Iris

CubeSat Compatible DSN Compatible Transponder

337G

Burgett, Chase, Holmes, Yarlagadda, Duncan

2019 May 23, Noon

180-101

Jet Propulsion Laboratory
California Institute of Technology

Iris (Ιρις)

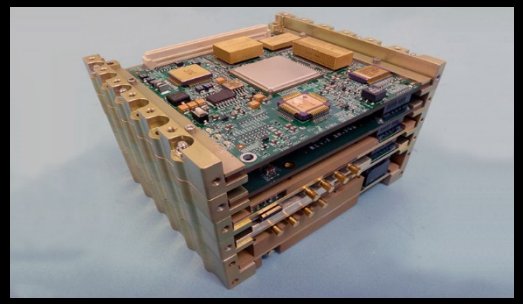
- Iris – a goddess associated with communication, messages, the rainbow and new endeavors
- “Little Sister” to Electra
- Cousin of Cassandra (Cassy)
- *Not* acronyms

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

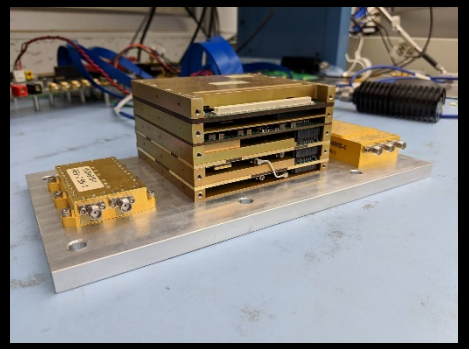
Abstract

With its sixth and final Exploration Mission One HRCR having been completed this month, we present the story arc of Iris, the JPL-developed CubeSat Compatible, Deep Space Network Compatible transponder: where it came from, where it has been, where it is, and where it is going. Iris team members from 337G, the Reprogrammable Signal Processing Group, will discuss Iris history, development, inner workings, flights, lessons learned, and future prospects.

Iris V1 (INSPIRE)



Iris V2.0 (MarCO)



Iris V2.1 (EM-1)

Team

- The authors are the 337G (Reprogrammable Signal Processing Group) members who work on Iris
- This photo of a recent “EM1 Iris Radio Team Bonus Award” pictures less than half of those involved just in this Iris iteration who are, in turn, less than half of those involved over the last half decade
- Leads have been: Amy Smith, Don Heyer, Mike Kobayashi, Tatyana Dobreva, Kris Angkasa, Lauren McNally, and Jim Lux

Iris Origins to V1

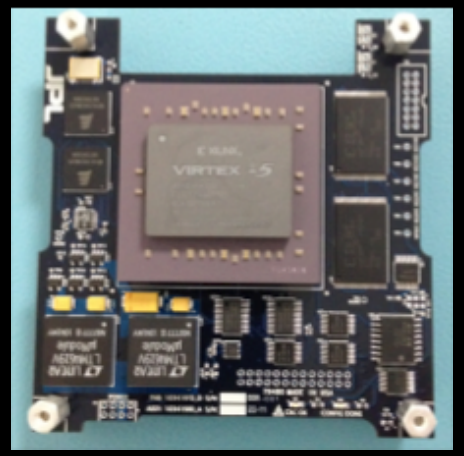
C. Duncan

Iris- CubeSat Compatible, DSN Compatible Transponder

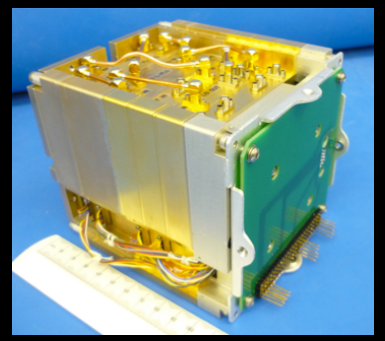
— the way it was initially marketed

- Iris = COVE + LMRST (think “V0”)
  - CubeSat Onboard Validation Experiment
  - Low Mass Radio Science Transponder
  - $1M -> INSPIRE
- UST / Electra Modems - MTIF FW
- Iris V1
  - Marina Board – COVE with Ports
  - New exciter / receiver / PSB
  - Passed DTF-21
  - Overheated in first EM TV
  - Redesigned for thermal -> V2

Historical Note:
LMRST-Sat was **first** (2007-2012)
Duncan JPL / Cutler *Stanford*
& Bill Folkner
Key Start Team: Nysoor, Dennis
then (2013-2015)
Duncan JPL / Kalman *Pumpkin-Stanford*
Key End Team: Aguirre, Lewis, Tripp, Chase



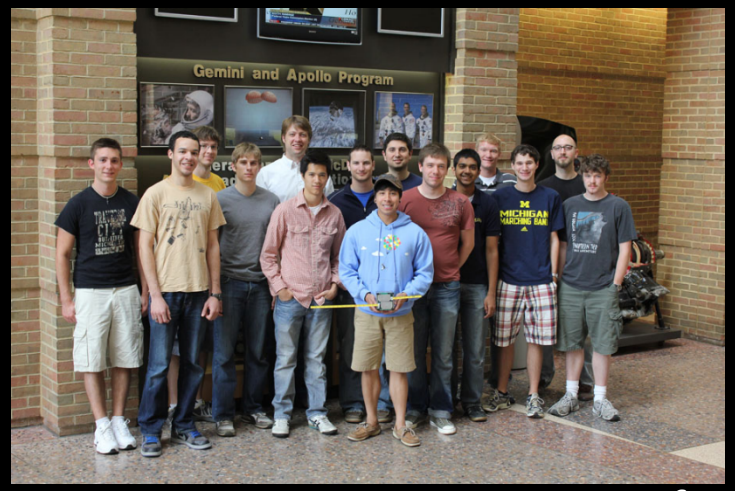
COVE Board – Rad Hard Virtex 5



LMRST
1.1 U version of
Radio Science Transponder Instrument (RSTI)

JPL COVE Team

U Michigan MCube Team



INSPIRE will be the ***world's first deep-space CubeSats***

(SolWise warmed over)

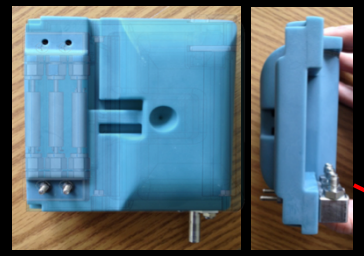
CubeSat Overview:
Volume: 3U (10x10x30cm)
Mass: 3.8 kg
Power Generation: 20 W
Data Rate: 62-64000 bps

Software:
Developed in-house

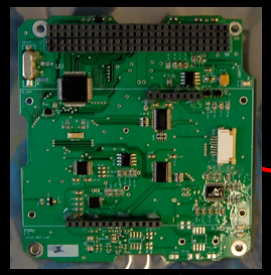
I&T:
In-house S/C I&T, CalPoly P-Pod/Launch Integration

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

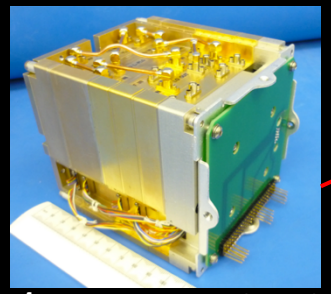
S/C components will provide ***the basis for future high-capability, lower-cost-risk missions*** beyond Earth expanding and ***providing JPL leadership in an emergent domain***



Cold-Gas ACS (U. Texas)



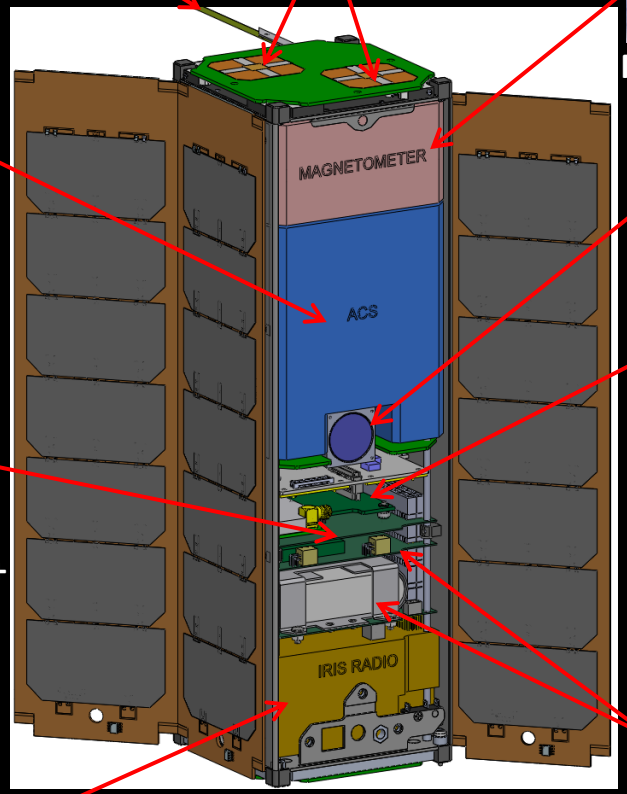
C&DH + Watchdog Board + Lithium UHF (U. Michigan)



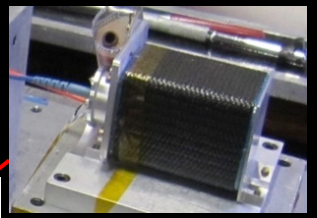
Nav/Comm X-Band Radio (JPL)

UHF Antenna

X-Band Patch Antennas (JPL) [two sets]



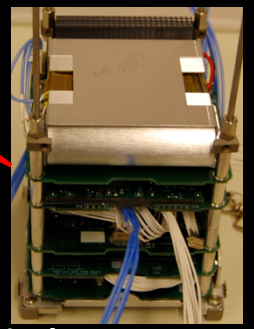
Solar Panels + Structure (Pumpkin)



Magnetometer (JPL)

Star Tracker (Blue Canyon)

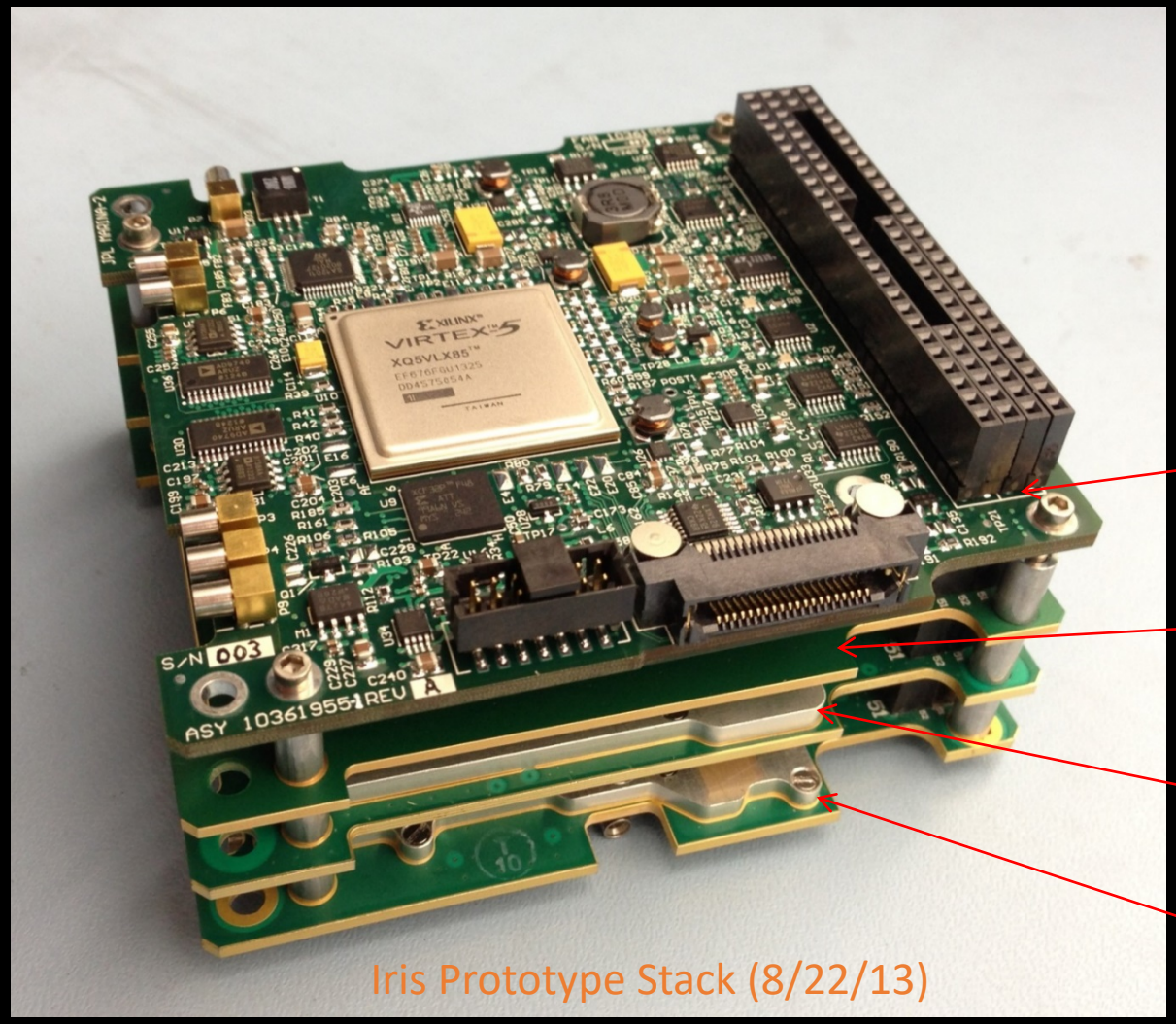
Processing Board (CalPoly)



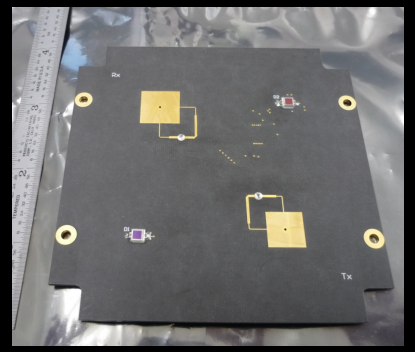
Electrical Power System + Battery Board (U. Michigan)

Iris V1 Description

Stack of Boards
CubeSat Paradigm
End-to-End solution



Iris Prototype Stack (8/22/13)



Antenna Board (x2)

- RX/TX antenna patch
- Sun sensor circuit
- One on each end of the S/C

Marina-2 FPGA
Modem Processor
Virtex 5

Power Supply Board

X-Band Receiver

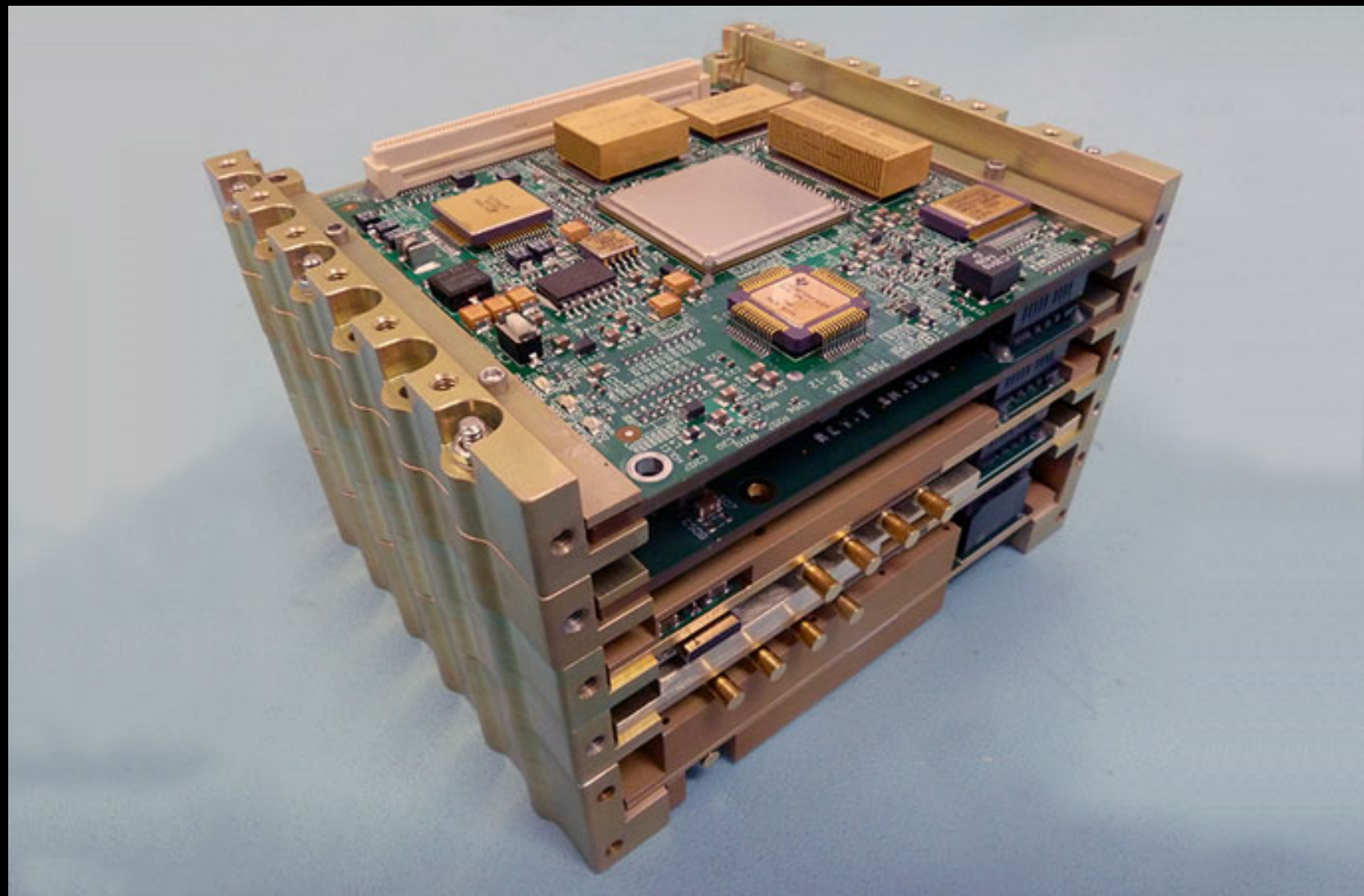
X-Band Exciter 23 dBm

Iris V2.0 MarCO

S. Holmes

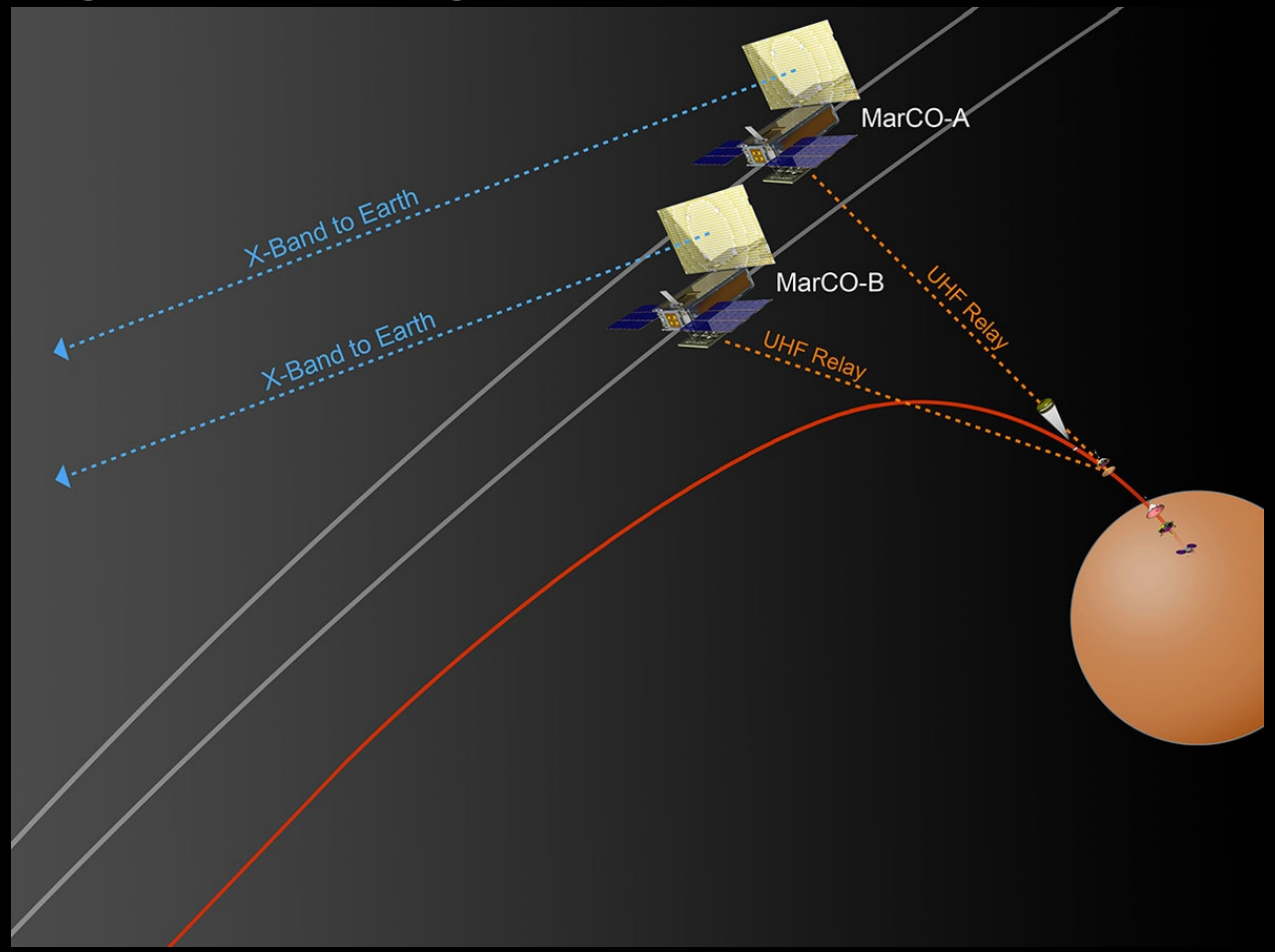
MarCO Iris (V2.0)

- 0.77U, 1.2kg, 35W (Tx/Rx), 4W RF output
- Five slices:
  - Digital
  - Power
  - X-Band Exciter
  - X-Band Receiver
  - UHF Receiver
- 15-month initial development cycle



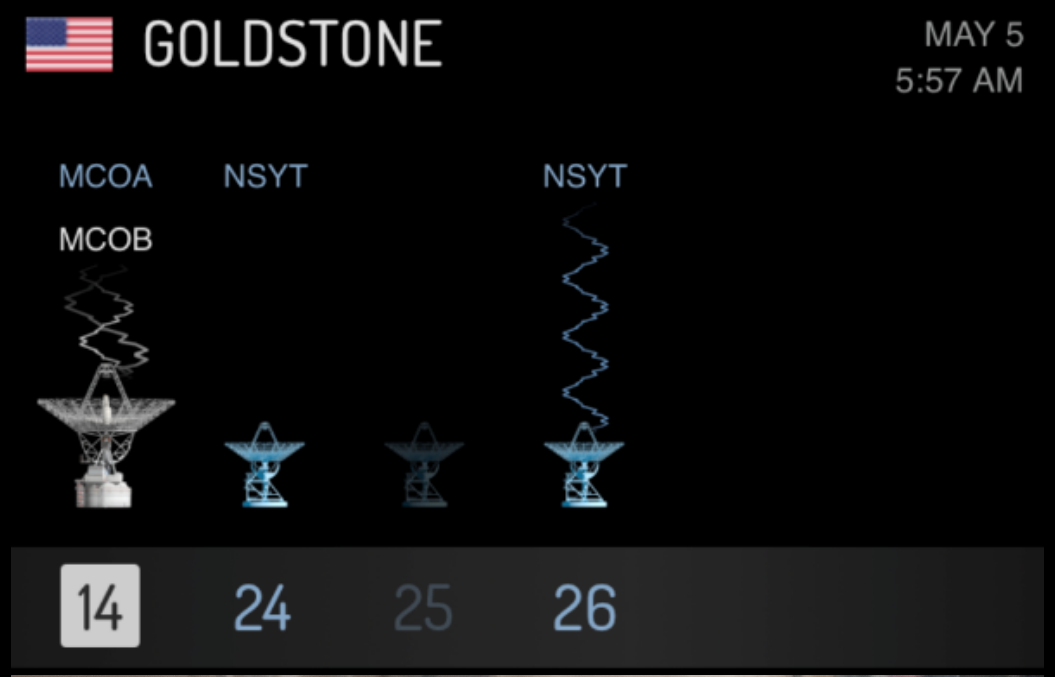
MarCO Mission Overview

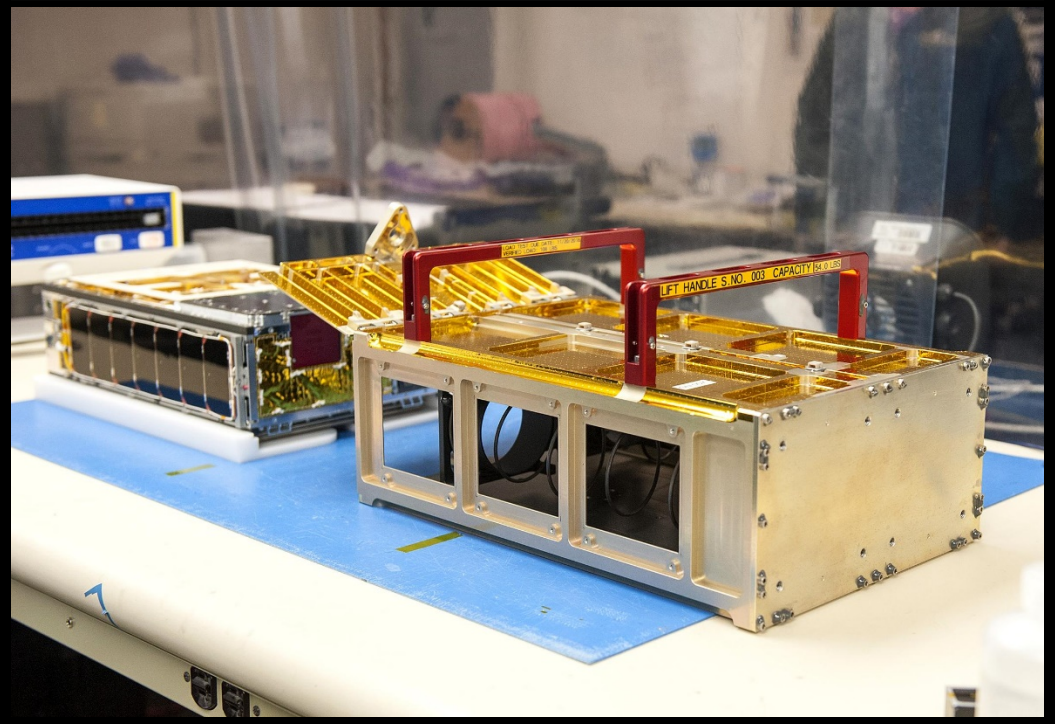
- Provide “real-time” data relay during EDL of InSight to Mars
- Bent-pipe:
  - UHF receive of EDL data
  - X-band transmit Direct-to-Earth
- Two MarCOs for redundancy
- Tech demo – InSight’s success is independent of MarCO’s success
- First deep space CubeSats
- MarCOs launch with InSight but travel independently to Mars



Activities on Launch Day

- May 5, 2018, from Vandenberg AFB
- MarCOs deployed after InSight
- First Contact:
  - Transponder beacons to say “I’m alive!”
  - Transmits telemetry data
  - MarCO-A: ~5:55am, 5 mins
  - MarCO-B: ~6:05am, 5 mins
  - Nominal telemetry on both SC
- Commanding performed during later pass
- Successful deployment of X-band reflectarray and UHF loop antenna



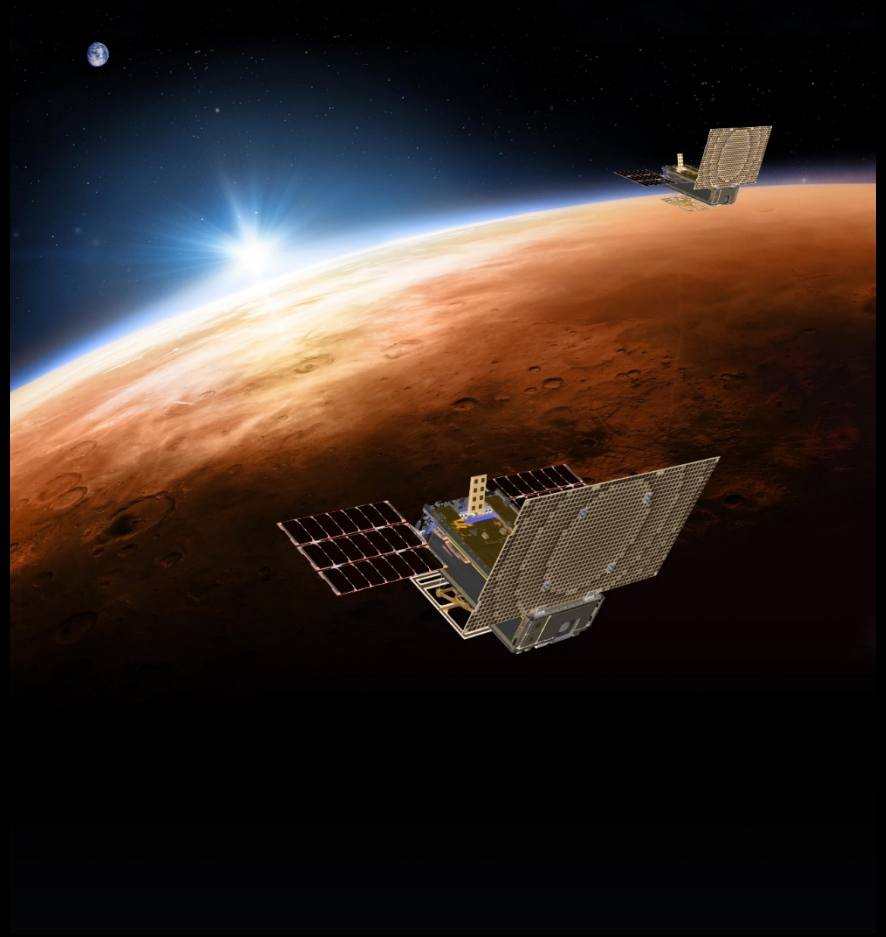


Activities During Cruise: Continuous

- Commanding (uplink data)
  - Pre-loaded command sequences in flight computer, allowing for some autonomous functionality
  - Uplinked new command sequences from ground as desired
- Telemetry (downlink data)
  - Downlinked telemetry data containing spacecraft health and status
  - Also downlinked images as available
- Navigation
  - Ranging Mode receives ranging signal (carrier tone) from ground and retransmits ranging signal back to Earth
  - DDOR Mode (delta differential one-way ranging) generates and transmits DDOR tones, which are received by multiple ground stations

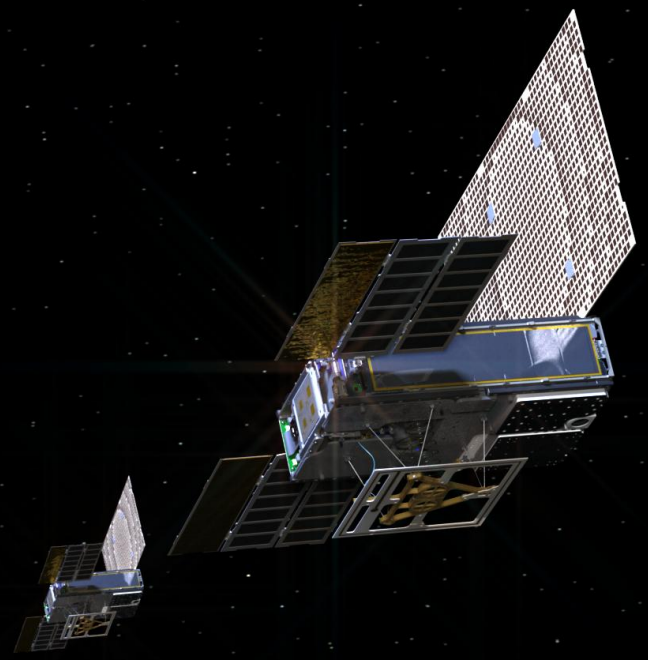
Activities During Cruise: Special Cases

- HGA characterization
  - Verification that HGA in good condition after launch (performed on both SC)
  - Point the antenna to different attitudes and measure how the receive power changes on the ground
    - Nominal boresight, then +/- 2 degrees on different axes
- In-flight test of bent-pipe (EDL) mode
  - Verification that UHF antenna in good condition after launch (performed on both SC)
  - UHF transmit from Stanford ground station (simulating InSight) to Iris,
    X-band transmit from Iris to DSN
- Receive tests with Morehead State University ground station



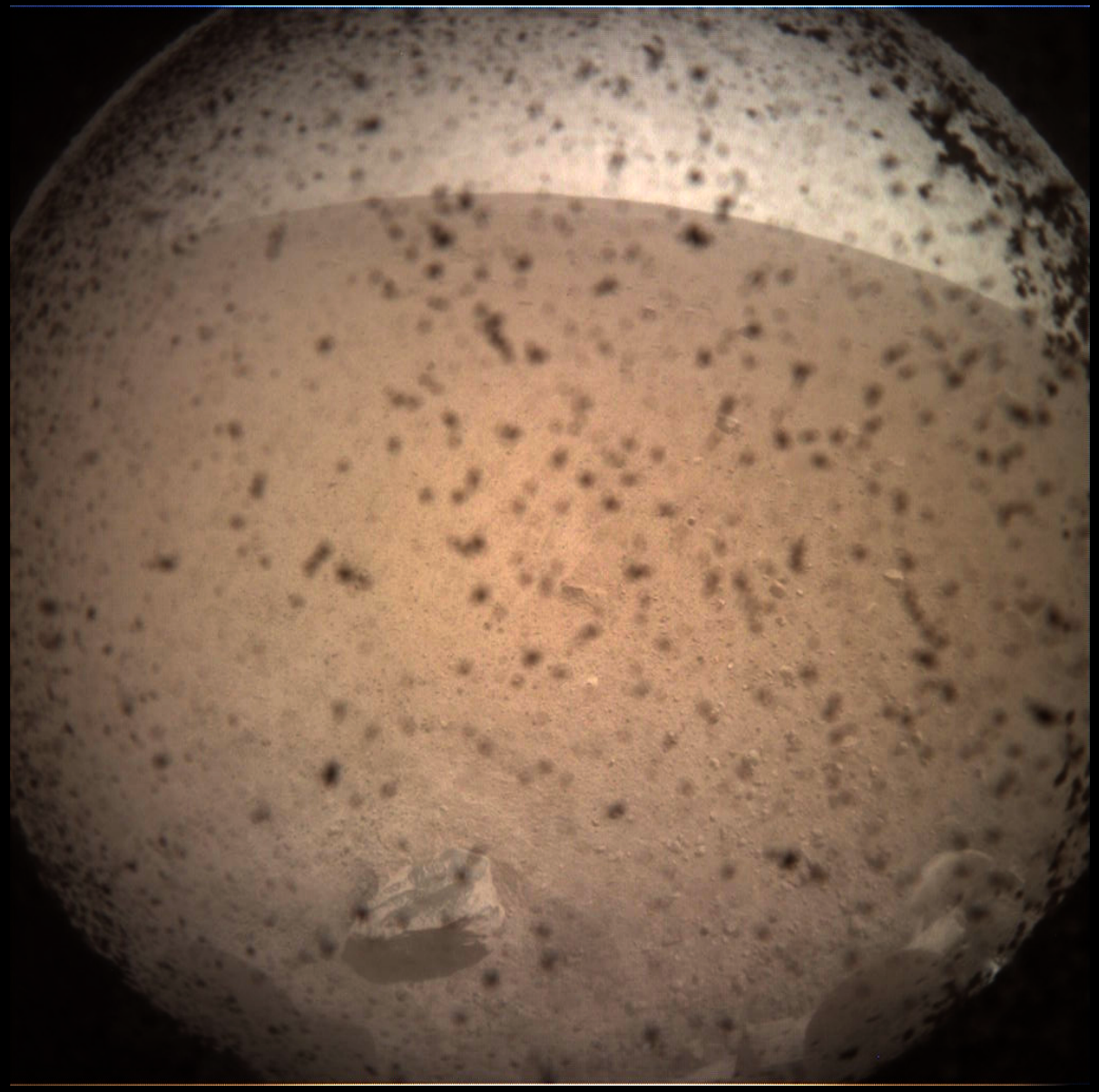
Post-Launch Updates

- Attempted many Iris configurations in flight to exercise as much functionality as possible (tech demo)
- Identified and uploaded new command sequences (did not reprogram Iris)
- Verified on MarCO Iris spare unit with Cassy GSE, and on MarCO SC testbed
- Examples:
  - Additional Data Rates
  - Tx/Rx with Ranging
  - Carrier-Only Downlink
  - Adjusting Data Arbitration

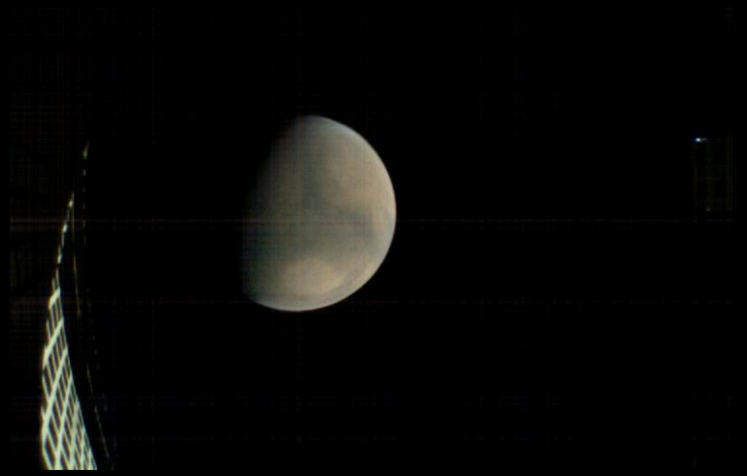


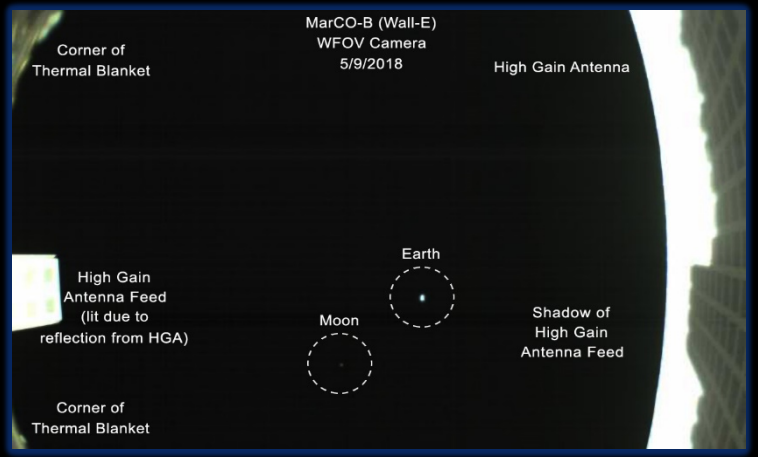
Mission Success at Mars

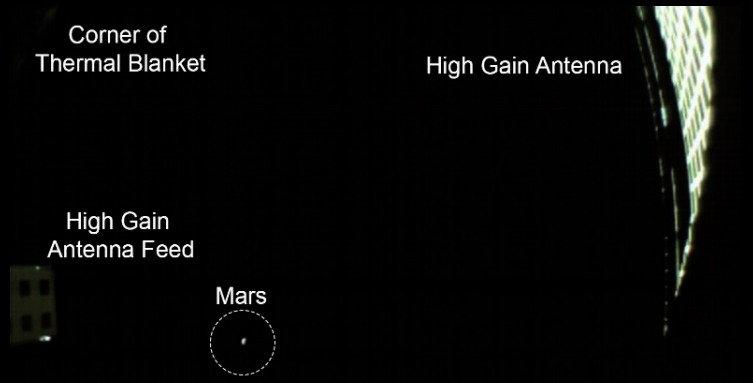
- Successfully completed EDL with zero data loss
  - Iris transmitted all data that it received
  - Each MarCO collected more data than MRO!
- Performed retransmission post-EDL
- MarCO enabled quick reception of InSight's first image on Mars
  - Utilized post-launch updates including data arbitration and rates



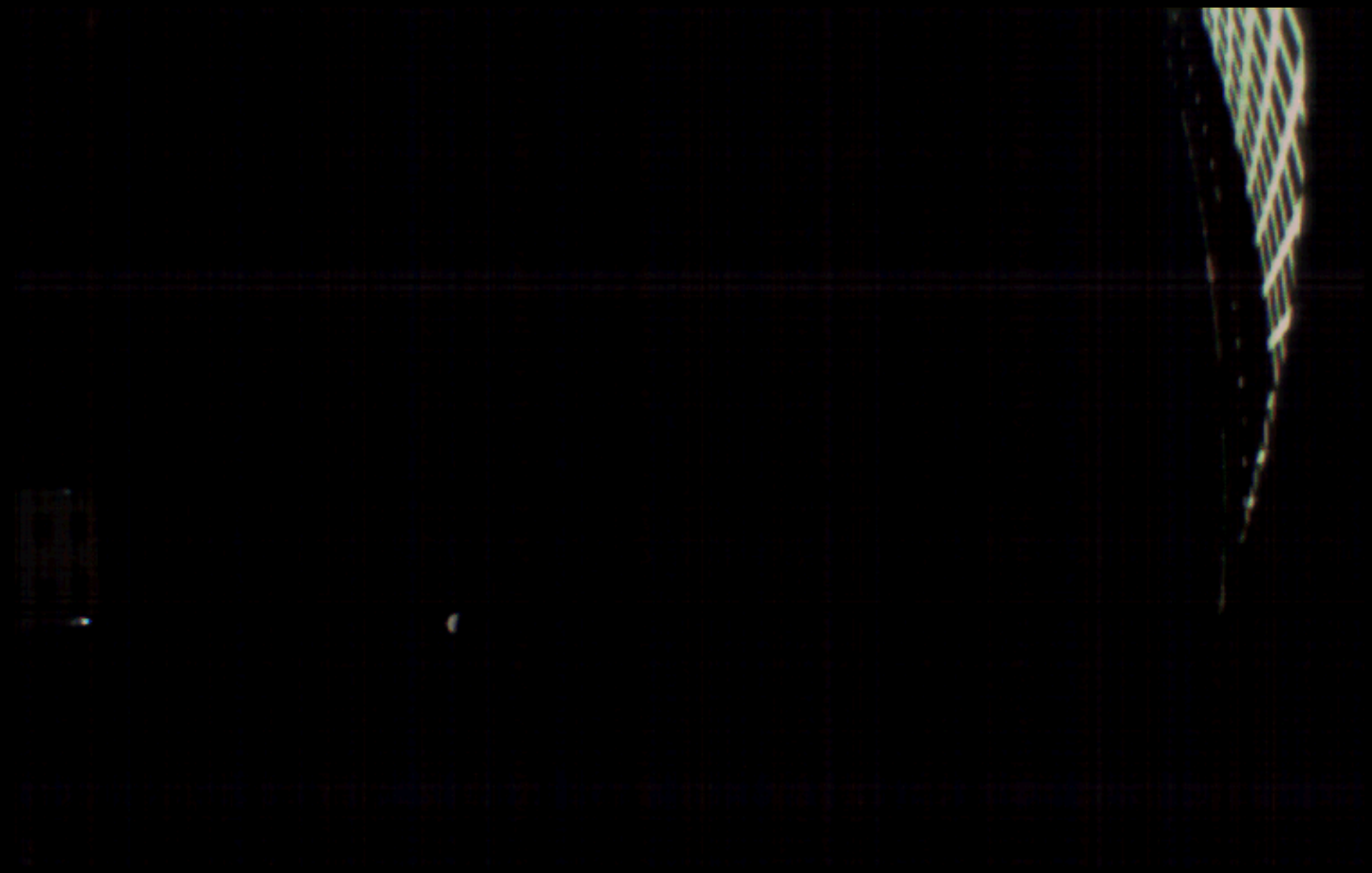
MarCO-B Images







Approach to Mars

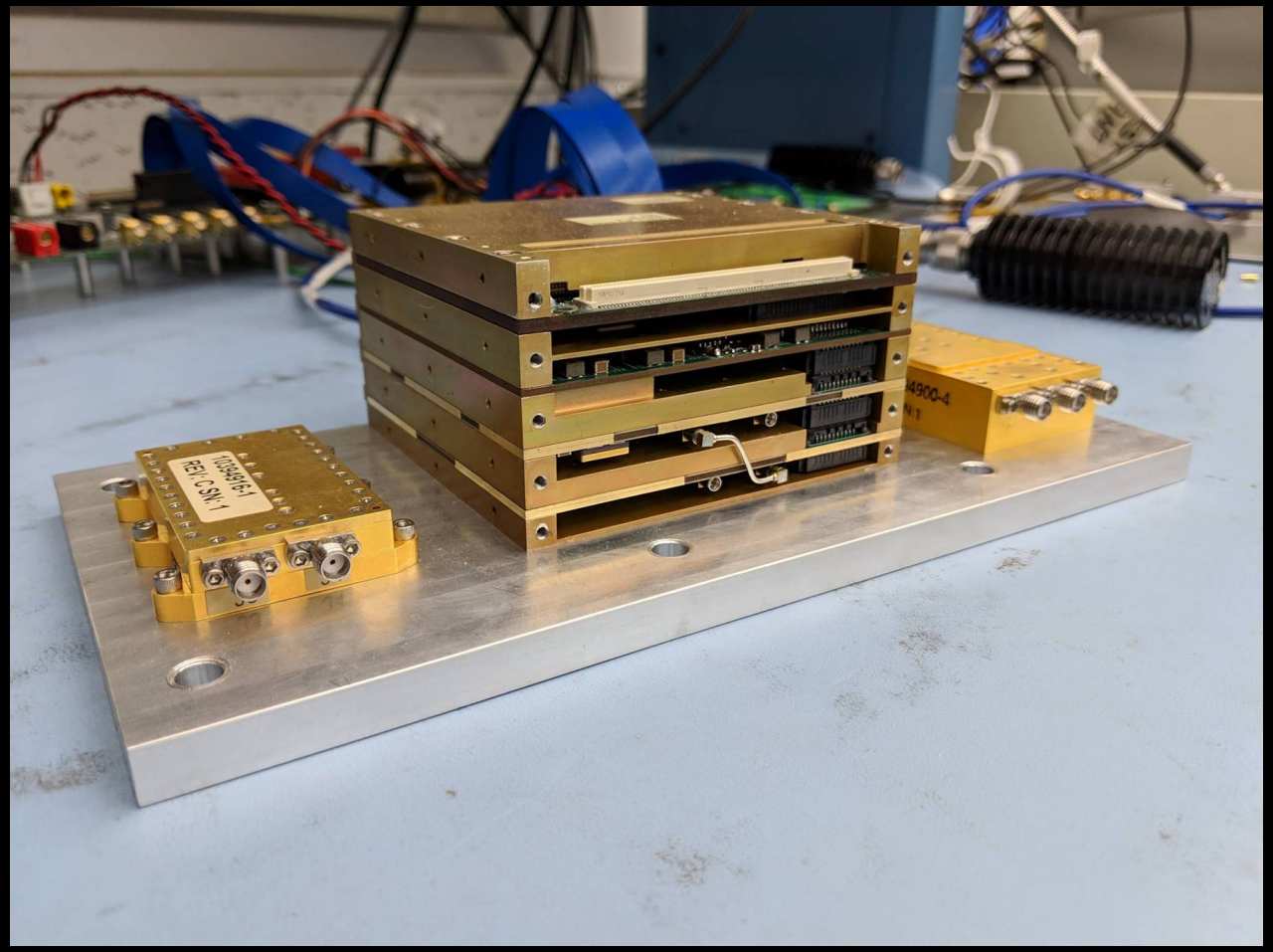


Iris V2.1 Exploration Mission One

C. Duncan

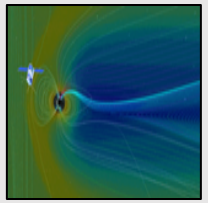
EM-1 Iris (V2.1)

- Four slices:
  - Digital
  - Power
  - Exciter
  - Receiver
- 2x LNA
- 3x SSPA

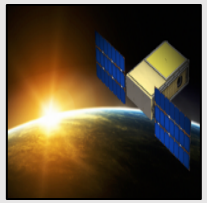


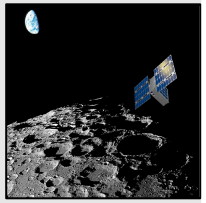
EM-1 CubeSat Missions

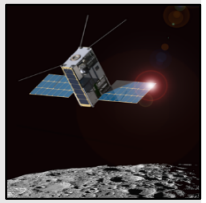
Lunar Flashlight, JPL

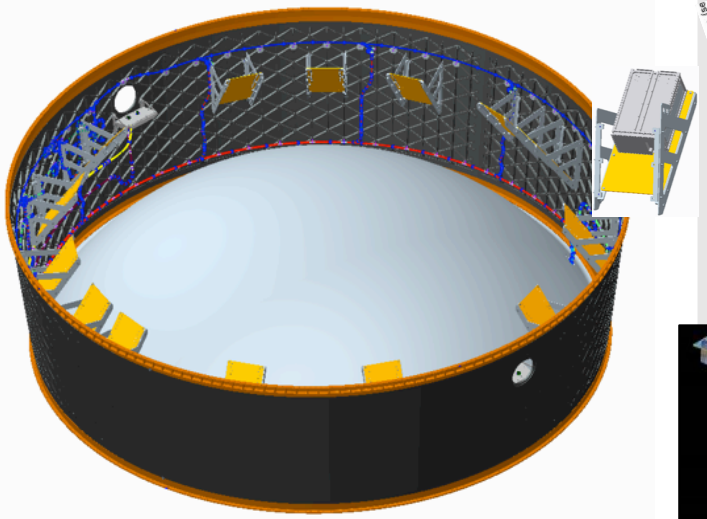

CuSP, SWRI

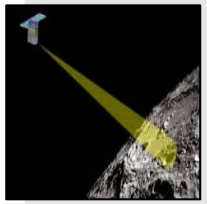
NEAS, MFSC

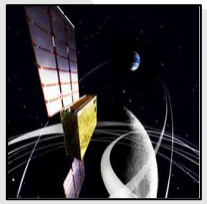

BioSentinel, AMES

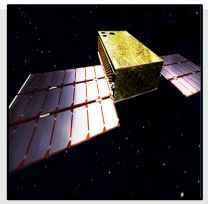

LunaH-Map, ASU


Lunar IceCube, MSU


Secondary Payload


SkyFire, LM


OMOTENASHI, JAXA


EQUULEUS, JAXA

Centennial Challenge

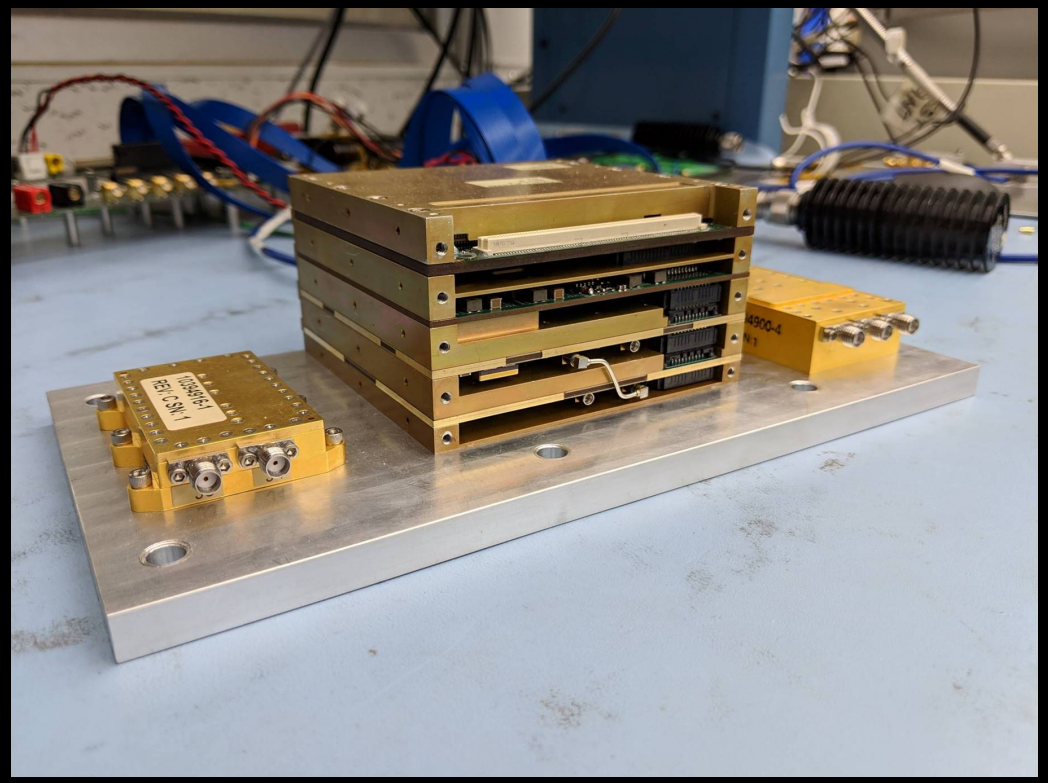
ArgoMoon, Argotec

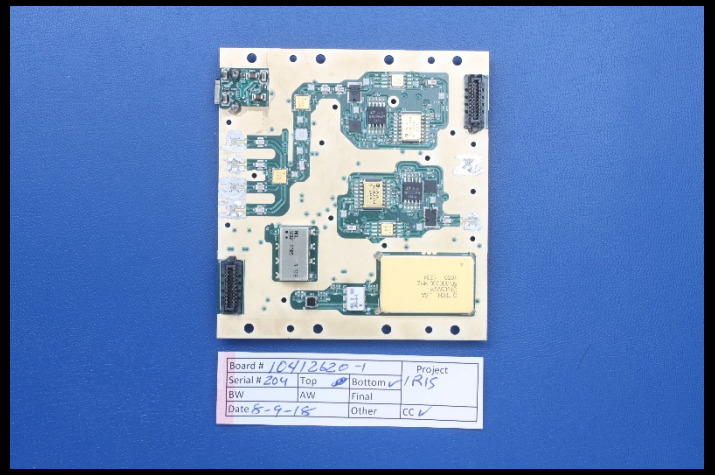
6 missions using Iris Transponder

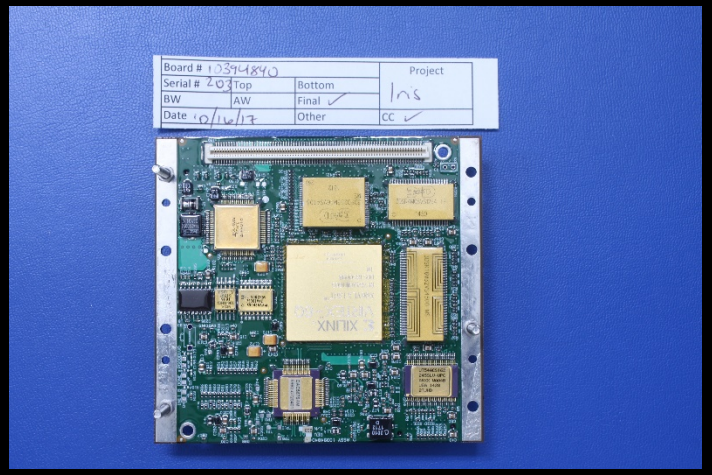
Iris Hardware

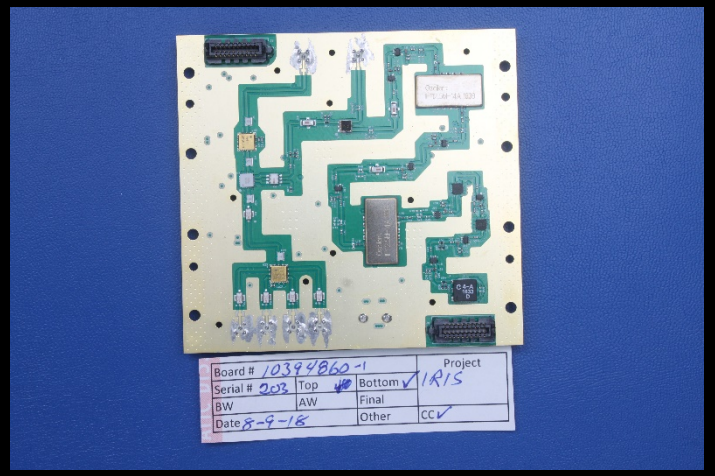
B. Burgett

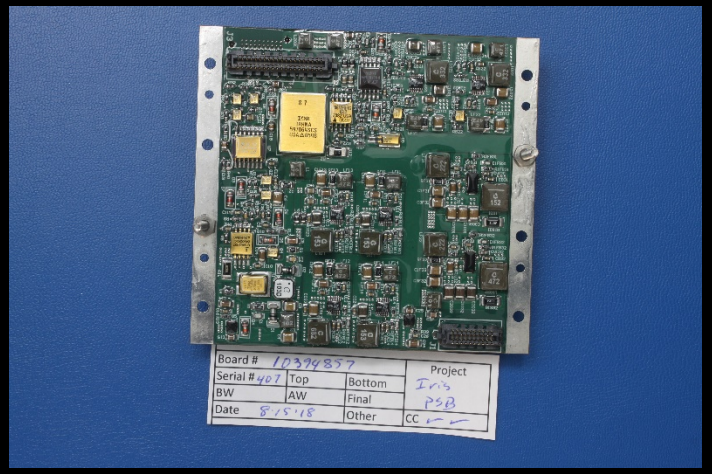
Hardware











SSPA, Transponder, LNA

Dimensions

Transponder: 100.5 x 101.0 x 56.0 mm; Mass: 858g

SSPA: 86.6 x 42.7 x 17.8 mm; Mass: 113g

LNA: 69.4 x 47.5 x 13 mm; Mass: 72g

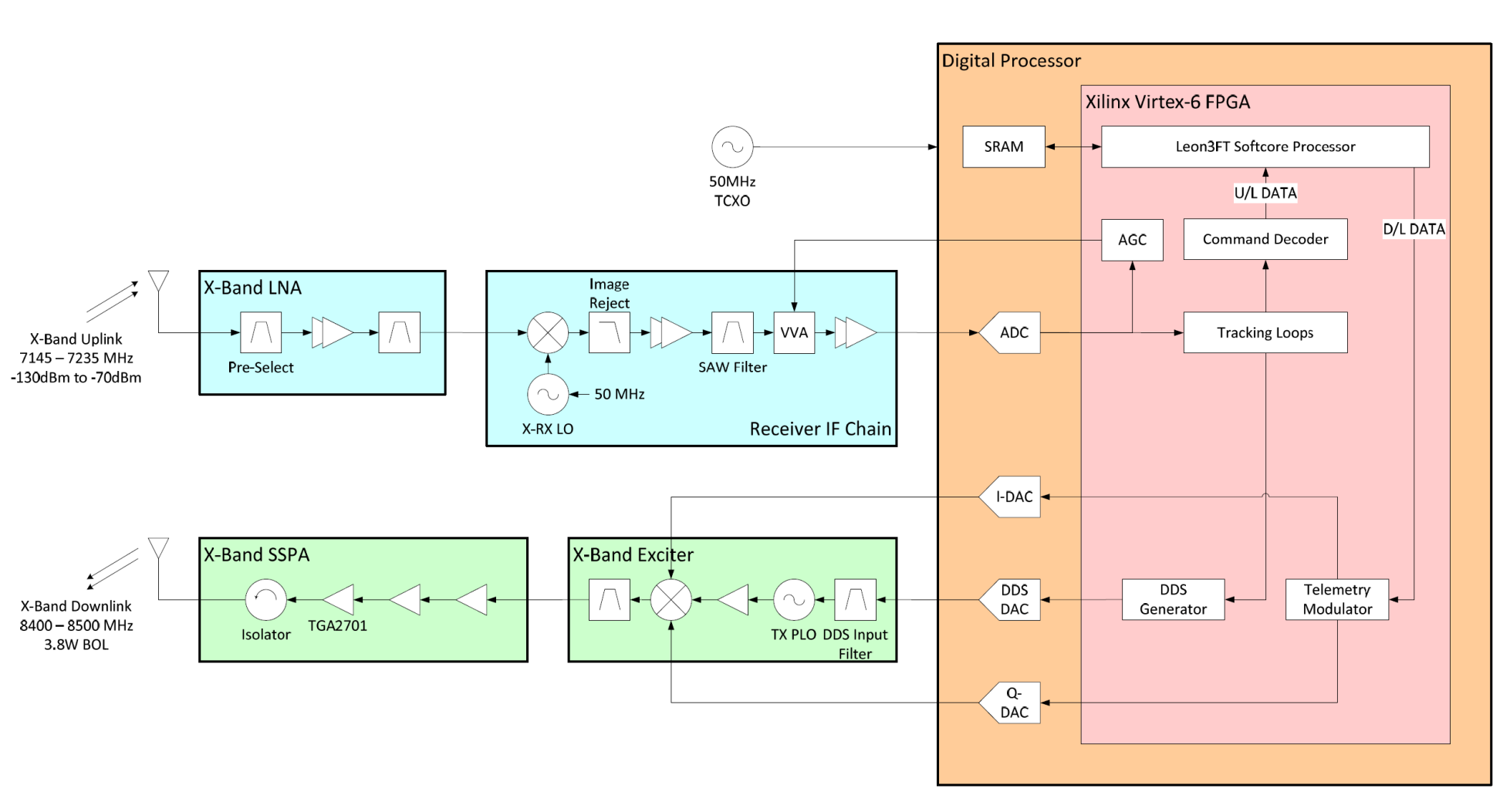
Top: Exciter

Bot: Receiver

Top: RaDiX

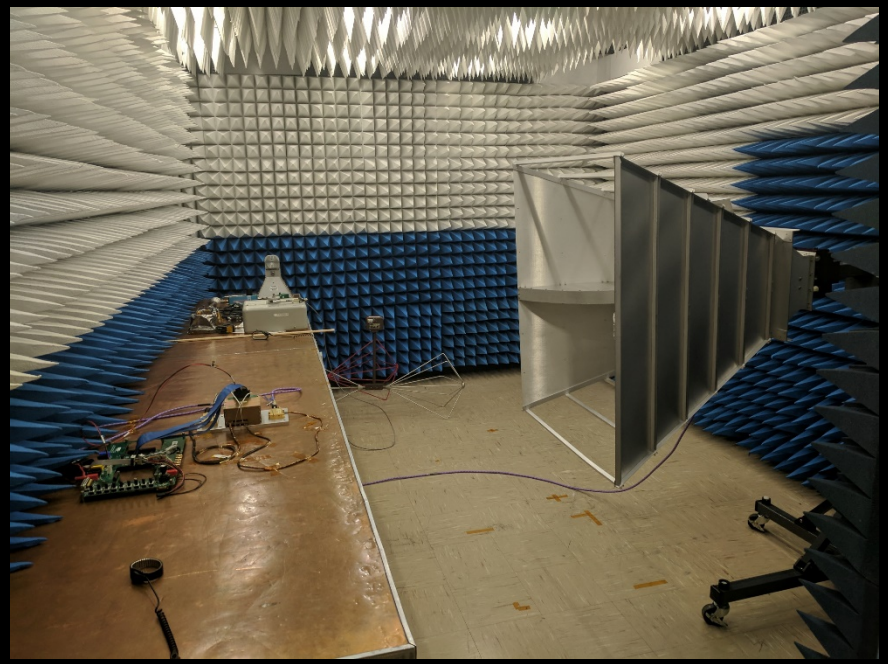
Bottom: PSB

High Level Hardware Overview



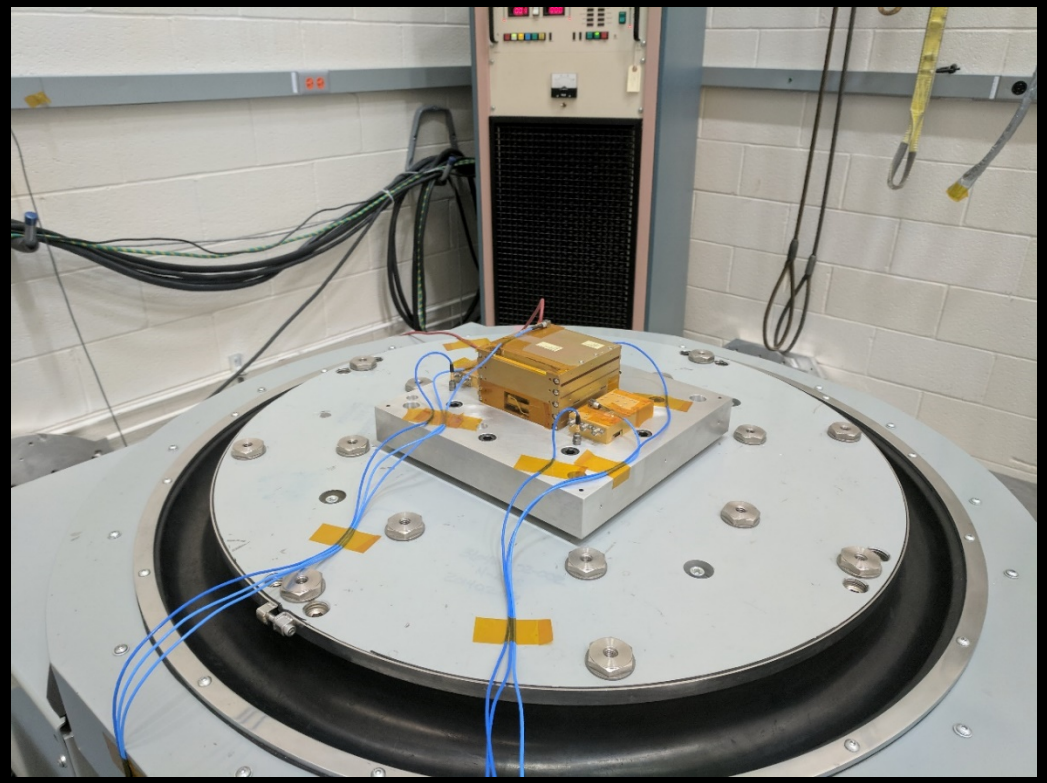
Manufacturing and Testing

- 1 EDU, 6 Flight Units manufactured and tested at Space Dynamics Laboratory
  - Take the JPL designs and fabricate the boards/chassis
  - Test and verify functionality
  - Assemble unit and perform ATP
  - Ship to JPL for final RF tests and delivery to mission
- Additional testing performed on EDU
  - Vibe testing on Iris, SSPA and LNA (SDL)
  - EMC Testing



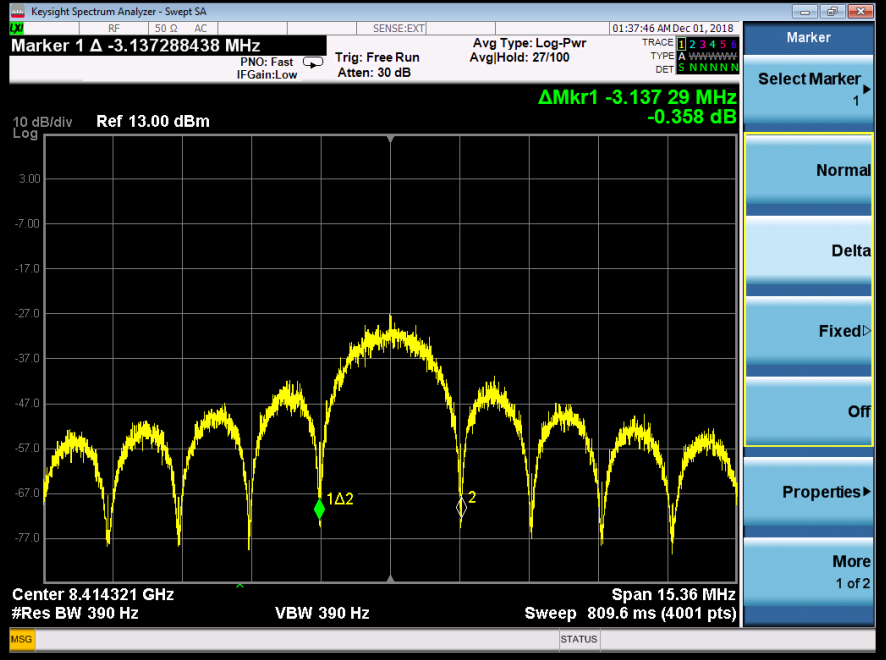
← Iris at EMC lab at JPL

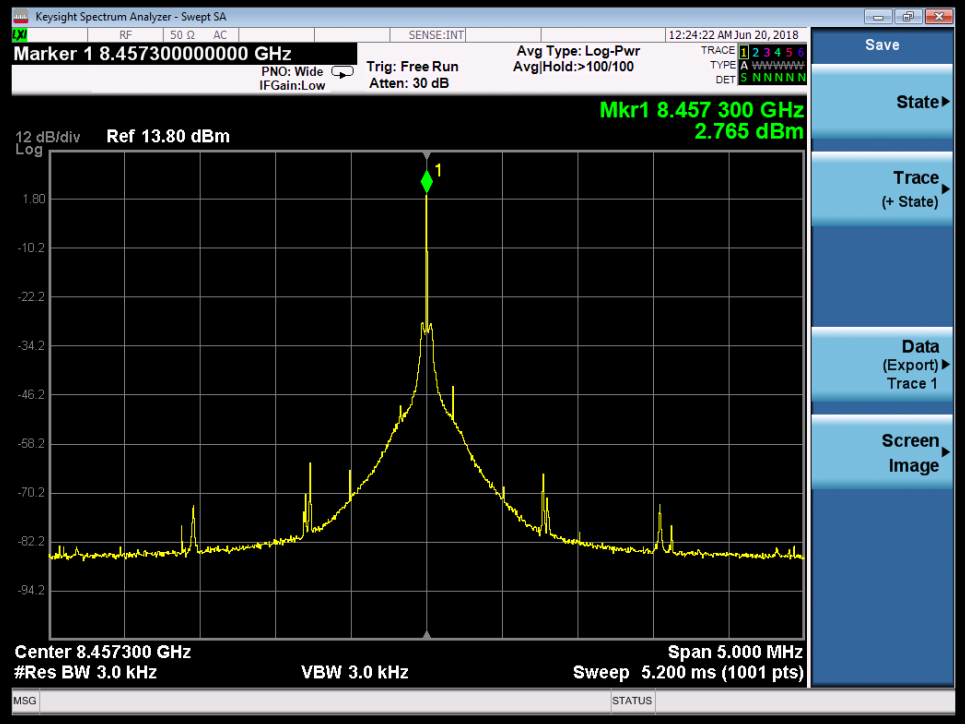
Iris at SDL on Vibe Plate →

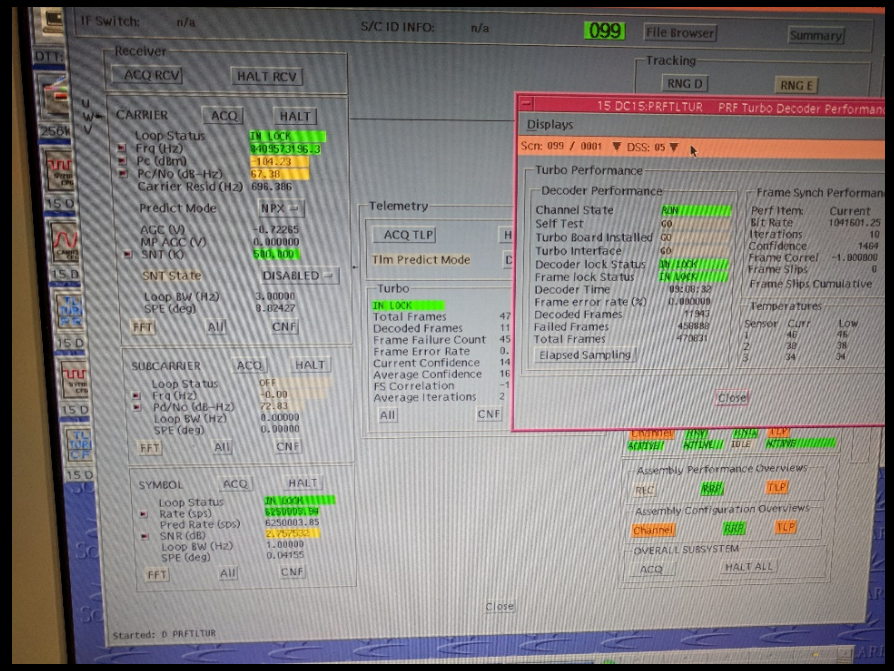


Downlink Performance

- Downlink Bit rates from 62.5 bps to 256 kbps
  - Experimentally achieved 6.25 MSps w/ BVR
- Output Power of 36 dBm
- Compatible with DSN hardware (Turbo ½, 1/3, and 1/6) at all data rates
- Phase Noise:
  - -72.7 dBc/Hz @ 1 kHz, -125.1 dBc/Hz @ 1 MHz
- Spurs/Harmonics are below -30 dBc

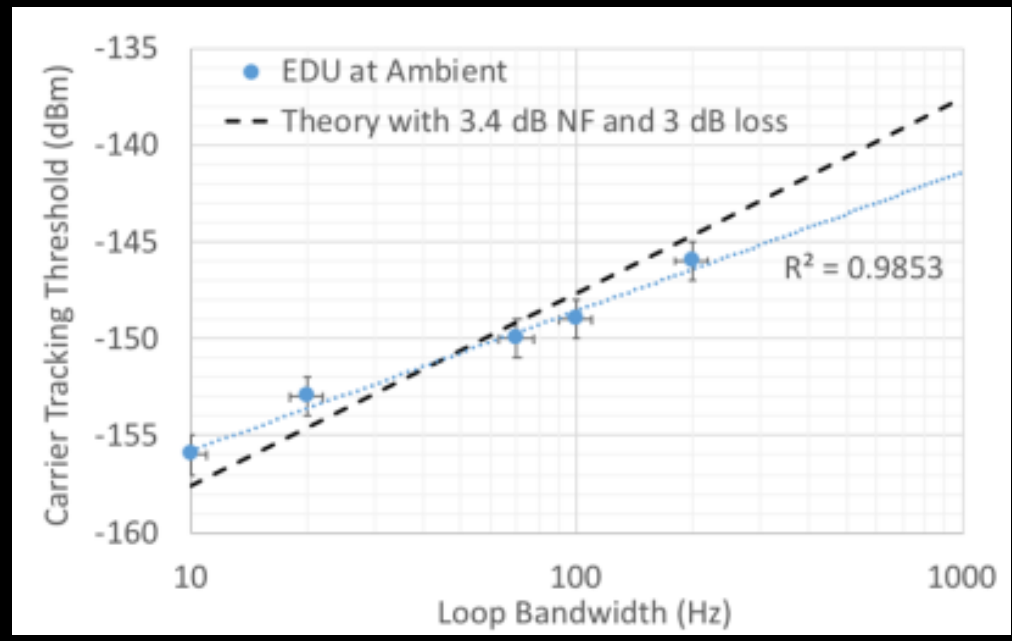


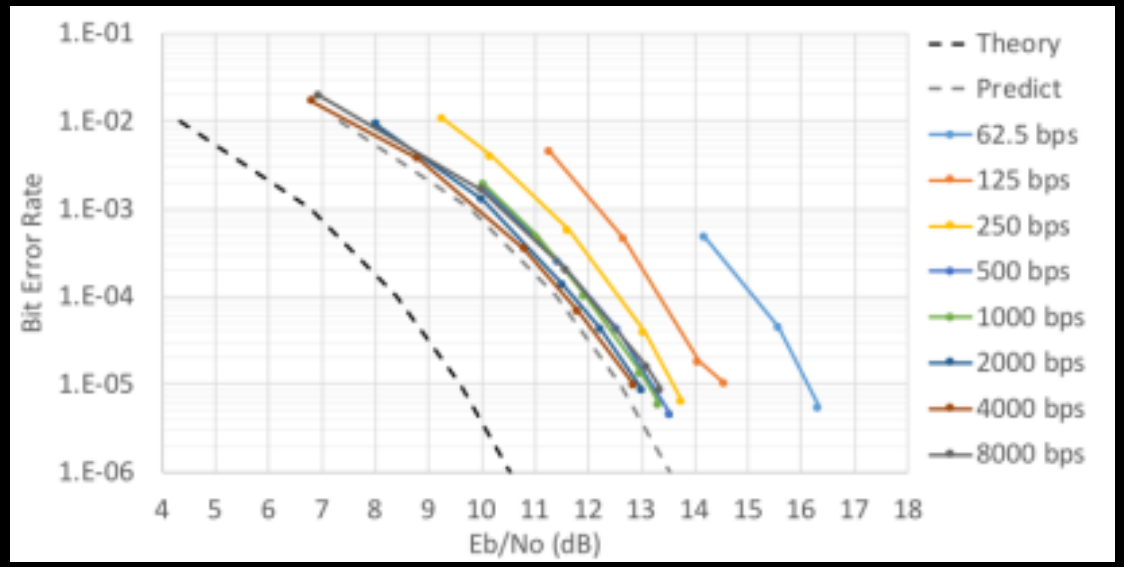




Uplink

- Carrier Tracking Threshold from -146 to -155 dBm depending on LBW
- Command threshold for 62.5 bps at -141 dBm (DTF-21)
  - For 1 kbps command threshold is < -130
- Data rates selectable from 62.5 bps to 8 kbps
- ACK and Track characteristics:
  - Up to 380 Hz/s at high power levels, 200 Hz/s near threshold
  - Tracks beyond 200 kHz



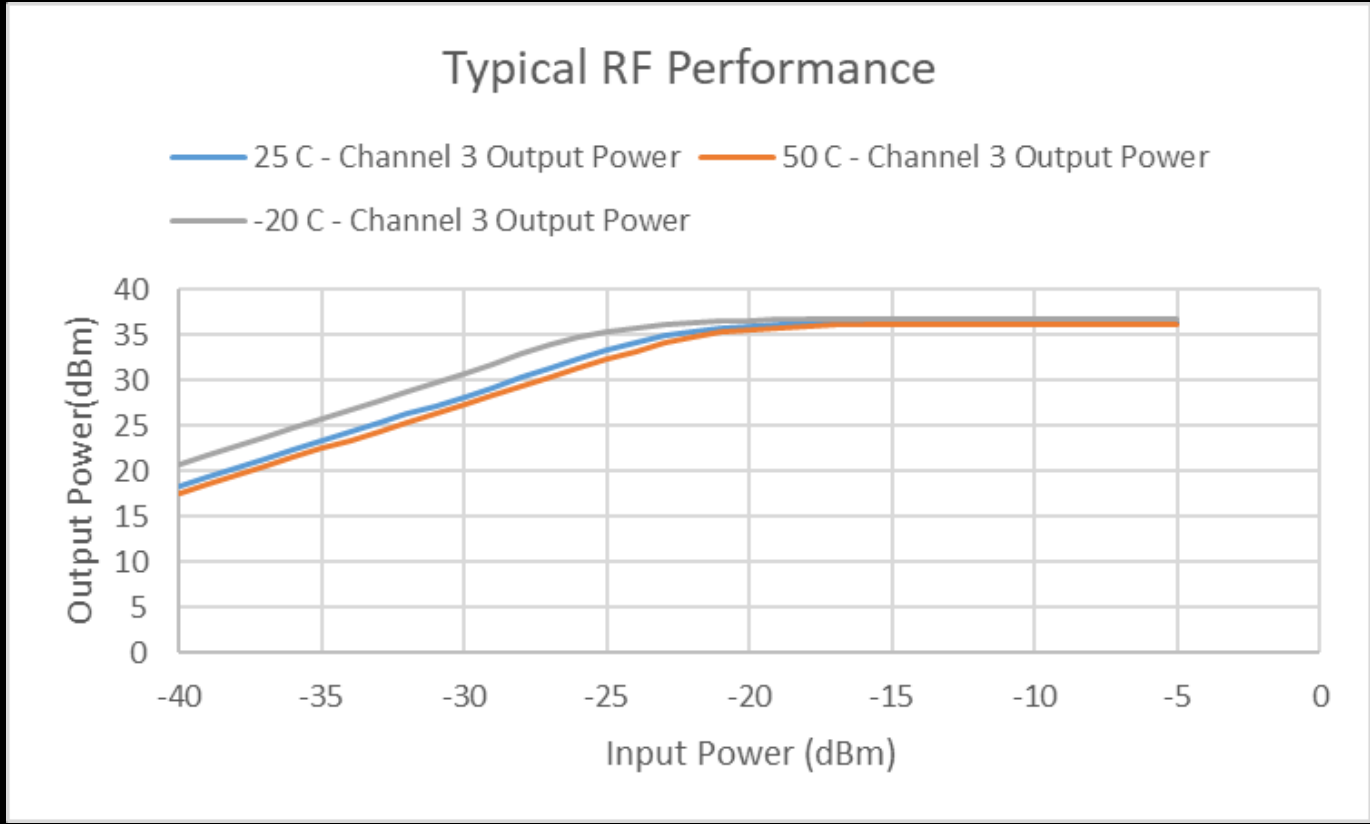


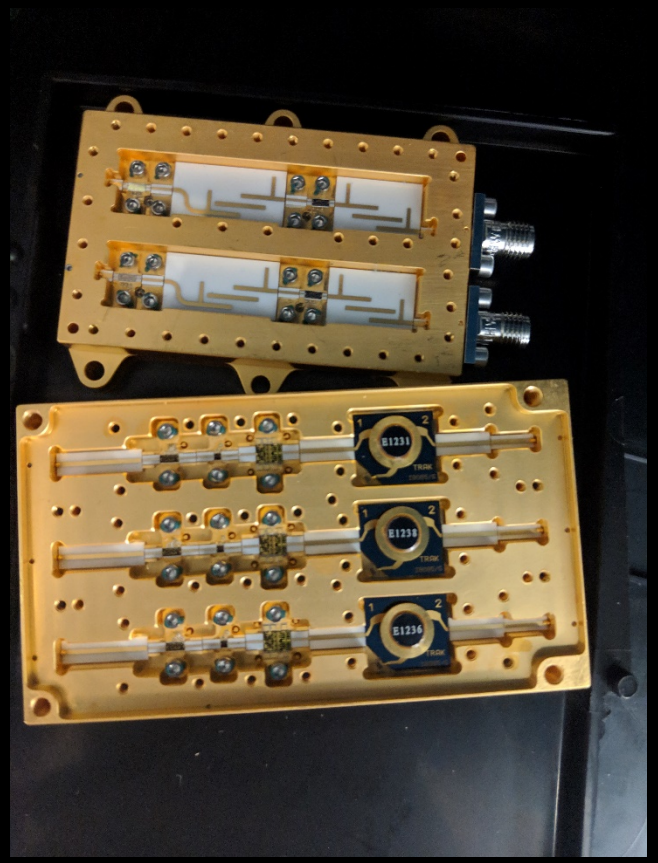
SSPA and LNA Performance

- SSPA
  - Output power: 36 dBm
  - Gain: 58 dB
  - Efficiency: 29%
  - 14 W Power Consumption

LNA

3.1 dB Noise Figure at 25C
Gain: 46 dB
Power Draw: 350 mW





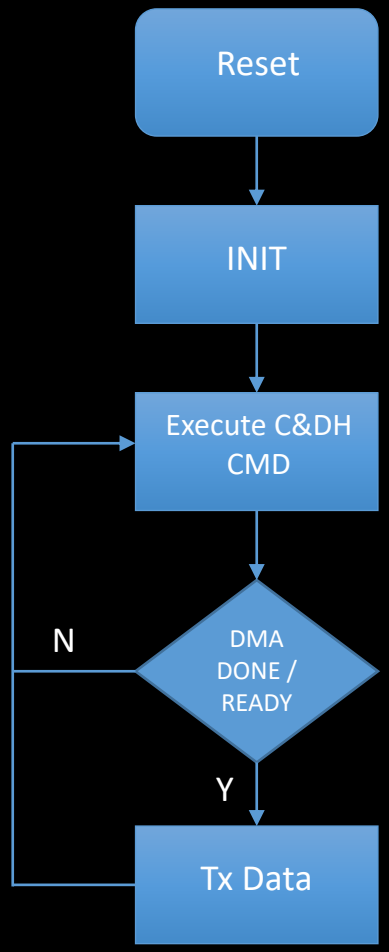
LNA (Top) and SSPA (Bottom) RF paths.

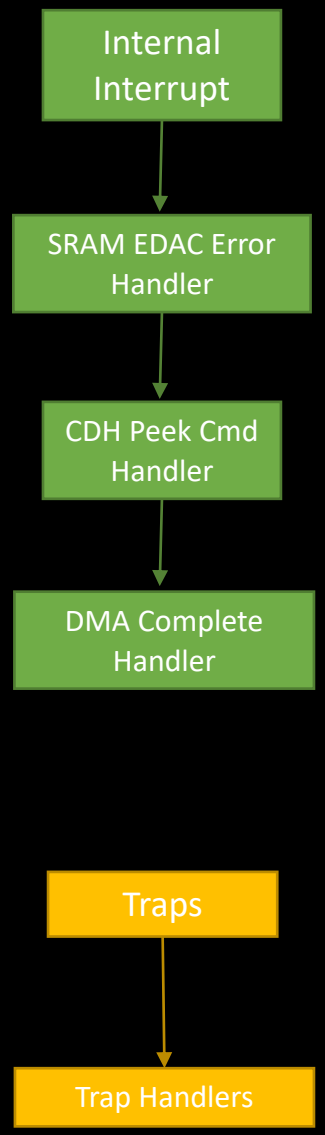
Iris Software / Firmware

S. Holmes / A. Yarlagadda

Software Specs / Architecture

- Single-threaded
  (like BCSW on UST, unlike Electra)
- SPARC V8 instruction set
  (same as AT697F, used on UST/Nisar)
- Softcore LEON3-FT processor
- SRAM: 2 MB total
  - Program size:
    - Text: 99.7 kB
    - Data: 2.9 kB
- Running at 50 MHz





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.	

Note that the configurations in the modes above are the default settings, and can be changed with additional commands.

Available Commands

Spacecraft (C&DH) to Iris

Command Name	Opcode	Description
Reset	0x0Bh	Commands a reset of Iris data buffers.
NOOP	0x16h	No-Operation command.
Mode	0x21h	Sets the Iris transponder mode.
Telemetry	0x2Ch	Reports the engineering telemetry collected by Iris.
Extended Telemetry	0x30h	Reports the extended engineering telemetry collected by Iris.
Downlink Data	0x42h	Transfer downlink data to Iris
Uplink Data Rate	0x4Dh	Sets the uplink data rate.
Downlink Data Rate	0x58h	Sets the downlink data rate.
Exciter Subcarrier Frequency	0x63h	Sets the subcarrier frequency.
Exciter Modulation Index	0x67h	Sets the exciter modulation index.
AOS Framing Mode	0x69h	Sets AOS framing mode, or modem pass-through mode.
Data Encoding Mode	0x72h	Sets the downlink encoding mode.
Coherency	0x7Dh	Sets the transponder coherency mode.
Ranging Mode	0x88h	Sets the ranging mode.
Ranging Modulation Index	0x93h	Sets the modulation index of the ranging tones.
Uplink Antenna	0x9Eh	Selects the uplink antenna.
Downlink Antenna	0xA9h	Selects the downlink antenna.
Peek	0xBFh	Read a single memory location
Poke	0xCEh	Write to a single memory location
Set/Clear Interrupt	0xE4h	Set or clear Iris interrupts
Mask Interrupt	0xEFh	Enable Iris interrupt

Iris to Spacecraft (C&DH)

Command Name	Opcode	Description
Read Interrupt	0xD9h	Request for Iris interrupt status
Uplink Data	0xFAh	Request for uplink data from Iris

Downlink Overview

- Receives data from C&DH
  - Downlink command, sent from C&DH across SPI
  - Data expected to be in space packet format **BEFORE** reaching Iris
  - If AOS framing mode is enabled, radio will form AOS frames around the space packet-ized data
  - If AOS framing mode is not enabled, data is expected to be in space packets in AOS frames **BEFORE** reaching Iris
  - Data format leaving Iris will be **DATA** in **SPACE PACKETS** in **AOS FRAMES**
- When transmit functionality is enabled, Iris will continuously downlink idle frames in lieu of actual downlink data
  - Idle frames consist of one byte repeated continuously
  - V2.1 idle byte: 0xDC
- Partial AOS frames are padded with idle bytes and, when AOS framing mode is enabled, are downlinked according to a prioritization scheme of their VCIDs
  - Telemetry data takes priority over idle frames, and partial frames go out immediately
  - Pre-defined VCIDs are 0x3F for idle, 0x2 for telemetry

Downlink Data Flow

FW only
SW/FW
SW only

DMA Ready Interrupt:
Signals that DMA has room for next AOS frame

From C&DH

SP of DL Data

SPI Module
- Receives and partially verifies DL Data command across SPI

SP of DL Data

CMD FIFO
- Interface from which SW reads DL Data command, 32 bits at a time

SP of DL Data

Frame Pool
- Contiguous data storage (TLM, etc)
- Generates and transfers AOS frames upon interrupt
- SRAM

AOS Frames of SP of DL Data

DMA Module
- Interface into which SW deposits AOS Frame of DL Data, 32 bits at a time

AOS Frames of SP of DL Data

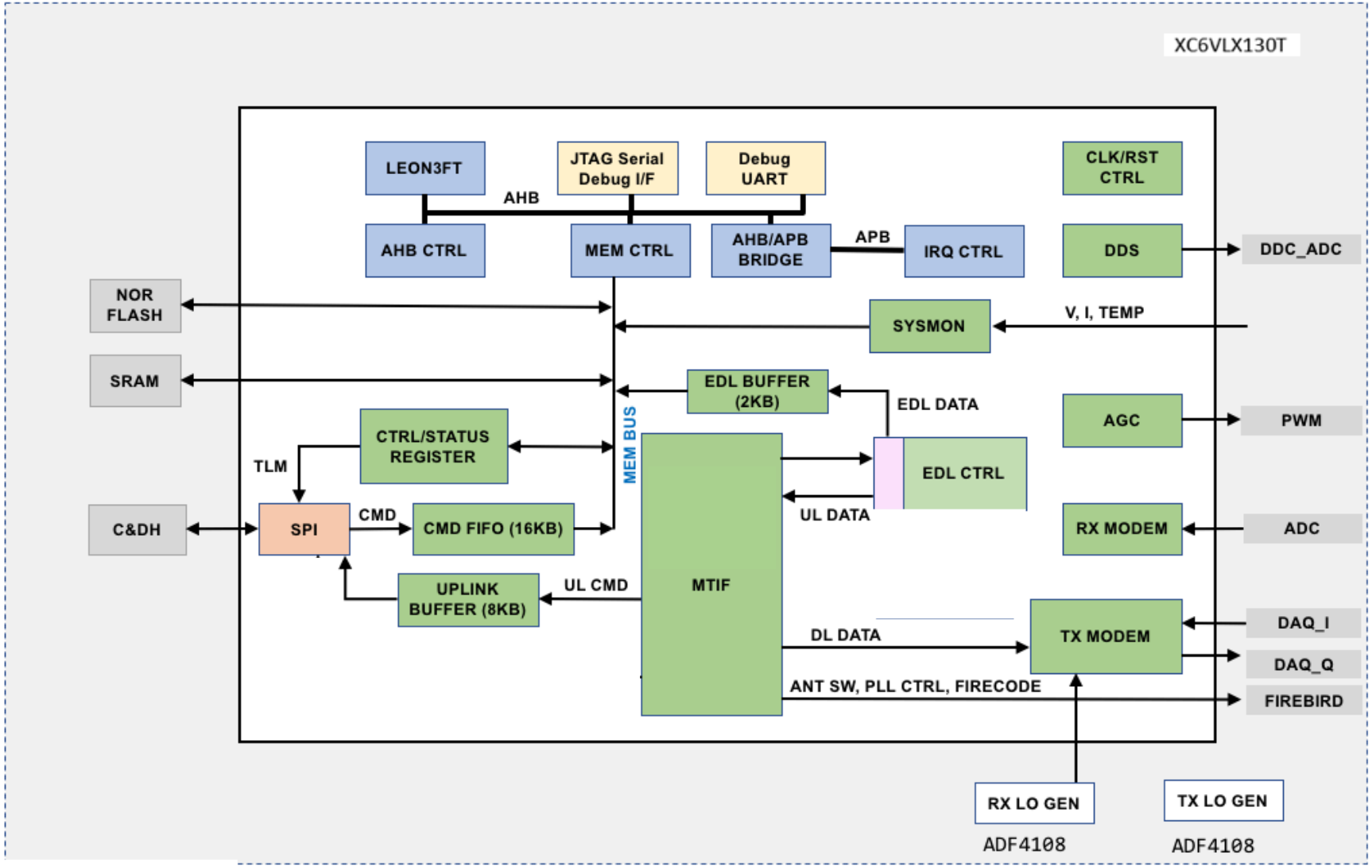
MTIF
- Encodes and modulates data for transmission

To DSN/Cassy

Encoded/modulated AOS frames of SP of DL Data

Note: This diagram is for the case where on-board AOS framing is enabled. If on-board AOS framing is disabled, the data will flow into Iris as AOS frames of SP of DL Data and be deposited in an SRAM buffer instead of the frame pool. The buffer is triggered by the same DMA Ready Interrupt, and the rest of the diagram is the same.

Iris Firmware



Cassy

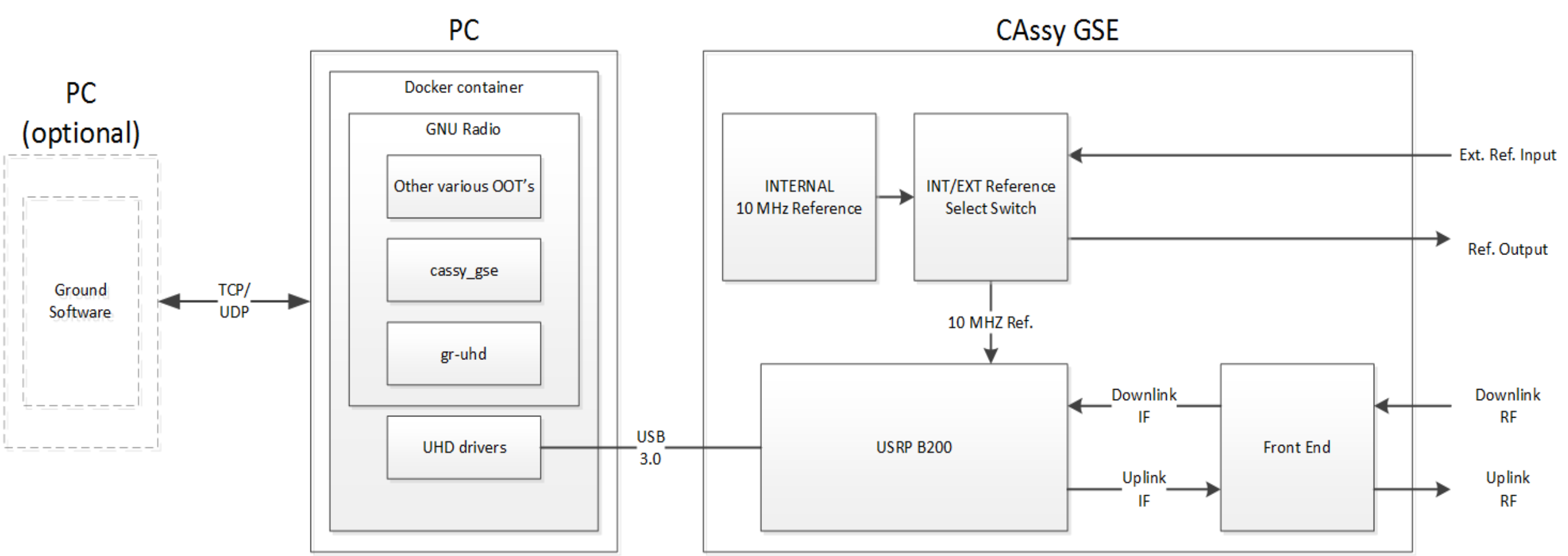
M. Chase

Ground Support Equipment for Iris Development

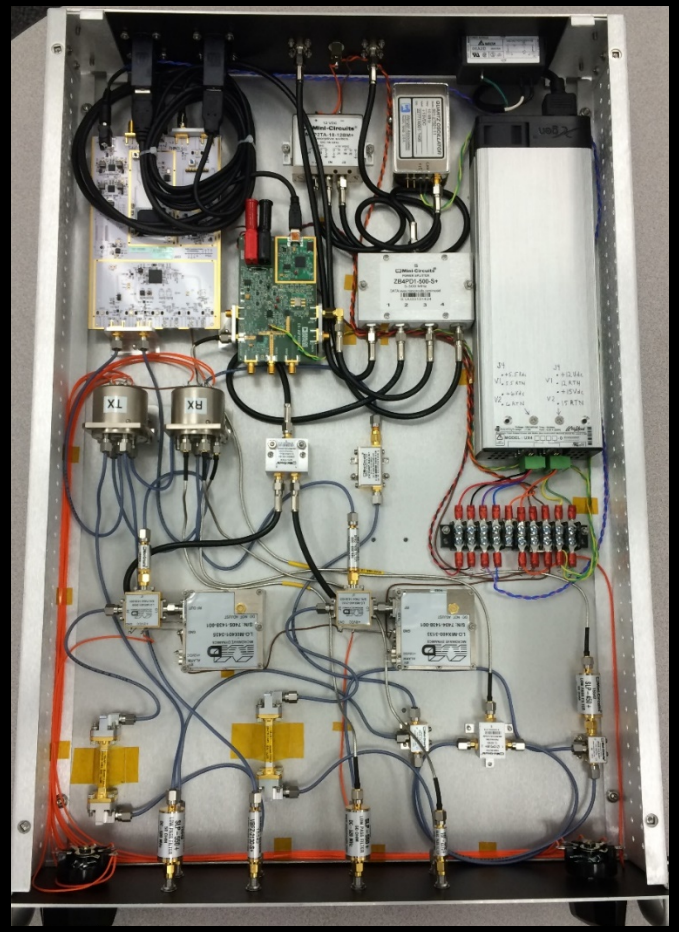
Cassandra, en.wikipedia.org/wiki/Cassandra.

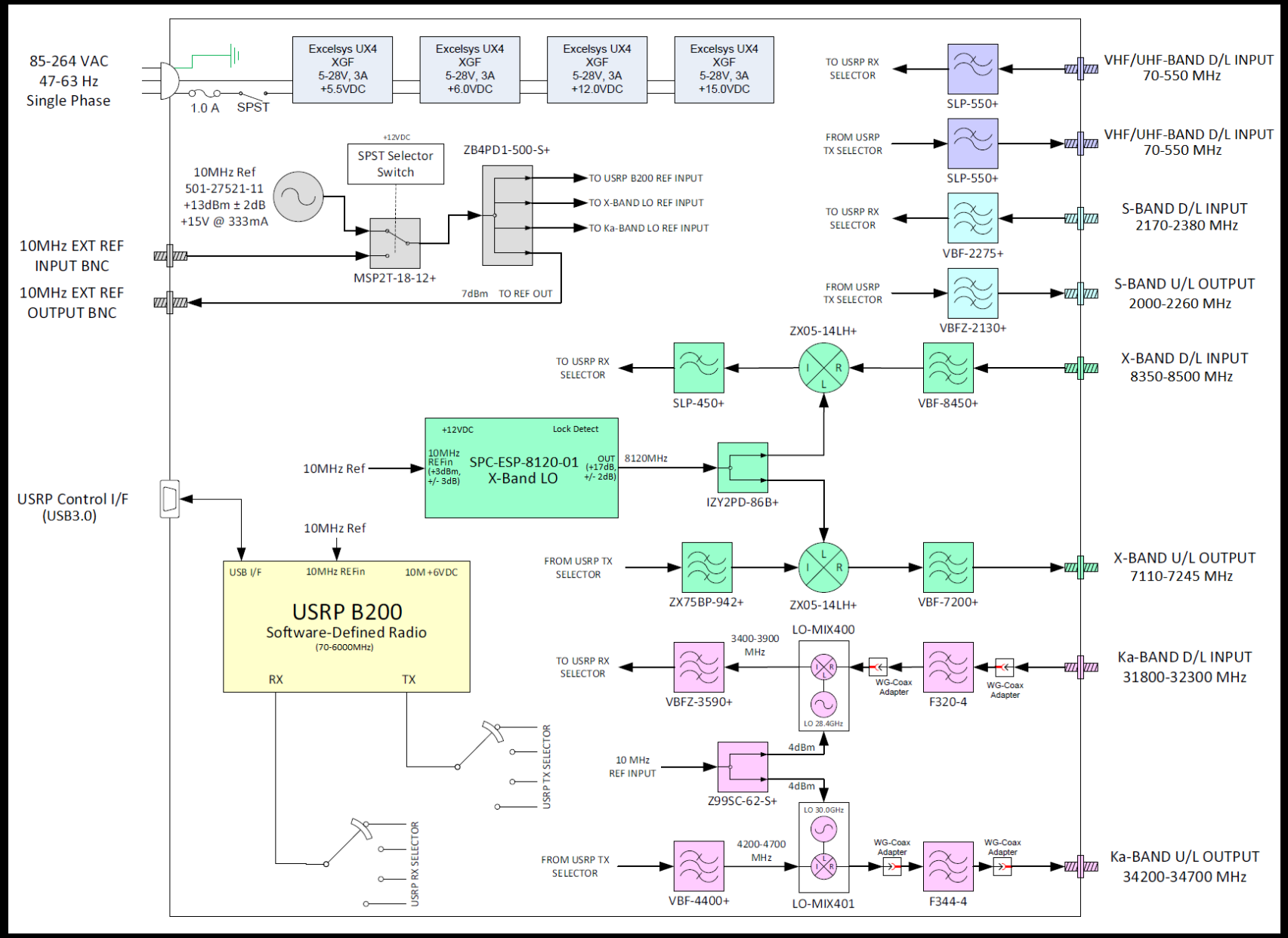
"Cassandra was cursed to utter prophesies that were true but that no one believed."

Cassy Architecture



Cassy Hardware





Cassy Is

Basic Front End Components

- BPFs, Mixers for X- and Ka-bands, switches

Universal Software Radio Peripheral (USRP)

- COTS hardware component of our software defined radio platform

GNU Radio (GR)

- software component of our software defined radio platform
- open source
- Linux (Ubuntu preferred)

Cassy Interfaces

Signal
- File
- TCP/UDP
- RF (UHF, S, X, Ka)

Control
- Command line scripts in Docker container
- Various GUI controls

Monitor
- Spectrum analyzer (UL/DL baseband)
- Runtime parameters (UL/DL)
- Oscope (UL)
- Constellation (DL)
- Frame count printout (DL)
- Frame printout (DL)

Cassy Modes of Operation

Uplink
- Carrier sweep around center
- Subcarrier 16 kHz: 62.5, 125, 250, 500, 1000, 2000, 4000, 8000 bps data rates
- BCH encoding

Downlink
- Subcarrier 25 kHz: 62.5, 125, 250, 500, 1000, 2000, 4000 bps data rates
- Direct carrier: 1k, 2k, 4k, 8k, 16k, 32k, 64k, 128k, 256k bps data rates
- Manchester or suppressed carrier
- Turbo decode: 1/2, 1/3, 1/4, 1/6
- Pseudo-randomized on/off

Full duplex
- Any combination of the configurations mentioned above

Ranging
- 200 kHz or 1 MHz tones

Record/playback
- raw IQ, symbols, aligned bytes

Simulation
- Remove hardware interface drivers

Test Payloads

Space Cat Wallpaper, wallpapersafari.com/space-cat-wallpaper/.

space kitty
- 32 kB

space cat
- 88 kB

space tiger
- 2 MB

Super Space Cat, www.pinterest.com/pin/239816748877046173/.

Space Tiger, mikarane.blogspot.com/2015/03/tbt-space-tiger.html.

Iris Future

C. Duncan

In addition to the EM-1 six, three more are being built by SDL for non-JPL customers today. There is significant additional interest. There are rumors of competition.

Selected Iris Lessons Learned

- Iris V1
  - If the customer says “CubeSats don’t do thermal analysis” – do it anyway
  - 8 amps inrush is “a lot for a CubeSat”
- Iris V2.0
  - Just because 1.1U fits in the MarCO design doesn’t mean it will fit in other CubeSats
  - Are we making a Product Line or one-offs?
- Iris V2.1
  - “Build to Print” means having buildable prints
    - And procedures That can be run by “someone else”

- * Jim Lux has an entire presentation on Lessons Learned

Selected Iris Lessons Learned

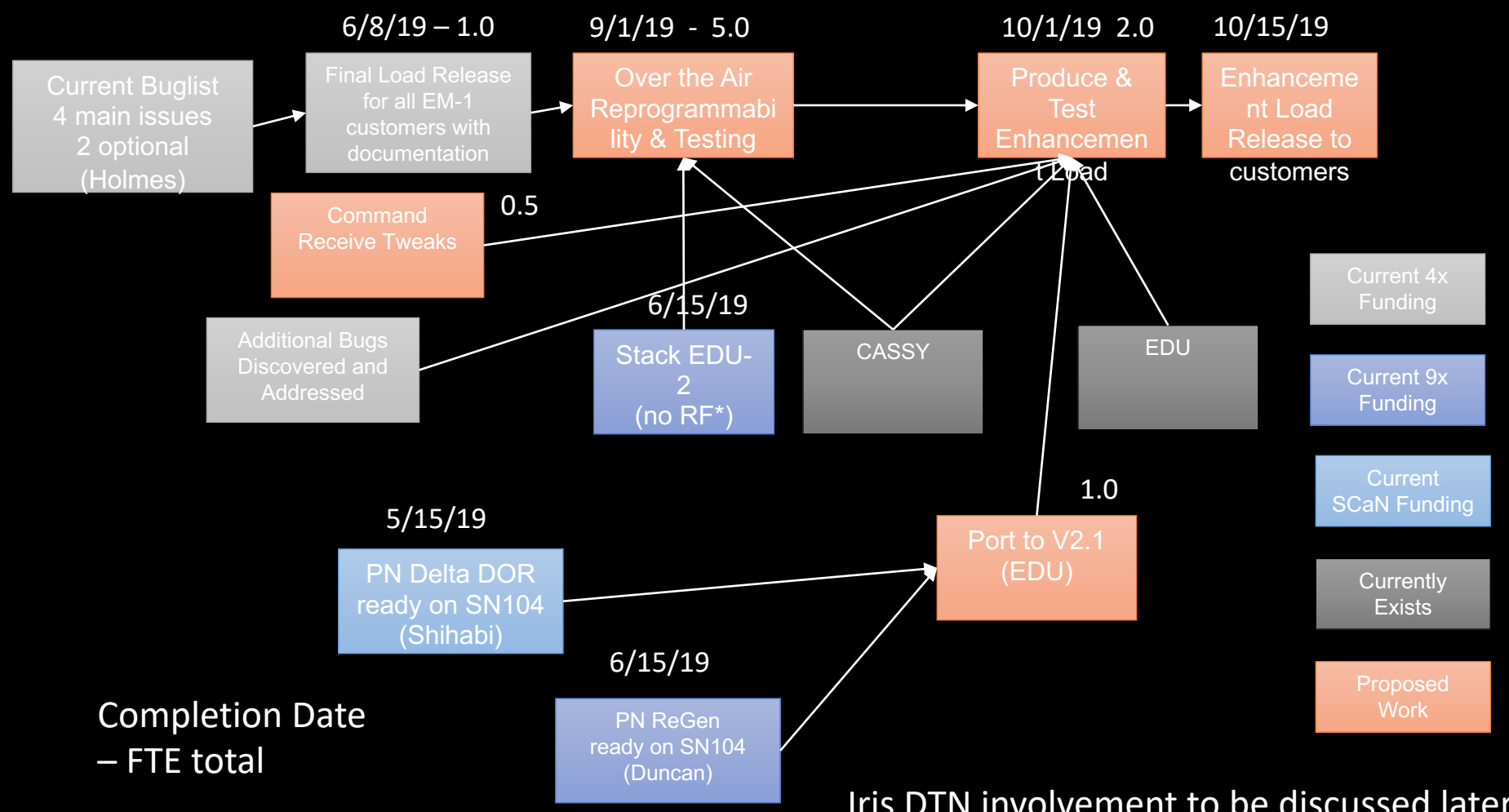
- Since we're contracting for "Build to Print" we really did want a Product Line
  - Product Lines must deal with manufacturability issues like manufacturing flow, parts obsolescence, parts cost and lead times
  - Product Lines should explore margins more thoroughly than single mission one-offs
    - Like different spurs at different assigned channels
    - Like VCO operating ranges
    - Like boot up sequencing issues
- Class D Type II does not lend itself to institutionally expected levels of rigor
  - That's one of the things traded for schedule / budget
- Software/Firmware is not "to print" either
  - Contractor should expect to receive and test many updates
- In general your contractor needs to
  - Understand theory of operation
  - Use the same test equipment
  - Use Configuration Management

Iris FW/SW Infusions Plan Overview

Near Future

All 6 EM-1 Irises are now delivered to missions via HRCR

This slide is part of an in-progress proposal to add in-flight reprogrammability and other features via pre-flight firmware / software update



Completion Date – FTE total

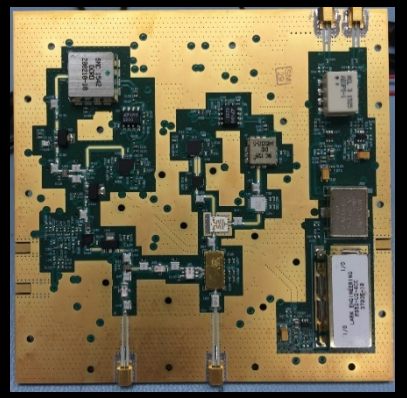
Iris DTN involvement to be discussed later

JPL/Caltech Business Discreet. Caltech Record Not For Public Distribution. This material has NOT been reviewed for export compliance. For planning and discussion purposes only.

In Consideration for Iris V3

- Ka/Ka and/or X/Ka
- UHF/UHF
- Higher efficiency SSPA
  - Lower DC power in general
- One-Way Ranging
  - E.g. with CSAC
- Class B
- ASIC instead of FPGA?

TRL-4 Ka- (and S-) Band exciter from FY16 R&TD

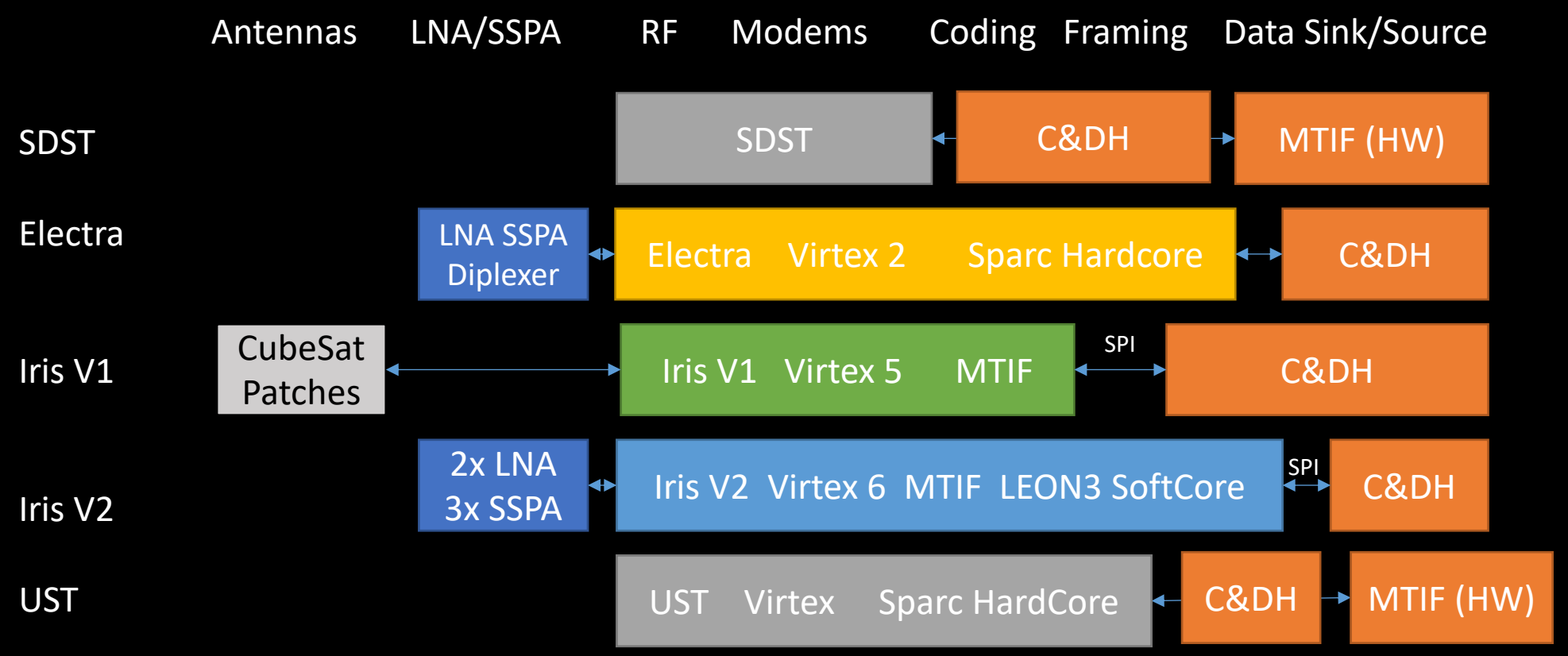


TRL-4 UHF exciter from FY16 R&TD

Backup

Last time there was a Section Seminar about Iris was in 2014, V1

Flight Radio Architectures



Our product lines don't solve all the same subsets of the communications / navigation problem in the same way

Parts selection can bite you in manufacturing

- MarCO chose parts that were available “today” to meet schedule pressure, not necessarily because we needed a particular performance.
  - Those may be expensive or very long lead when ordered by someone else a year later.
  - QTECH 50MHz TCXO is a long lead (28wk), expensive ($7k) medium performance TCXO in a big package – but they had 3 in stock when Fernando called them.
  - Lots of other 50 MHz space TCXOs with same or better performance in smaller packages
- JPL tends to choose certain parts based on experience and common availability *at JPL.*
  - MSK5986RH regulator- $1400 each, 50 pc minimum order, 1 used in Iris, long lead (46 week)
  - If you want one Iris, SDL has to buy $70,000 of inventory and wait nearly a year
  - And that’s one part – there’s half a dozen like this
- If you’re designing for production – choose parts that can be procured quickly in small quantities and have easy substitutes
  - This is what drives a $1.5M Iris quote – in reality, Irises cost about $400k each (in qty 6)

from Jim Lux

Power supply sequencing

- We had a lot of problems which wound up being due to sequencing and turn on rates of the power supplies
  - Inrush current problems
  - Bi-directional voltage shifting buffer sensitive to power supply waveforms
  - Incorrect sequencing depending on how long the Iris had been turned off
  - Temperature sensitivity
- Recommendation:
  - Explicitly sequence power supplies with a suitable design for the purpose
  - Cubesat power systems are not well controlled – some are very “stiff” and turn on instantly, others have some soft-start, others have sags and ripple as the load is applied – this can affect your sequencing
  - Figure out how to test a wide variety of bus voltage/current behavior

from Jim Lux

Jet Propulsion Laboratory

California Institute of Technology