Range
LunaH-Map	Lunar	~ 1 Mkm
Lunar IceCube	Lunar	~ 1 Mkm
Lunar Flashlight	Lunar	~ 1 Mkm
CubeSat for Solar Particles	Heliocentric	~ 15 Mkm
BioSentinel	Heliocentric	~ 84 Mkm
Near Earth Asteroid Scout	Asteroid	~180 Mkm



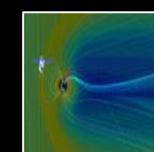
Deep Space Network (DSN)



LunaH-Map

Lunar IceCube

Lunar Flashlight



CuSP

BioSentinel

- ArgoMoon is an Italian 6U CubeSat to be injected in a high elliptic – high apogee orbit. Several Moon fly-bys and imaging of the surface will be performed.

ArgoMoon

NEA Scout

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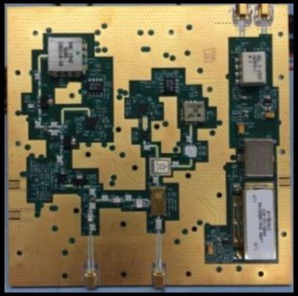
Future Considerations for Iris

- Other frequency bands (S, Ka)
- Low-Density Parity-Check (LDCP) code
  - More efficient on relatively large code rates (e.g. 3/4, 5/6, 7/8) than Turbo codes
- Reliable space-link protocols for relay functionality (CCSDS Prox-1 protocol)
- Delay/Disruption Tolerant Networking
- SpaceWire interface for high-rate data transfers to S/C C&DH unit
- Higher efficiency SSPA
  - Lower DC power in general

TRL-4 Ka- (and S-) Band exciter



TRL-4 UHF exciter

Backup

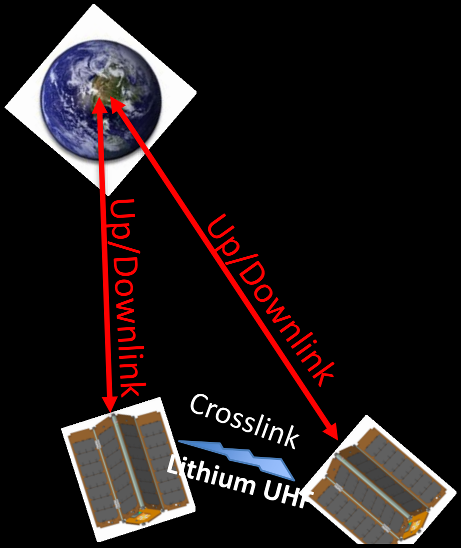
Deep-Space Missions Used/Using Iris

INSPIRE *Interplanetary Nano Spacecraft Pathfinder in a Relevant Environment (2014)*

INSPIRE-A INSPIRE-B

INSPIRE Mission Concept

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



INSPIRE was funded by NASA's Planetary Science Division (PSD) as a collaboration between the Jet Propulsion Laboratory (JPL), California Polytechnic-San Luis Obispo (CalPoly), Goldstone-Apple Valley Radio Telescope (GAVRT), Massachusetts Institute of Technology (MIT), University of California – Los Angeles (UCLA), University of Michigan (UMich), and University of Texas-Austin (UTexas).

(Did not Launch; before a flight could be arranged, the goals of INSPIRE became obsolete)