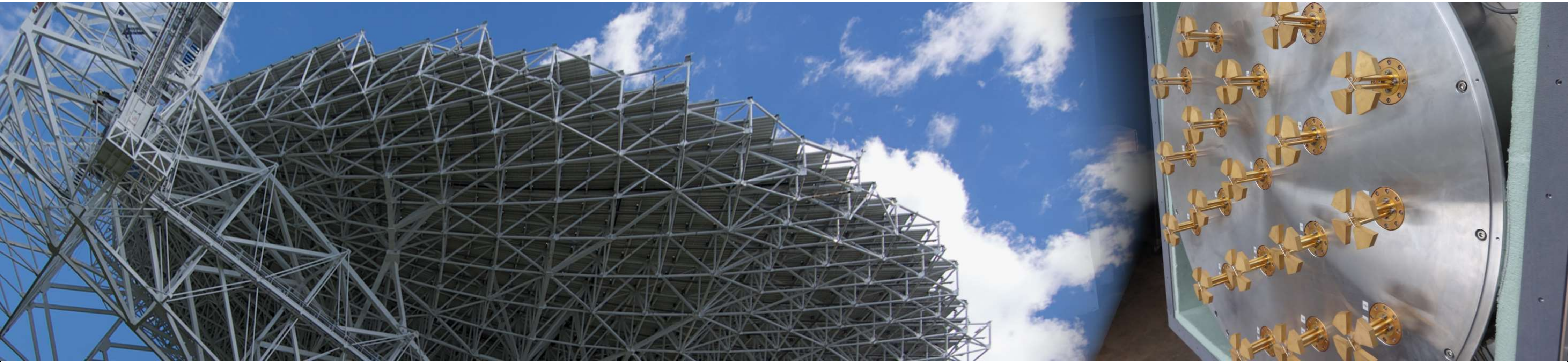

ALPACA: The Advanced L-band Phased Array Camera For Astronomy

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Phased Array Feeds & Advanced Receivers Workshop 2022

ALPACA Project Overview

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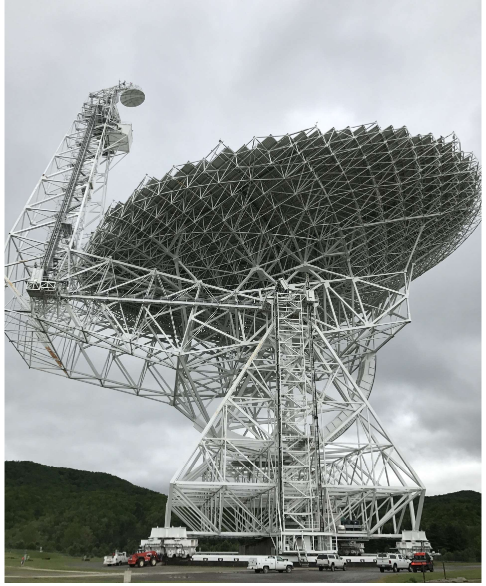
ALPACA Project

- National Science Foundation Award AST-1636645
- Brigham Young University and Cornell University
  - 4 years, $5.8M, started July 2018
  - Currently in 5th year, commissioning expected July 2023
- Arecibo Telescope
  - Decommissioned and then Collapse on Dec. 1, 2020
  - Evaluation and funding efforts under way for transition to the Green Bank Telescope
- Cornell: PAF front-end, including electronics, array elements, dewar, cryogenics, mechanical engineering
  - Subaward to ASU for LNA
- BYU: project management, RFoF signal downlink, F-engine firmware, digital beamformer, and data handling



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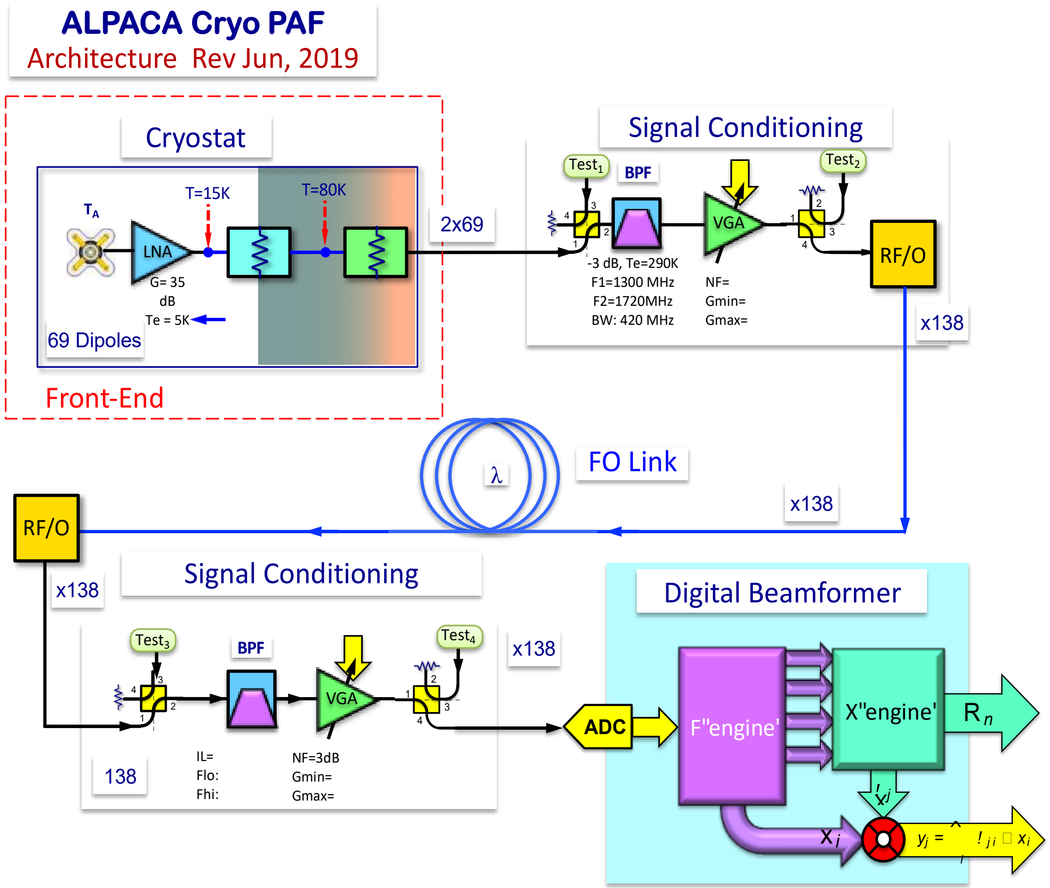
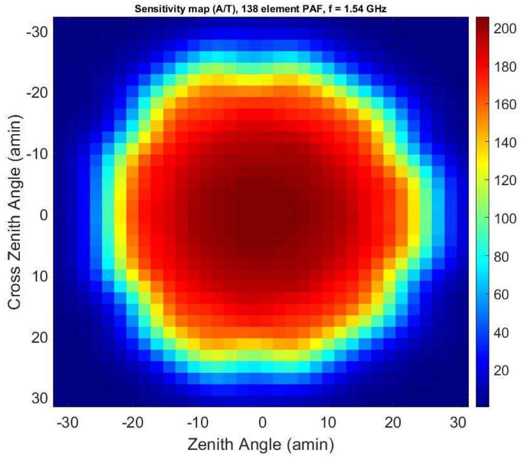
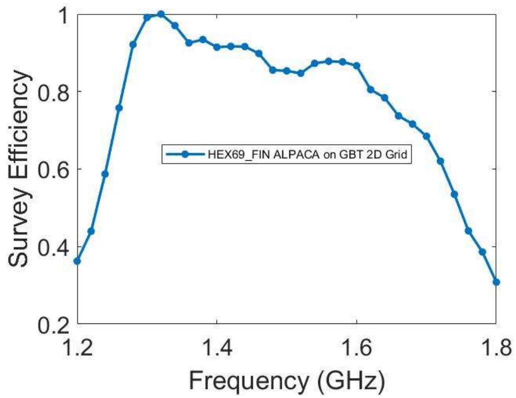
ALPACA Overview







Noise Component	Contribution
Sky	5 K
Spillover	1 K
Loss, Scattered Ground, Unmodeled	10 K
LNA	10 K
Signal Transport	1 K
Total, T_{sys}	27 K

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ALPACA Science Cases

ALPACA Cryostat

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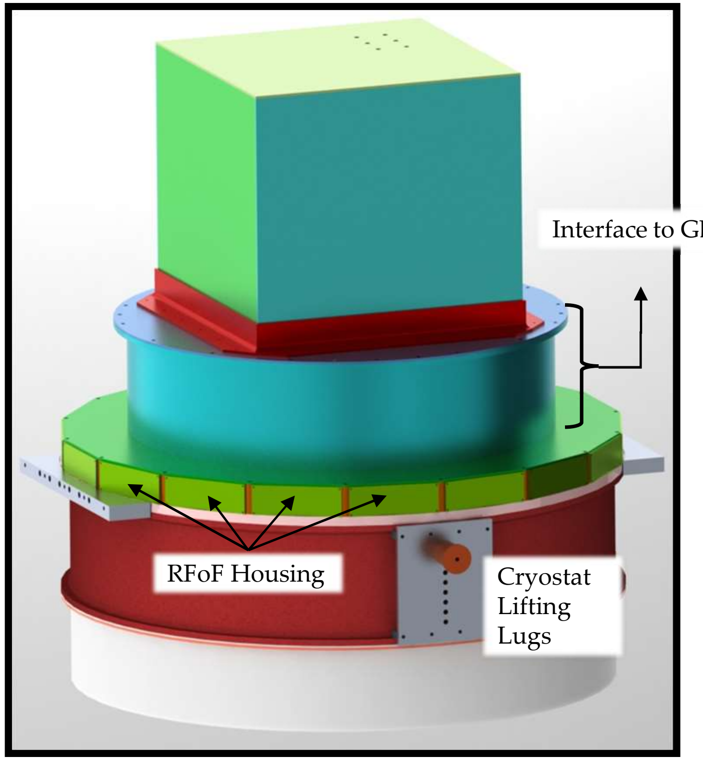

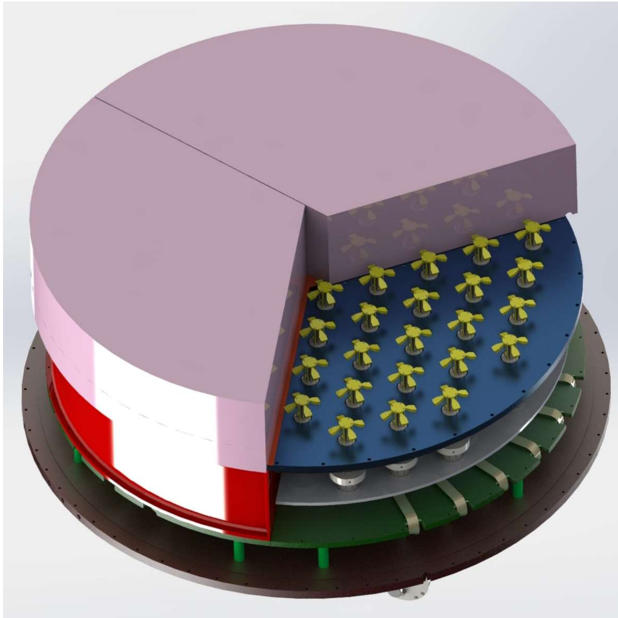

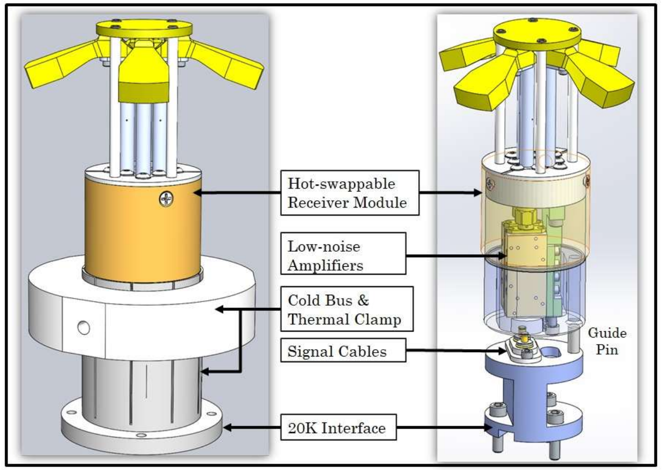

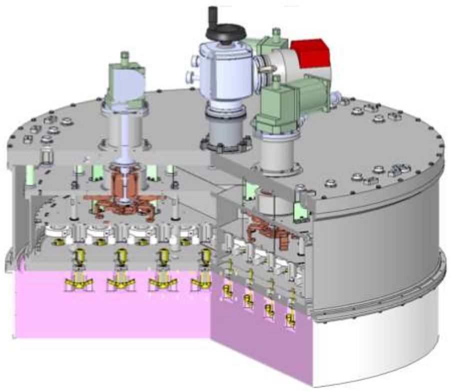

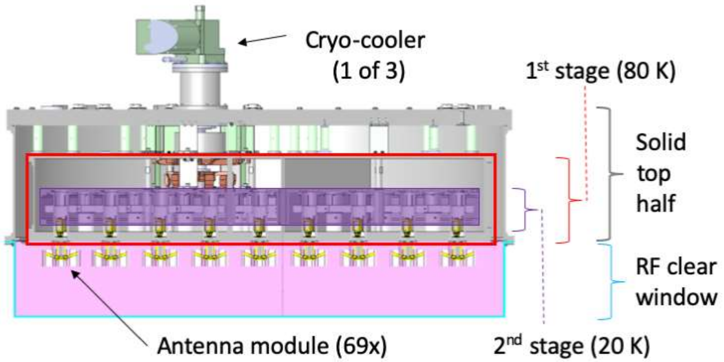

RFoF

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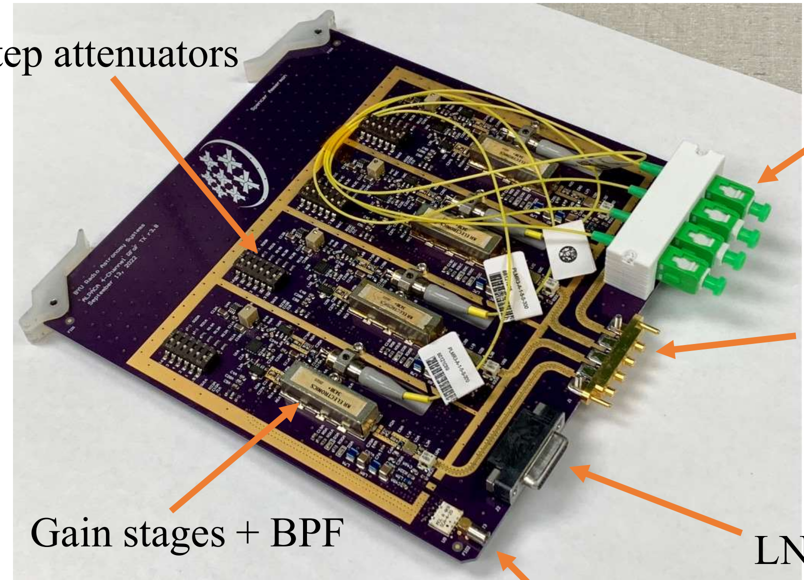
RF-over-Fiber Link

Step attenuators

Fiber interface to downlink receiver

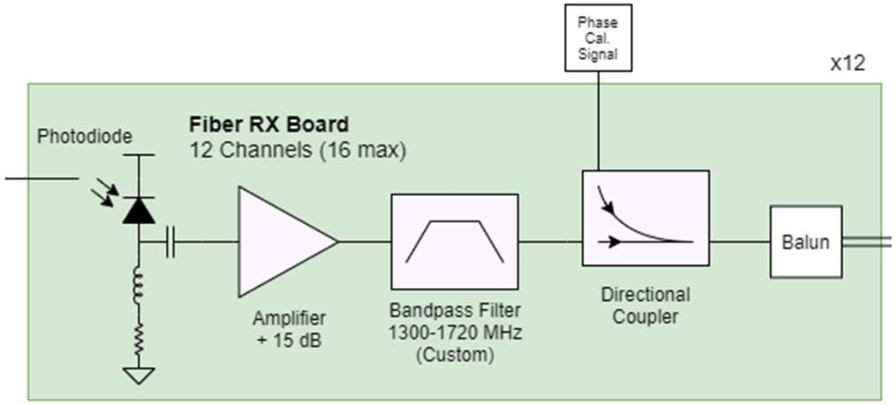


SMP connection to flexible stripline from cryostat

Gain stages + BPF

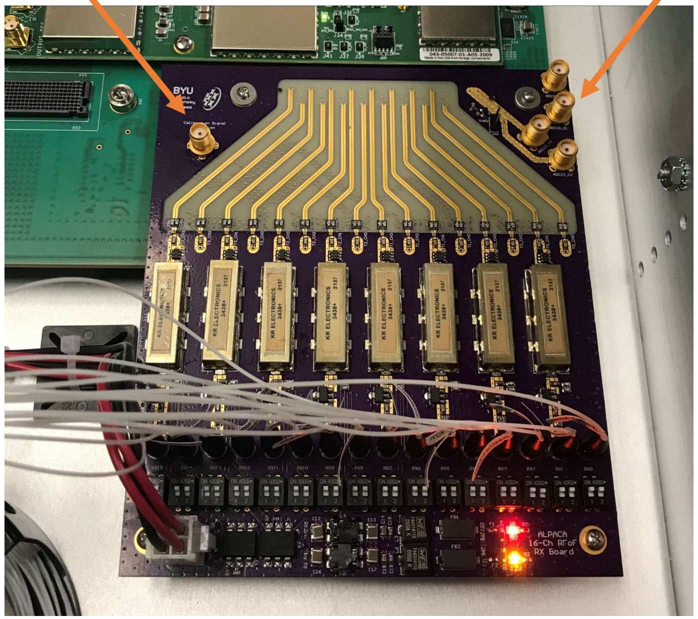
LNA Bias, Monitor + Control

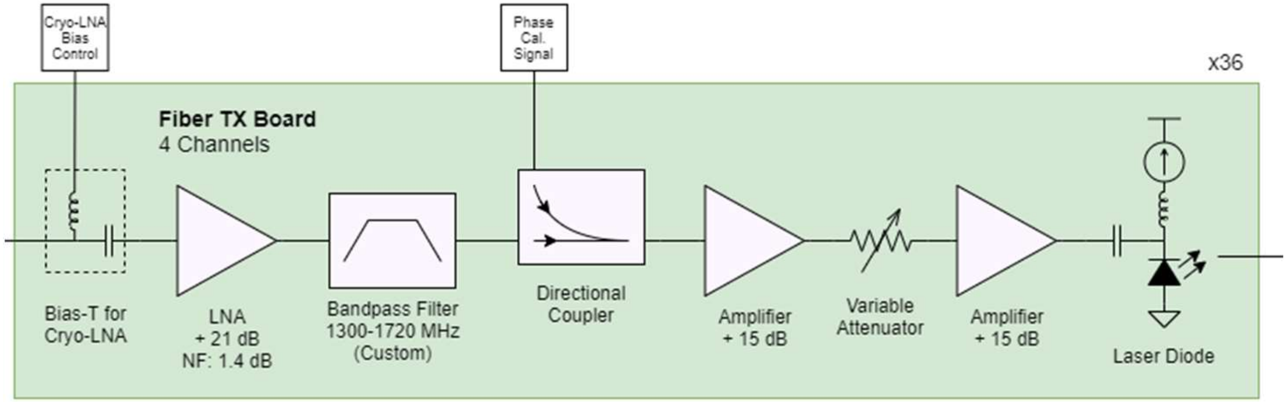
Uplink wideband noise calibration noise injection



Downlink test/calibration input

RFSoC ADCIO





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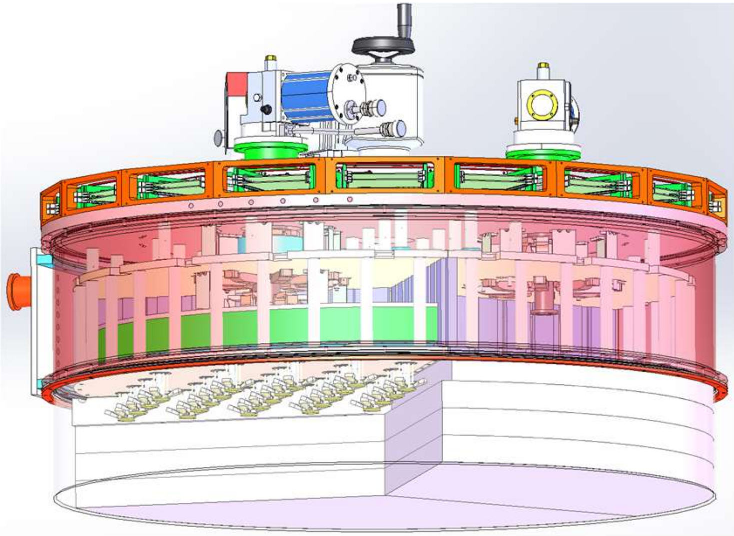
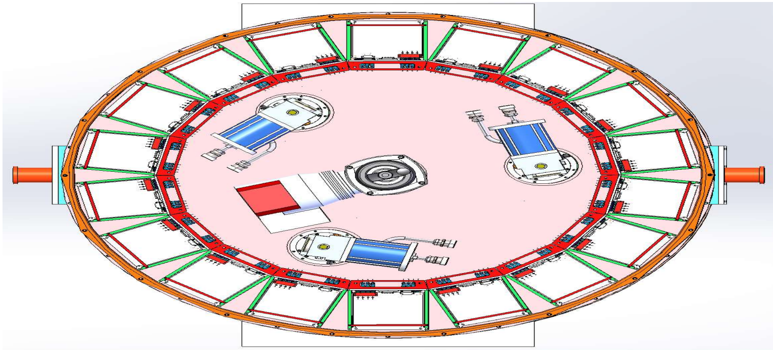
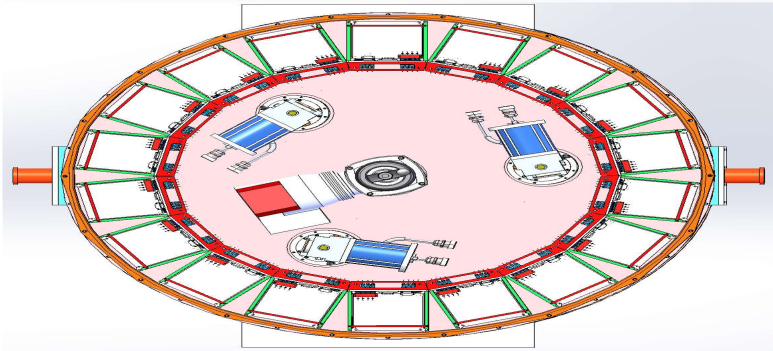
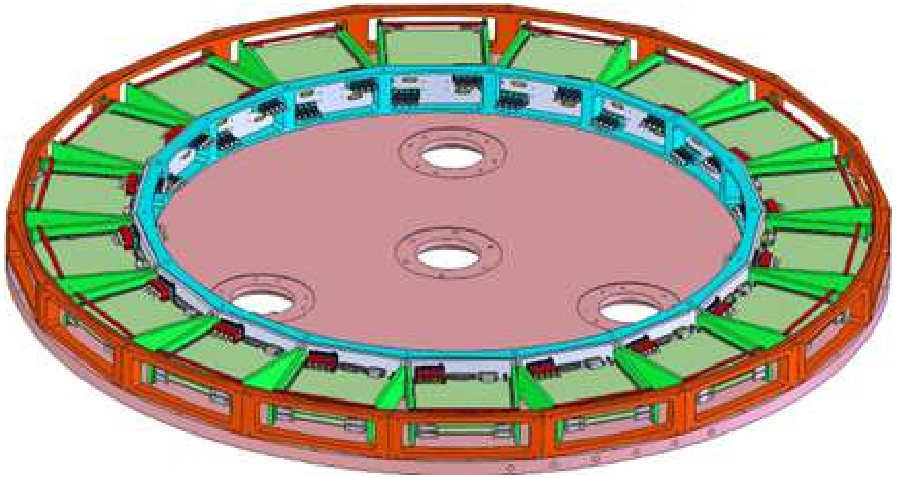
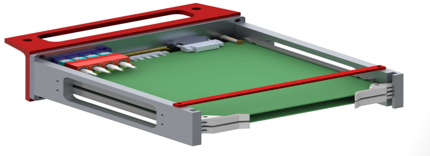
RFoF, Cryostat Interface

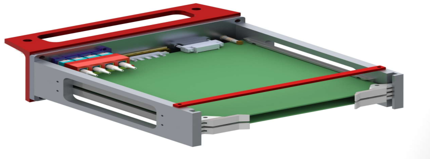


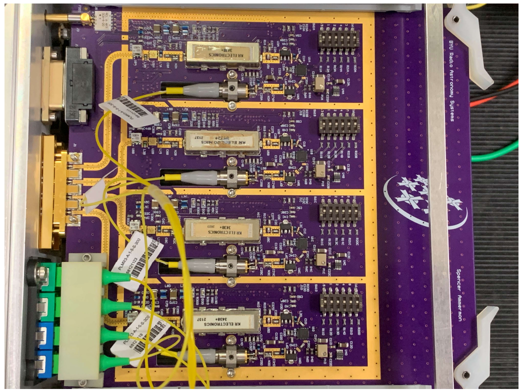












RFoF, Link Performance

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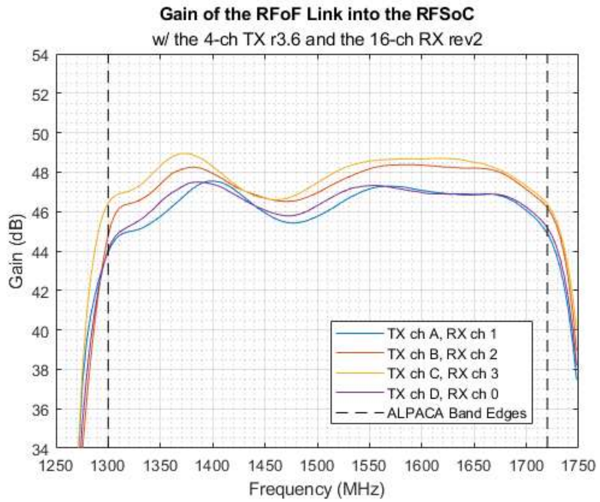
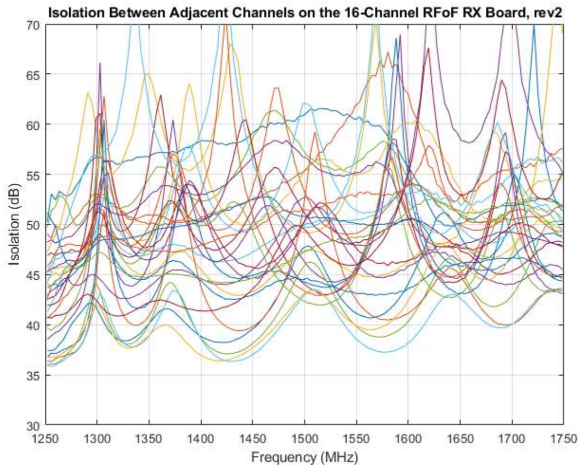
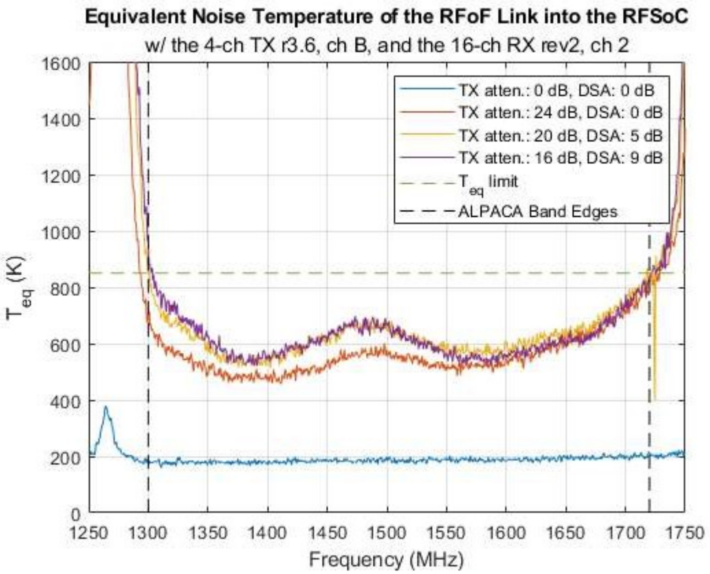
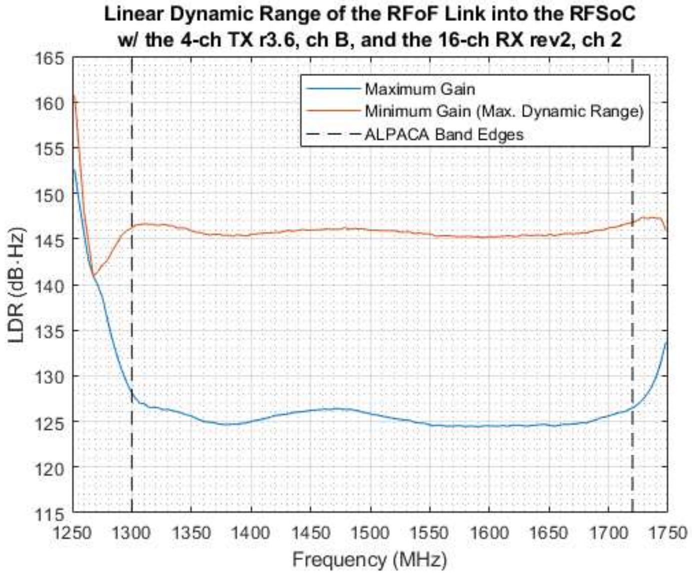
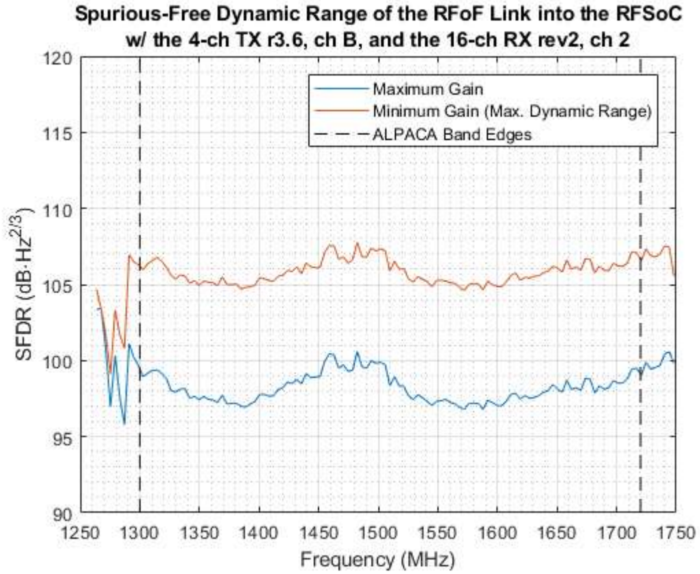
Parameter\Condition	Performance Target: Maximize Dynamic Range	Performance Target: Minimize Noise
TX Attenuation	14.5 dB	0 dB
RFSoC DSA Setting	9 dB	0 dB
Average Gain	24 dB	47.5 dB
Link only T_{eq}	850 K	200 K
LDR	145 dB·Hz (59 dB)	124 dB·Hz (38 dB)
SFDR	105 dB·Hz$^{2/3}$ (47 dB)	97 dB·Hz$^{2/3}$ (39 dB)











Digital Back End

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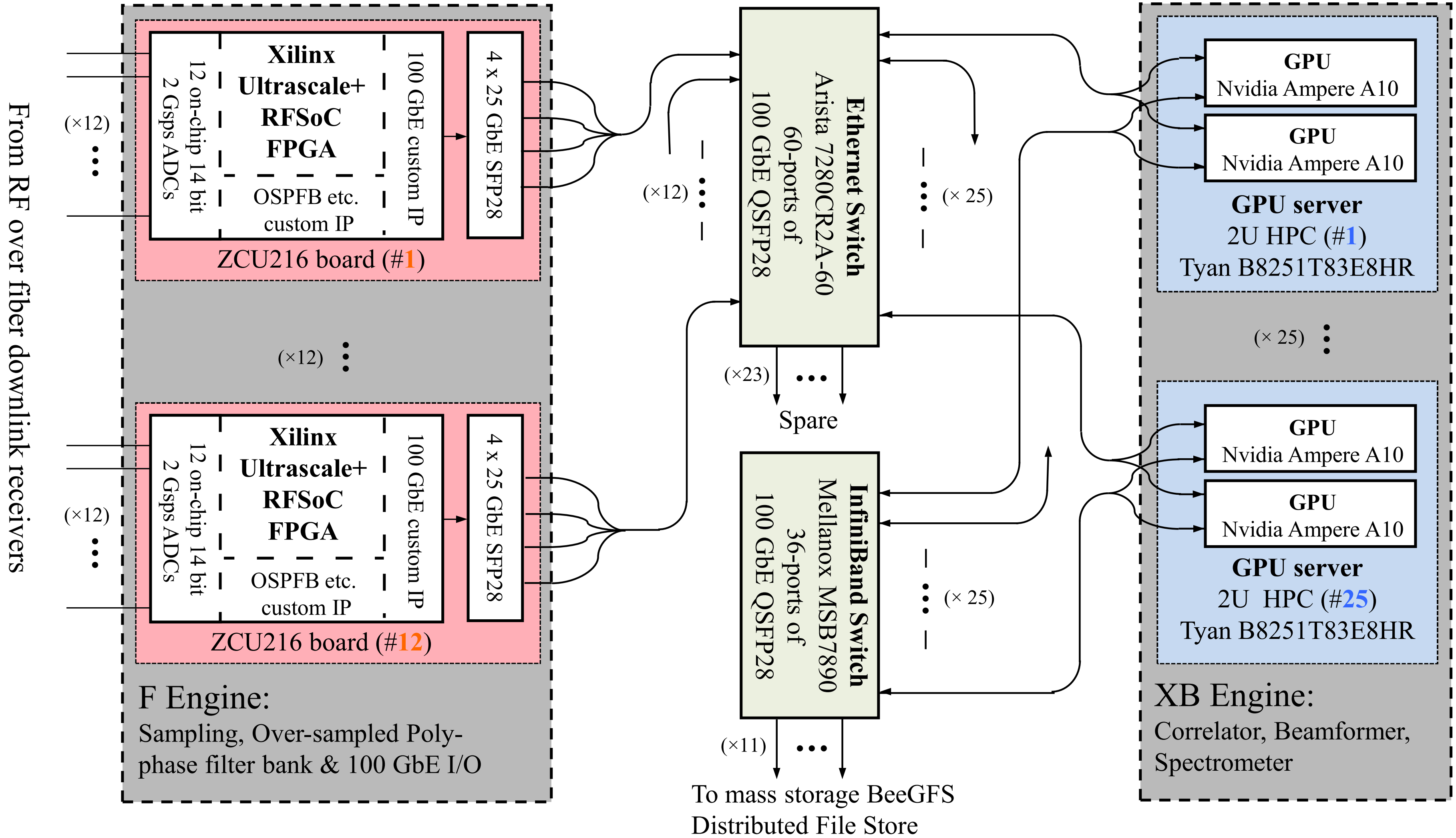
Digital Back End, Architecture



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Digital Back End, Specifications (1)

Performance Characteristic	**Specification**
Frequency Coverage (tunable within this range)	1300 – 1720 MHz (420 MHz total BW)
Beamformer real-time processing bandwidth	305.2 MHz
Number of real-time simultaneous beams	40
Full Stokes Integrated PSD output per beam, per channel	XX pol (real float), YY pol (real float), XY pol (complex)
Pulsar / Transient mode:	
Number of OSPFB frequency channels | BW per channel	1250 coarse chan. | 244.1 kHz separation, 325.5 kHz BW
Shortest integration dump interval	64 microseconds
HI Spectral Line (zoom spectrometer) mode:	
Total number of PFB frequency channels | BW per channel	96,000 (spanning 122.1 MHz) | 1.27 kHz
Shortest integration dump interval	100 ms
Beamformer calibration mode:	
Covariance matrix outputs per each of 1250 coarse channels	Lower triangular 144x144 matrices, 500 ms max dump rate

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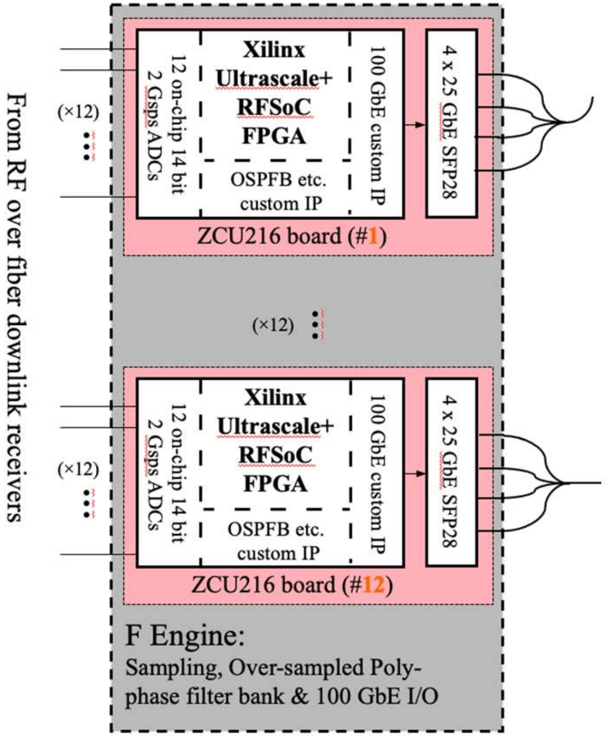
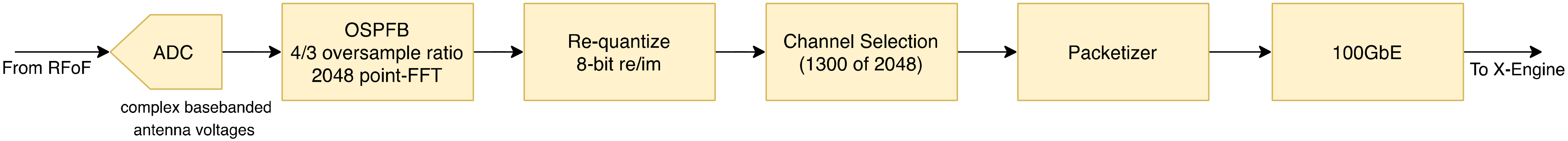
Digital Back End, Specifications (2)

Performance Characteristic	Specification
LO and IF frequencies	NONE: direct sampling of bandpass RF
ADC sample rate | resolution | Noise Spectral Density	2,000 Msamp/s | 14 bits (10 enob) | -147 dBFS/Hz
Complex baseband sample rate for beamformer	500 Msamp/s
1st stage PFB FFT length | oversample ratio	2048 channels | 4/3 oversampled
2nd stage (zoom) PFB length | oversample ratio	256, pruned to 192 non-overlapped channels | 1/1
Peak I/O data rates:	
Output data rate per RFSoC board | input rate per HPC	81.8 Gbps | 39.3 Gbps (8 bit real + 8 bit imag. samples)
Total max output data rate in pulsar spectrometer mode	50.0 Gbps (16 bit int real & 32 bit int complex: 16r+16i)
Optional (unfunded) beamformed voltage data mode:	(Ability to support this mode is undetermined)
Beamformed raw voltages data rate, total over all HPCs	520.8 Gbps (cmplx int 16, 40 beams, X&Y pol)
Beamformed raw voltages data rate, one HPC	20.83 Gbps (cmplx int 16, 40 beams, X&Y pol)

Digital Back End, F-engine



- Xilinx ZCU216 board
- 16 on-chip 14-bit 2.5 Gsamp/sec ADCs, w/ digital down conversion, decimation, and lowpass filtering to complex baseband.
- On-chip ARM A53 processor
- 4x25 SFP28 network ports support up to a 100 Gigabit I/O data rate to HPC/GPUs.
- 12 of these boards w/ 12 inputs each to be used to support the 138 antenna inputs.
- Will directly sample RF over fiber downlinks with no analog mixer.

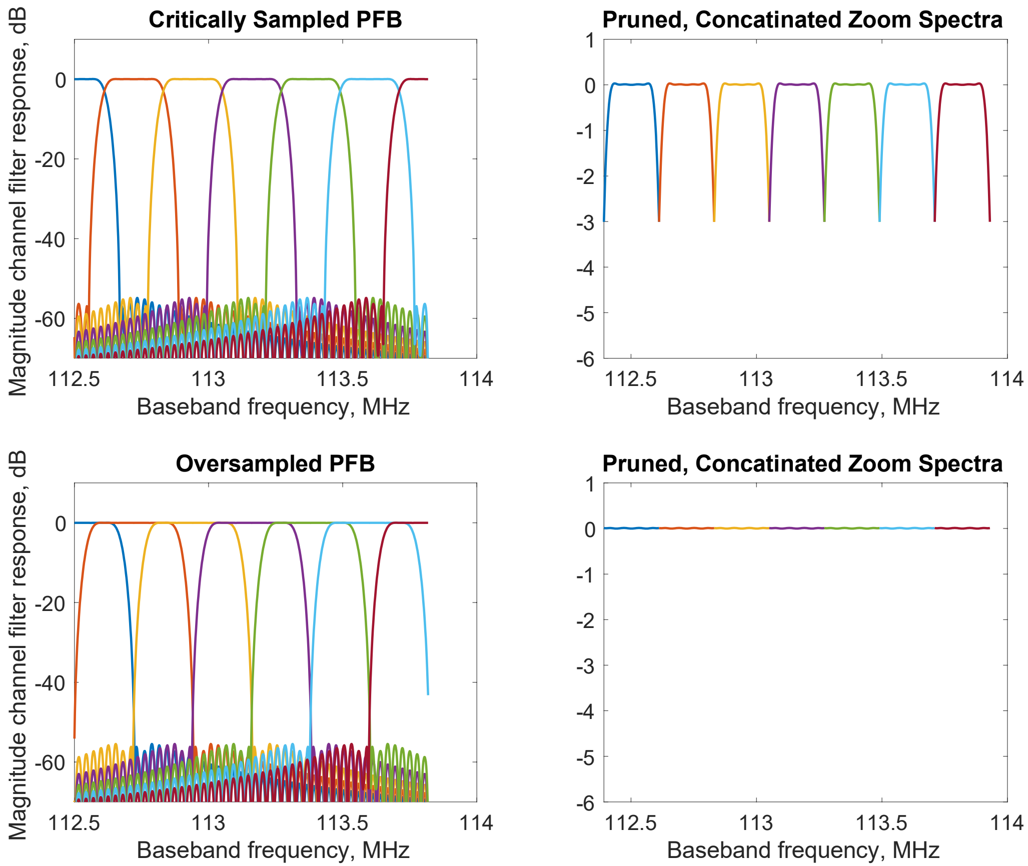


F-engine, Oversampled PFB

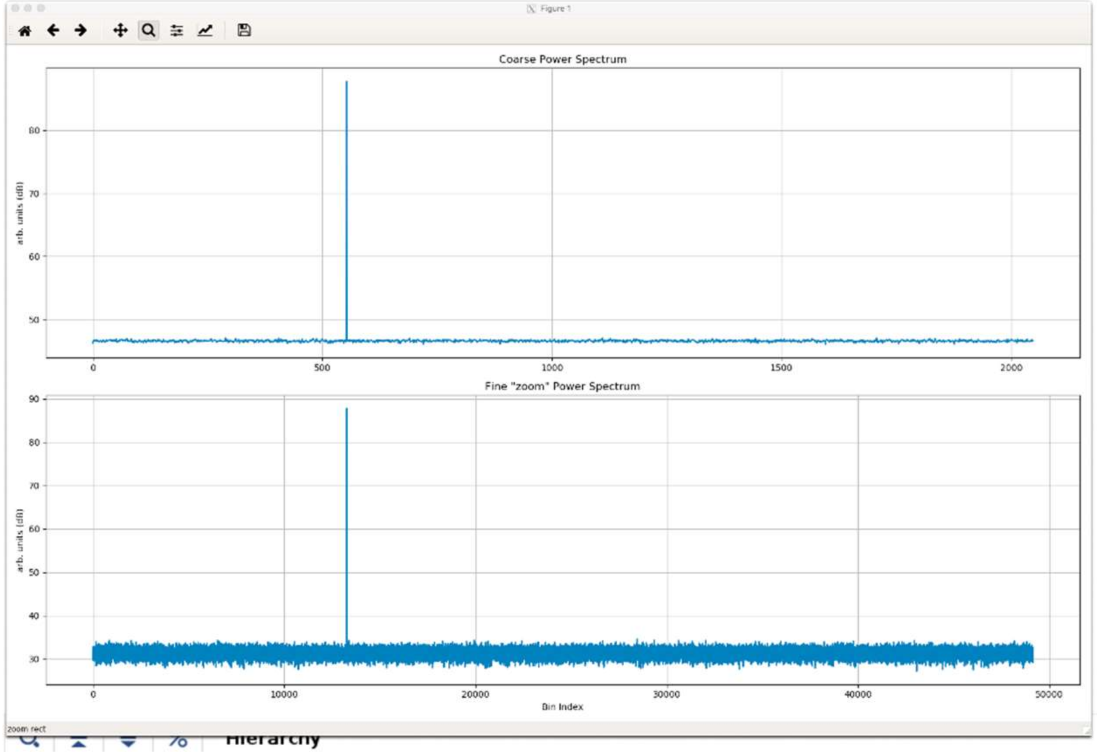
- comparing a fine "zoom" frequency response of 2048 point critically sampled and 4/3 oversampled PFB (both use 8-tap branch filters)

- When using the oversampled PFB:
  - Flat in-channel passband response
  - No gain scalloping

- Resulting in:
  - Very low spectral leakage to adjacent channels
  - No aliasing near coarse channel band edges



F-engine, Oversampled PFB

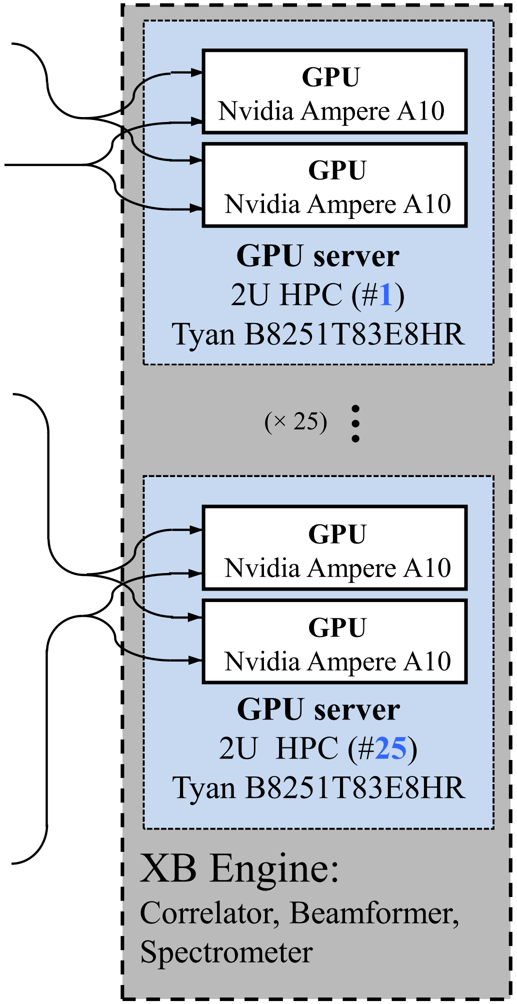


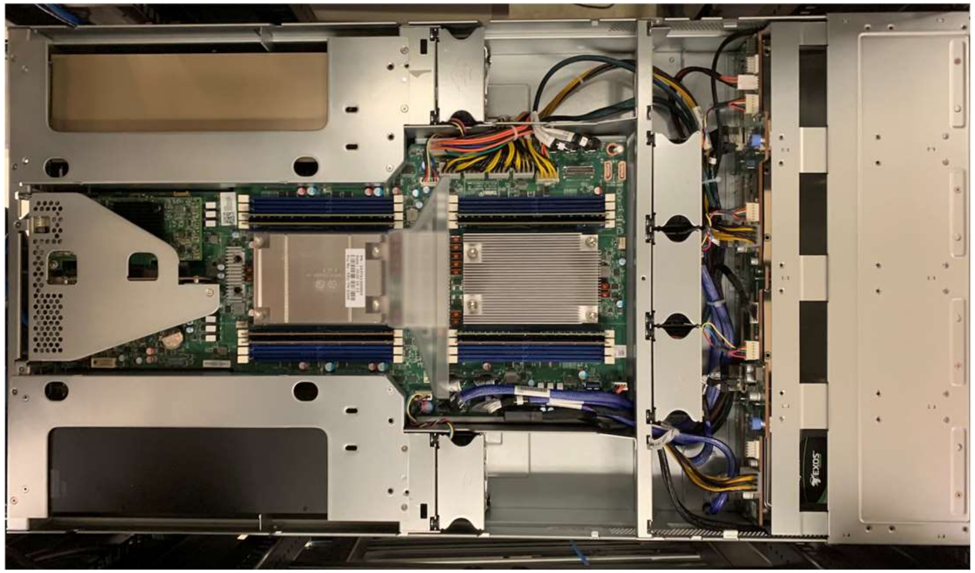
- Hardware outputs from an ALPACA specified OSPFB (2048 branches, 8 polyphase taps per branch)
- Followed by a software second stage critically sampled PFB (32 point, 8 polyphase taps).

Hierarchy

Name	CLB LUTs (425280)	CLB Registers (850560)	CARRY8 (53160)	F7 Muxes (212640)	F8 Muxes (106320)	CLB (53160)	LUT as Logic (425280)	LUT as Memory (213600)	Block RAM Tile (1080)	DSPs (4272)
top	24423	24659	744	457	5	5299	19996	4427	103	68
zcu216_clk_infr_inst (zcu216_clk_infrastructure)	0	0	0	0	0	0	0	0	0	0
zcu216_base_inst (zcu216_base)	8706	6451	46	201	5	1829	8543	163	0	0
zcu216_alpaca_ospfb_tlast_unexpected_reg (cdc_synchroniser__paramet	0	32	0	0	0	20	0	0	0	0
zcu216_alpaca_ospfb_tlast_reg (cdc_synchroniser__parameterized0_12)	0	32	0	0	0	22	0	0	0	0
zcu216_alpaca_ospfb_tlast_missing_reg (cdc_synchroniser__parameterize	0	32	0	0	0	23	0	0	0	0
zcu216_alpaca_ospfb_sum_a_b (cdc_synchroniser__parameterized0_10)	0	32	0	0	0	11	0	0	0	0
zcu216_alpaca_ospfb_saxis_rdy_led (gpio_simulink2ext_9)	0	0	0	0	0	0	0	0	0	0
zcu216_alpaca_ospfb_ovflow_led (gpio_simulink2ext_8)	0	0	0	0	0	0	0	0	0	0
zcu216_alpaca_ospfb_ospfb_inst (xpm_ospfb_top)	15193	16190	665	256	0	3207	10929	4264	71	67

Digital Back End, XB-engine



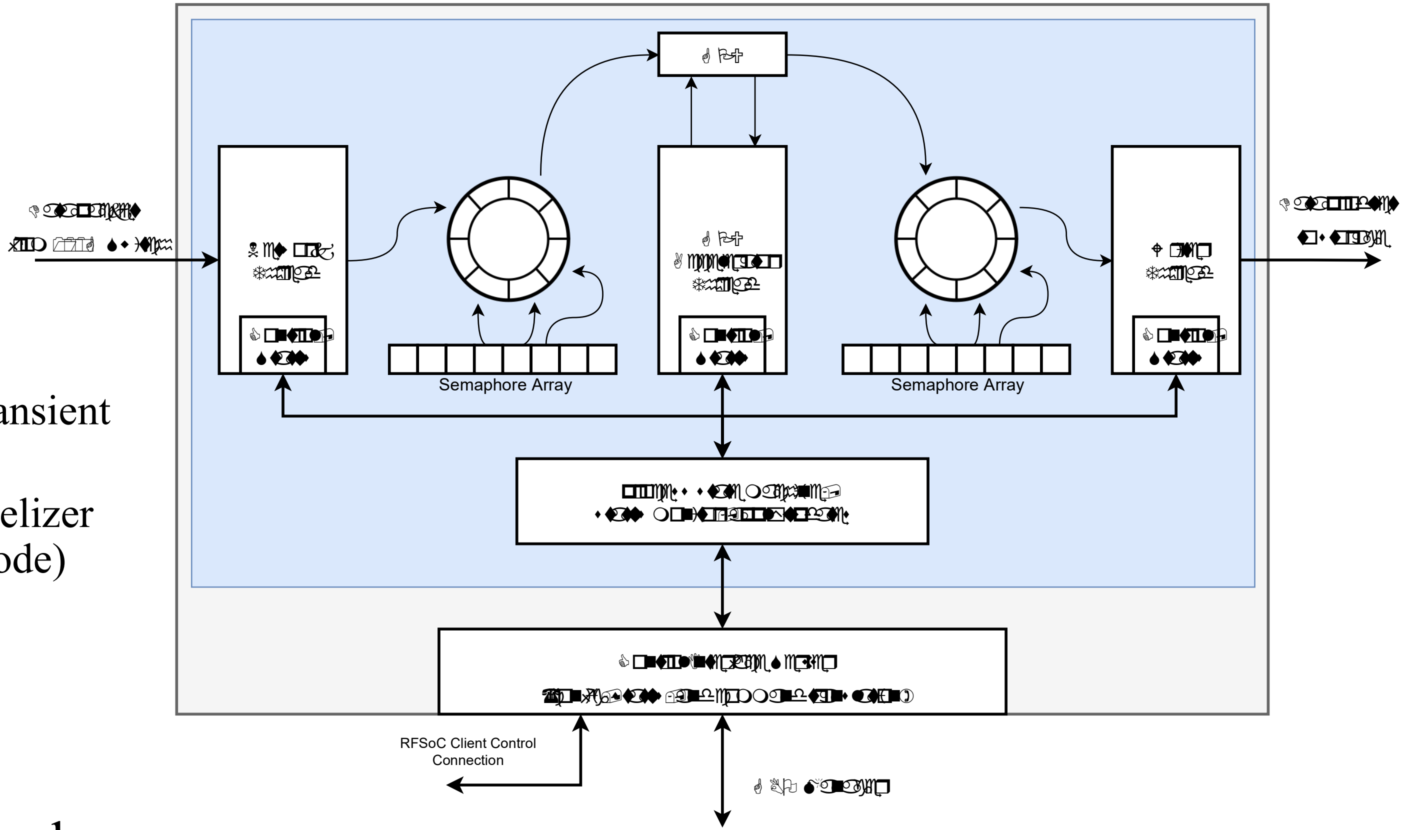


25x 2U Tyan Transport HX, AMD EPYC
96 GB DDR4 RAM, PCIe 4.0

50x (2 per server) NVIDIA A10 GPU and ConnectX-5 dual-port InfiniBand EDR NIC

XB-engine Software Block Diagram

- Hashpipe processing pipeline
- Three primary tasks:
  - Capture network packets
    - ibverbs
  - Implement data processing modes
    - Calibration Correlator
    - Beamformer (Coarse frequency Transient mode)
    - Beamformer + Second stage channelizer (Fine frequency HI/spectral line mode)
  - Format and send output
- Communication through shared memory KV buffers
- Coordination among nodes managed by back end portion of M&C



Antenna Y Factor
and Radiation Efficiency Measurement

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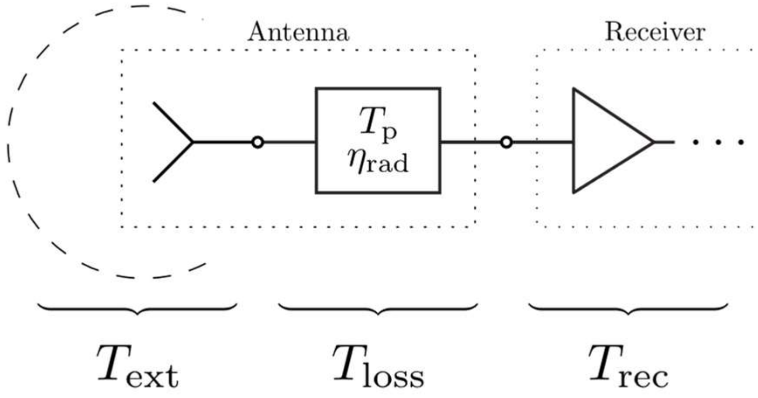
Measuring Radiation Efficiency

- Measurement Methods
  - Wheeler Cap
  - Anechoic Chamber
  - Radiometric (extended hot/cold RF sources)
    - Two antenna, with reference $\eta_{rad} = 1$
    - Link Budget T_{rec}
    - Heated T_p
    - Use the antenna Y factor and standard Y factor measurement of Radiometer to obtain T_{rec} (this experiment)



System noise contributions to SNR loss

$$T_{sys} = \eta_{rad} T_{ext} + \underbrace{(1 - \eta_{rad}) T_p}_{T_{loss}} + T_{rec}$$

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Measuring Radiation Efficiency

- The antenna Y factor is the ratio of noise powers at the system output when exposed to extended hot/cold loads

$$Y = \frac{P_{\text{hot}}}{P_{\text{cold}}} = \frac{\eta_{\text{rad}} T_{\text{hot}} + T_{\text{loss}} + T_{\text{rec}}}{\eta_{\text{rad}} T_{\text{cold}} + T_{\text{loss}} + T_{\text{rec}}}$$

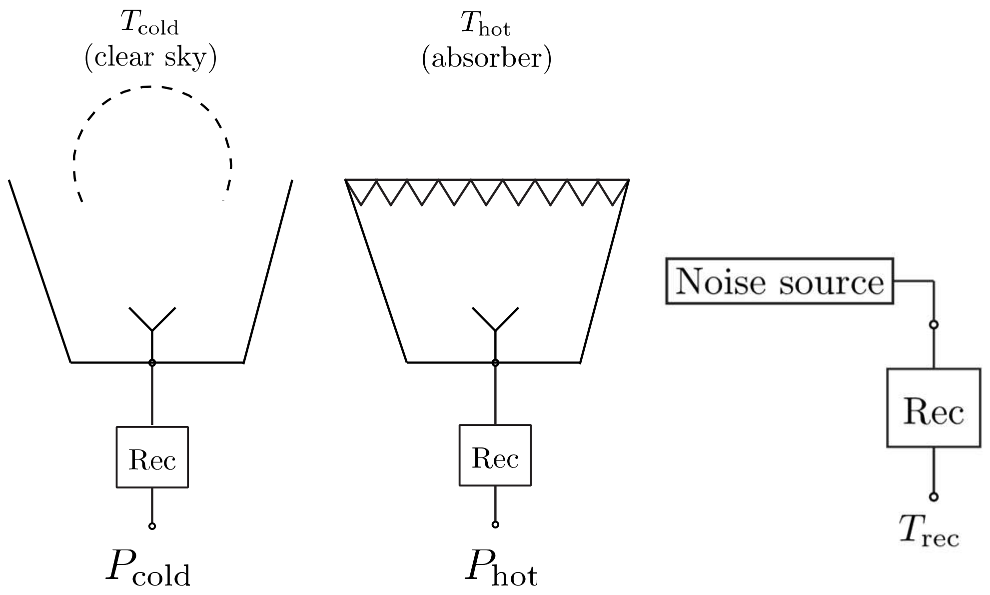
- From the antenna Y factor, an equivalent active antenna temperature is computed as (Kerr 1999)

$$T_{\text{eq}} = \frac{T_{\text{hot}} - Y T_{\text{cold}}}{Y - 1}$$

- If we move the reference plane for the system noise temp to before antenna losses (e.g., to an equivalent sky temperature)

$$T_{\text{sys}} = \eta_{\text{rad}} T_{\text{ext}} + \underbrace{(1 - \eta_{\text{rad}}) T_{\text{p}}}_{T_{\text{loss}}} + T_{\text{rec}}$$

$$\frac{T_{\text{sys}}}{\eta_{\text{rad}}} = T_{\text{ext}} + \underbrace{\frac{T_{\text{loss}} + T_{\text{rec}}}{\eta_{\text{rad}}}}_{T_{\text{eq}}}$$



$$\eta_{\text{rad}} = \frac{(T_{\text{p}} + T_{\text{rec}})(Y - 1)}{T_{\text{hot}} - T_{\text{p}} + Y(T_{\text{p}} - T_{\text{cold}})}$$

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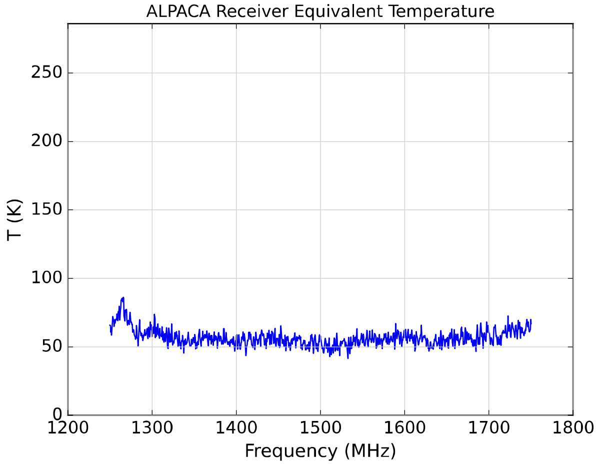
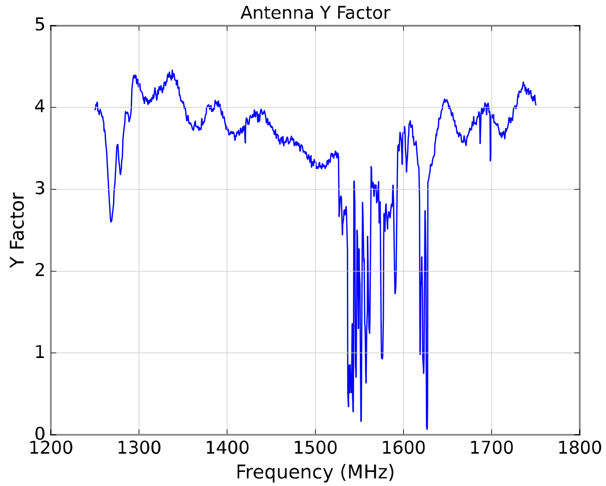
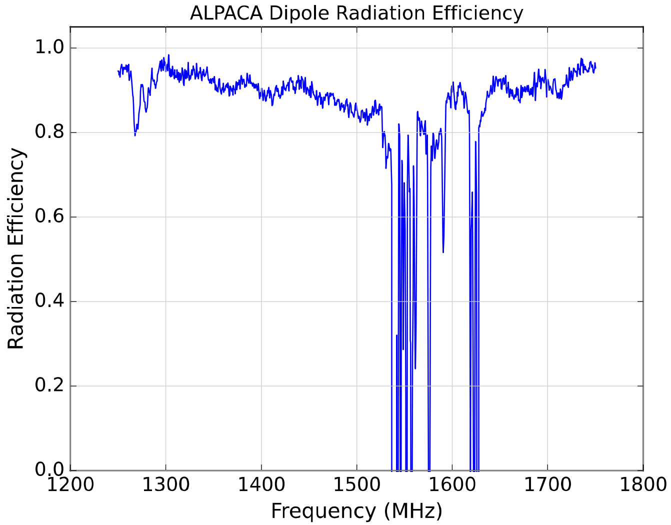
Measuring Radiation Efficiency

Ground shield with absorber foam (hot load)







Extrapolation to Cryogenic Temperatures

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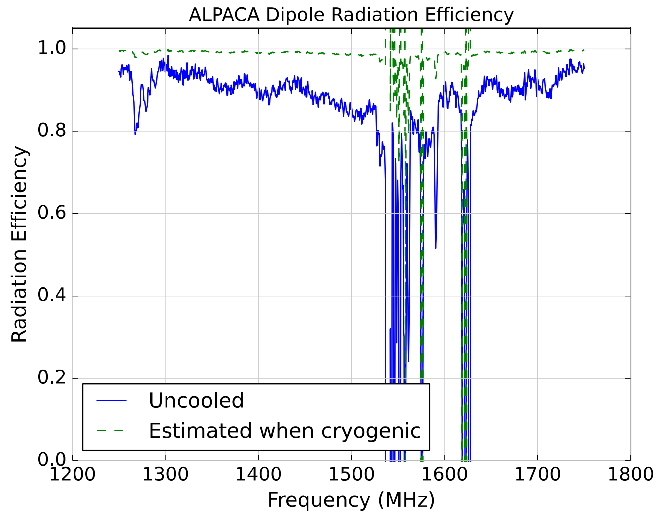
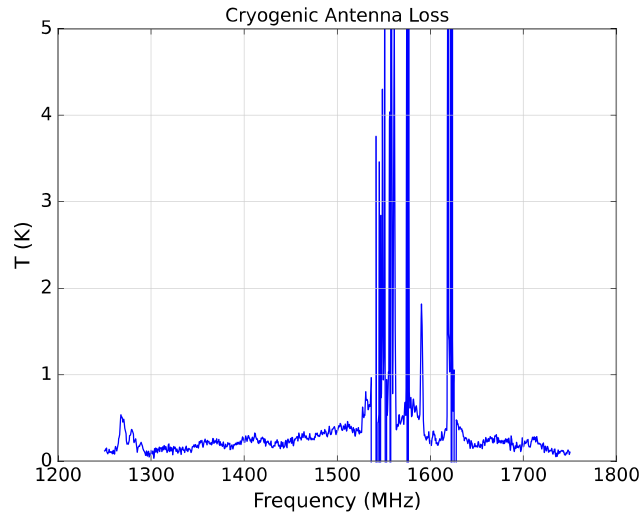
- At cryogenic temperatures, electrical conductivity is quantified by relative resistivity ratio (RRR)
- ALPACA dipole is fabricated primarily from Aluminum 6061
- coax core that runs from the wedge arms to SMA connector of the LNA is BeCU C17300.
- Dipole is 99.7% pure gold plated with minimum 100 micro-in (2.54 um) thickness and a layer of copper for adhesion
- At L band, the gold plating is several skin depths thick, so the gold substantially determines the electrical conductivity of the antennas.
- Using a value of 12 for the RRR (Finger & Kerr 2008) of gold at 20 K we extrapolate the antenna radiation efficiency and estimated loss contributed by the antenna

$$\eta_{\mathrm{rad},\ 20\,\mathrm{K}} = \frac{R_{\mathrm{rad}}}{R_{\mathrm{rad}} + R_{\mathrm{loss}}/\mathrm{RRR}} \qquad T_{\mathrm{loss}} = (1 - \eta_{\mathrm{rad}})T_{\mathrm{p}}$$





CASPER Integration

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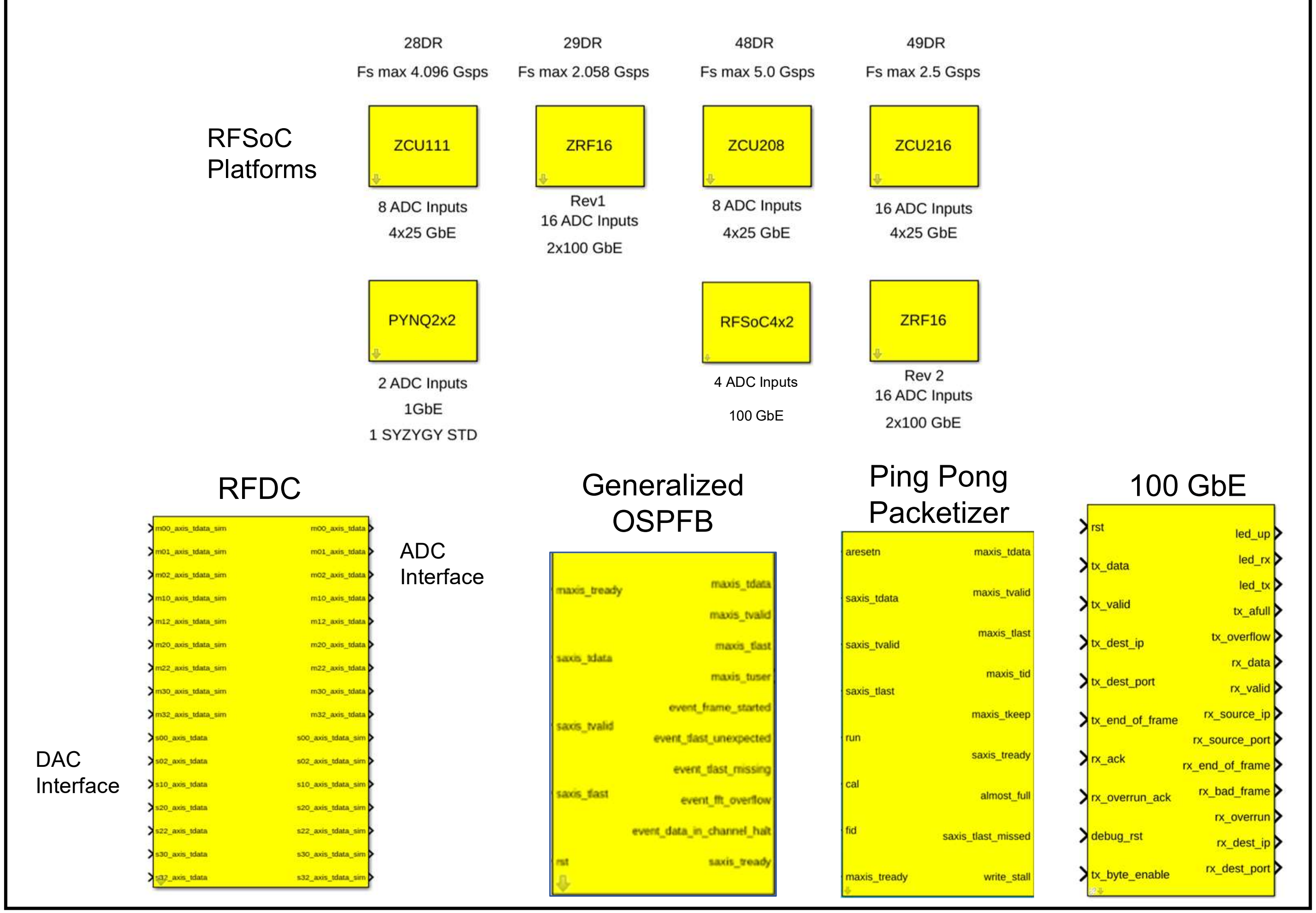
CASPER Integration

- Gen1 and Gen 3 RFSoC Platforms:
  - RFSoC 4x2, ZCU216, ZCU208
  - ZCU111, ZRF16
- RFSoC ADC and DAC
- Generalized OSPFB
- URAM Packetizer
- 100GbE Core

RFSoC, RF Data Converter, packetizer and 100GbE Yellow Blocks library



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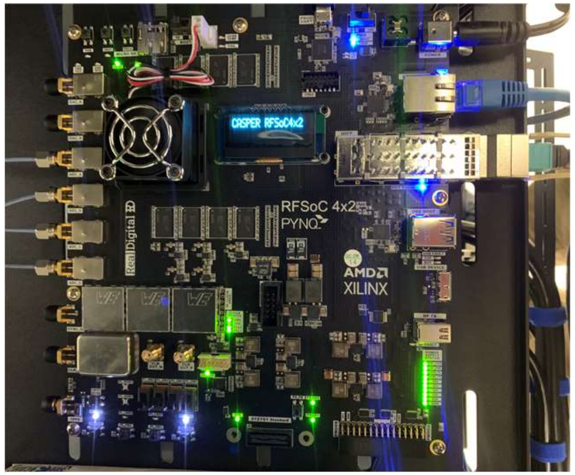
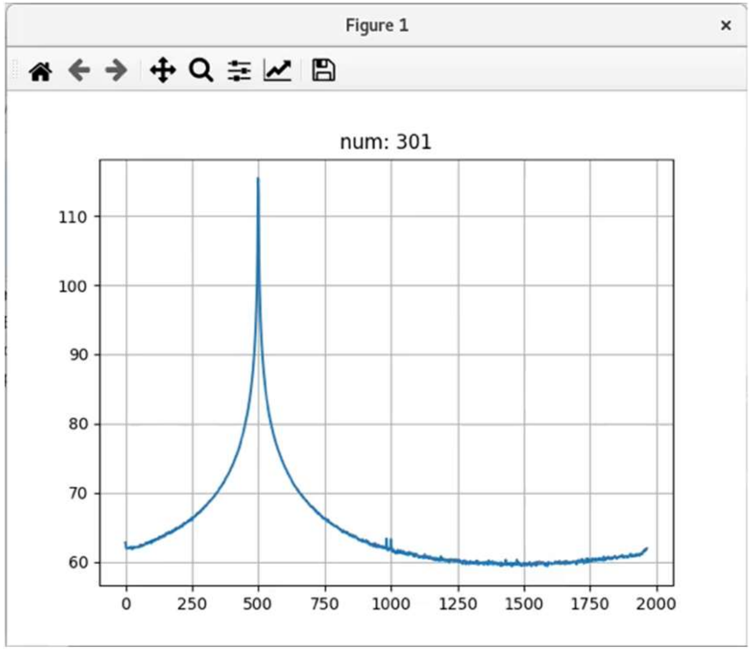
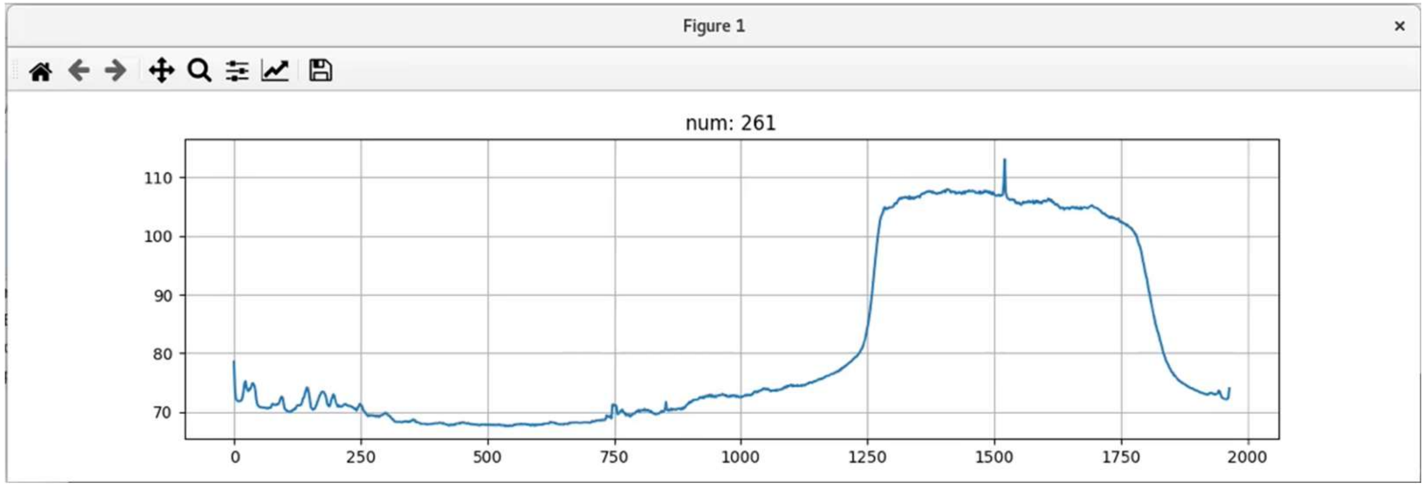
CASPER Integration

RFSoC Tutorials: https://casper-toolflow.readthedocs.io/projects/tutorials/en/latest/

- From Getting started with RFSoC
- To using the RFDC
- And how to stream ADC samples using 100 GbE and capture data packets at a NIC for processing







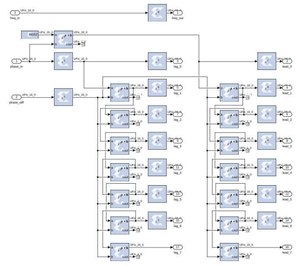
Thank you!

RADIO ASTRONOMY SYSTEMS | BYU

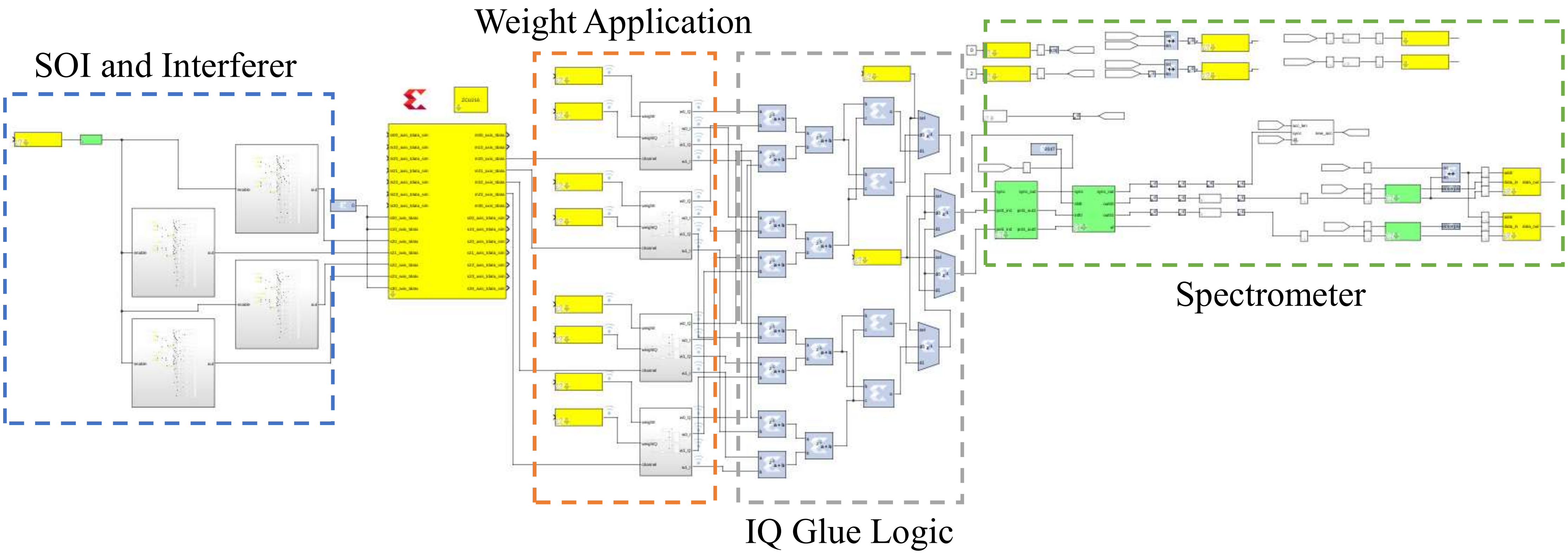
RADIO ASTRONOMY SYSTEMS BYU

CASPER Integration

- 4 element ULA
- System Generator Polyphase DDS for generating 2 signals from different directions

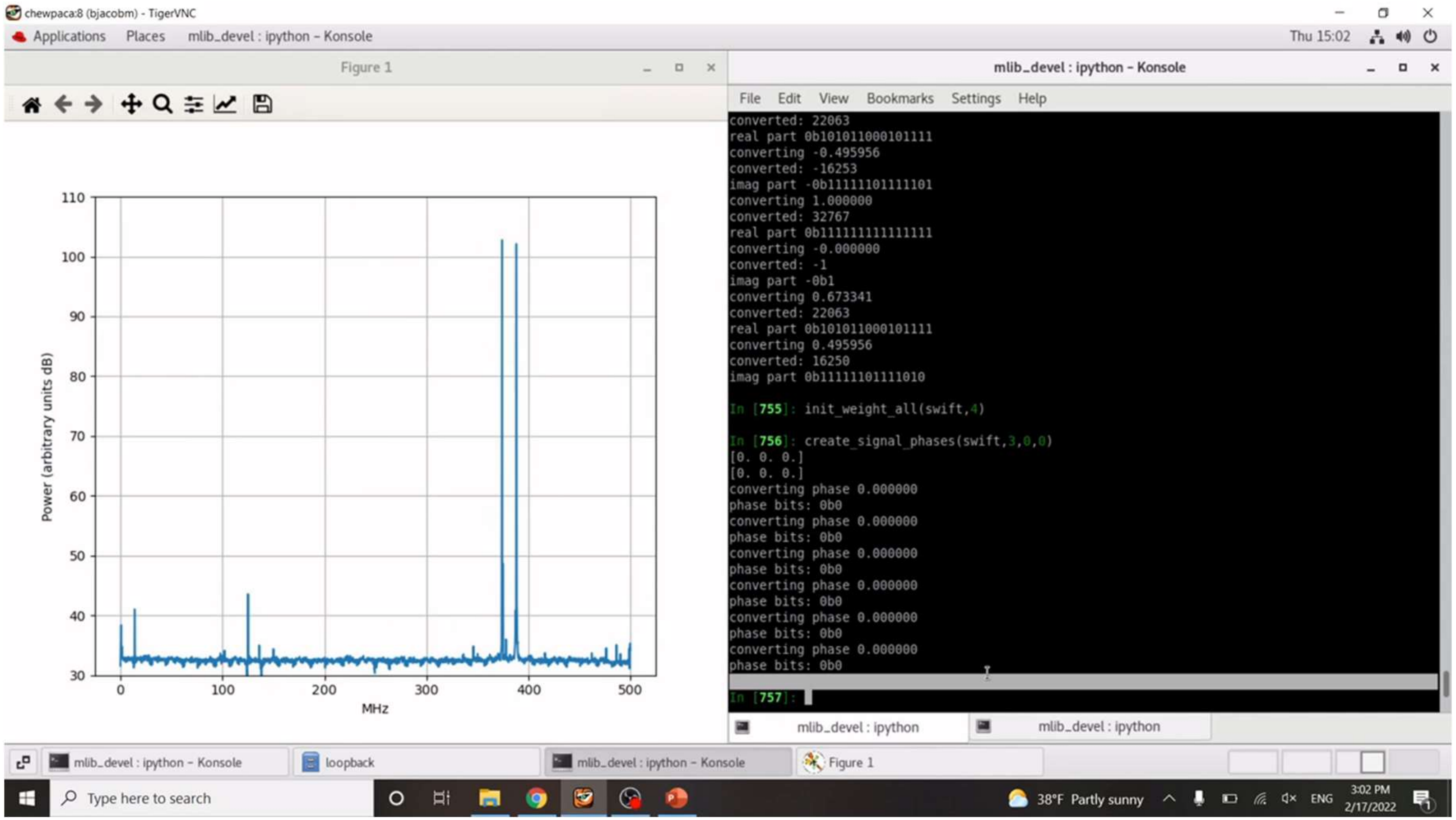


- Complex multiply blocks for weight application
- Beamforming weights computed in python
- PFB-based spectrometer



RADIO ASTRONOMY SYSTEMS BYU

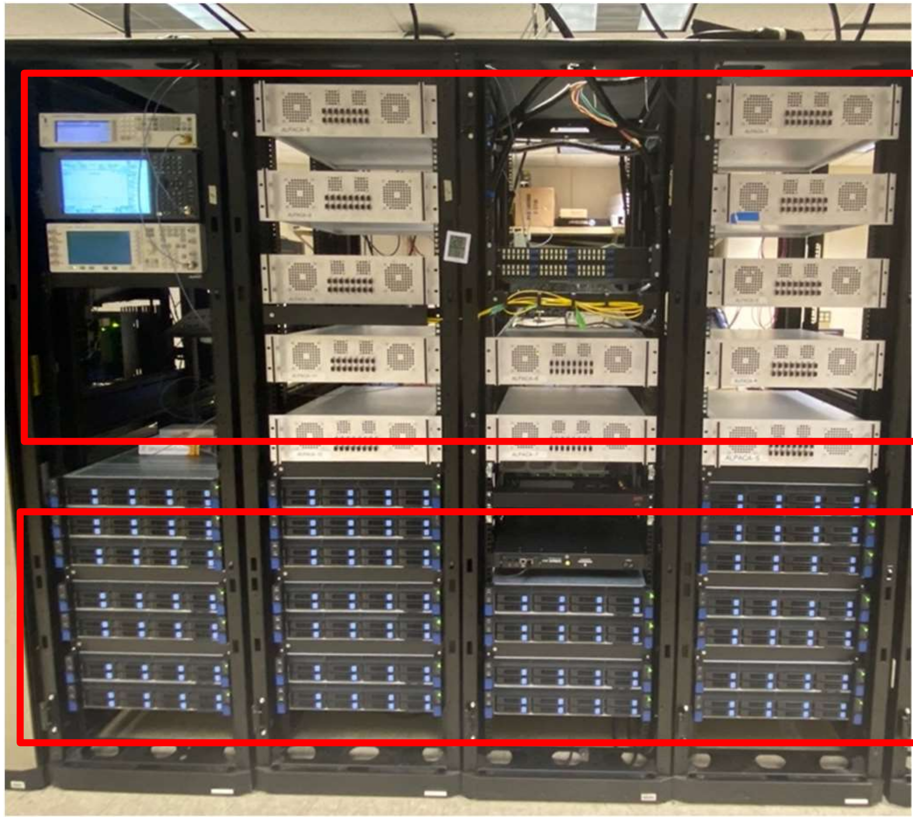
- SOI tone sweep from 260 – 410 MHz at 20°
- Interferer tone random FSK from 260 – 410 MHz at 70°



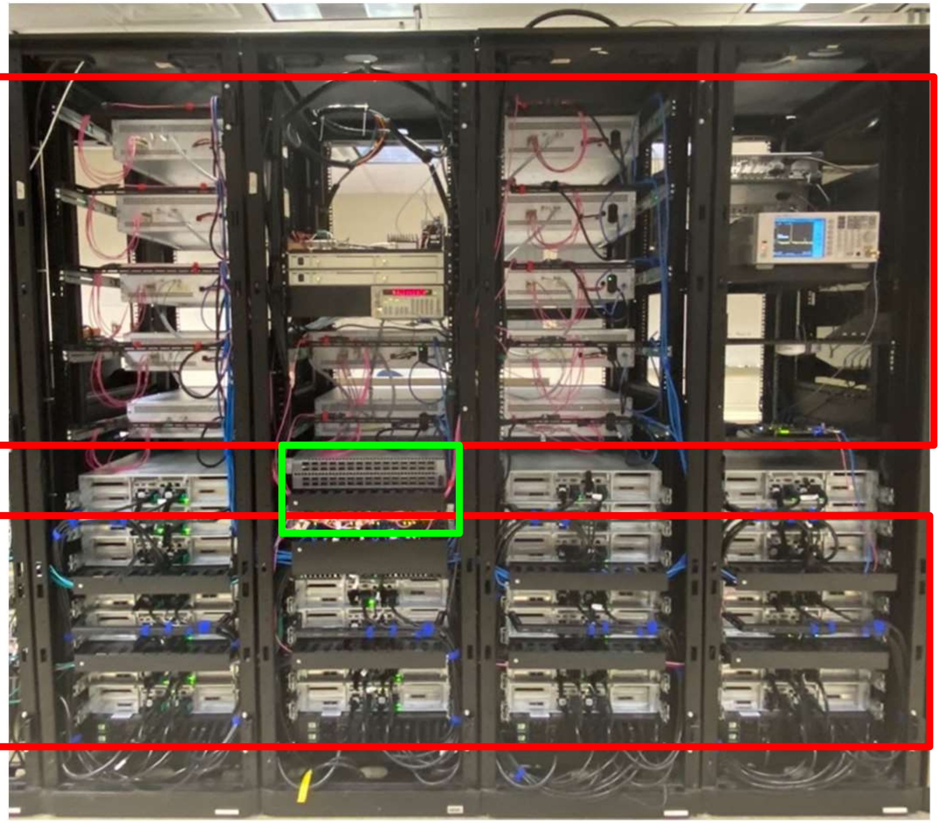
RADIO ASTRONOMY SYSTEMS BYU

XB-engine

Front



Back



RFSoC Frequency channelizer (F-engine)

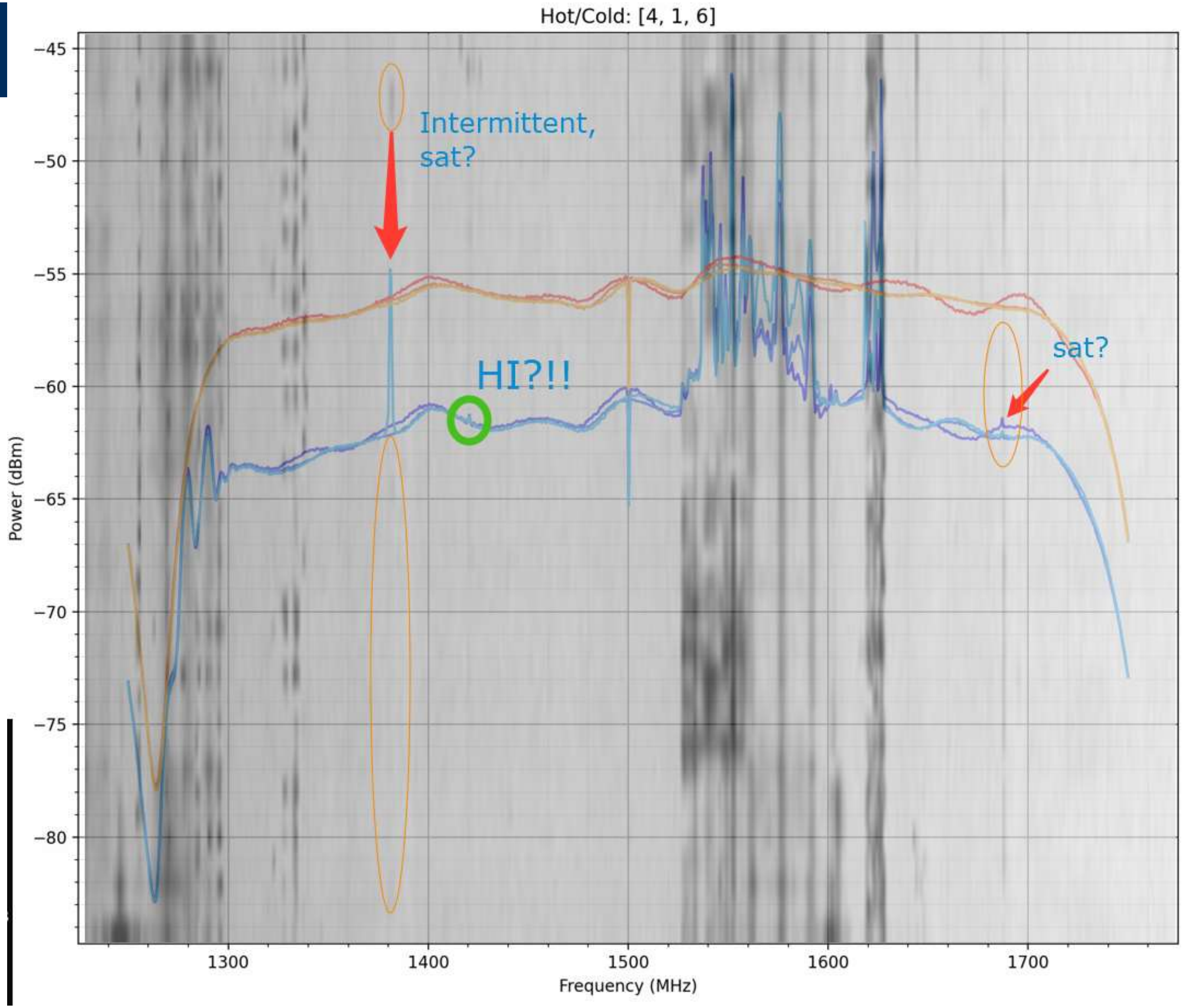
Ethernet Switches

GPU Correlator/Beamformer (X/B-engine)

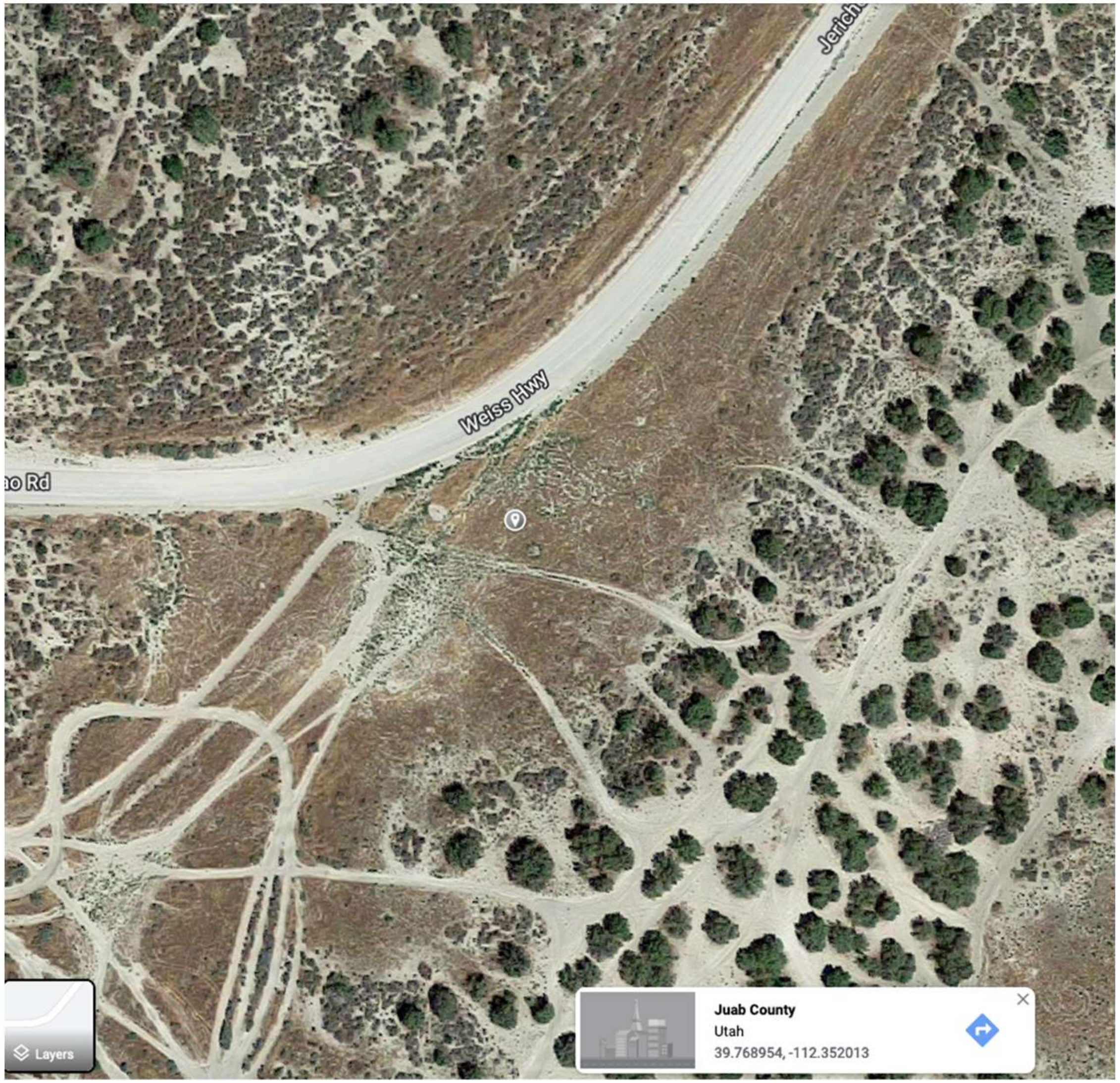
RADIO ASTRONOMY SYSTEMS BYU

VLA RFI monitoring data from:
http://www.vla.nrao.edu/cgi-bin/rfi.cgi

Using W8Mon for Mar 24 5-6 PM MST



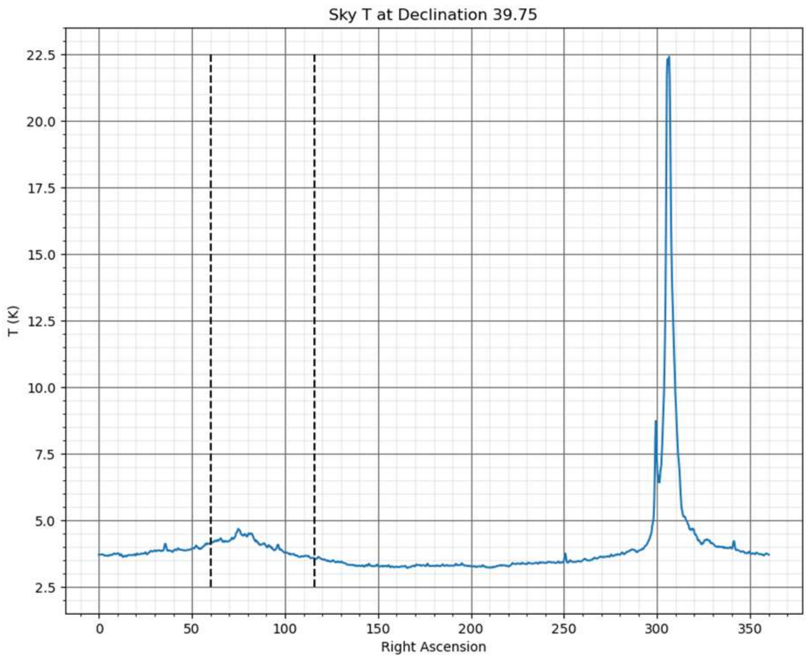
RADIO ASTRONOMY SYSTEMS BYU

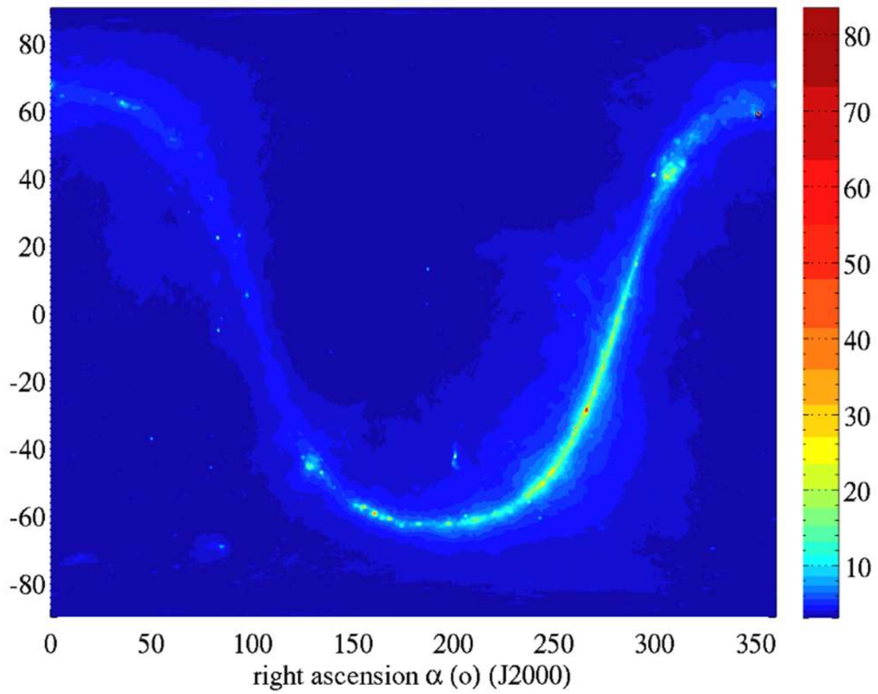



```
SIDEREAL TIME FOR GIVEN DATE, TIME AND LONGITUDE

Local Date  =  20220324    =  2022 Mar 24 [Thursday] Gregorian
JD00        =  2459662.5   = JD number for 00h TT of date

Local Time  =  17:23:00 =  0.724305555556 day
T Zone Diff = +06:00      = +0.250000000000 day
Delta T     = +00:00:00 = +0.000000000000 day

Full astronomical JD number = Sum of all given date/time elements above
JD = 2459663.474305555556 = (JD00 + LTFrac + TZFrac + dTFrac)

Date/Time TT Corresponding to Full JD
20220324 23:23:00.0 TT

Longitude = -112° 21' 07.2" = -112.3520000000° (W)
          = -07h 29m 24.5s = -7.4901333333 h

===============================================================
Local Mean Sidereal Time at Longitude -112.3520000000° (W)
04h 03m 15s = 4.0540970100 h
60° 48' 41" = 60.8114551506°

Local True Sidereal Time at Longitude = -112.3520000000° (W)
04h 03m 14s = 4.0538593534 h
60° 48' 28" = 60.8078903011°
```

```
SIDEREAL TIME FOR GIVEN DATE, TIME AND LONGITUDE

Local Date  =  20220324    =  2022 Mar 24 [Thursday] Gregorian
JD00        =  2459662.5   = JD number for 00h TT of date

Local Time  =  21:04:00 =  0.877777777778 day
T Zone Diff = +06:00      = +0.250000000000 day
Delta T     = +00:00:00 = +0.000000000000 day

Full astronomical JD number = Sum of all given date/time elements above
JD = 2459663.627777777778 = (JD00 + LTFrac + TZFrac + dTFrac)

Date/Time TT Corresponding to Full JD
20220325 03:04:00.0 TT

Longitude = -112° 21' 07.2" = -112.3520138889° (W)
          = -07h 29m 24.5s = -7.4901342593 h

===============================================================
Local Mean Sidereal Time at Longitude -112.3520138889° (W)
07h 44m 51s = 7.7475140431 h
116° 12' 46" = 116.2127106460°

Local True Sidereal Time at Longitude = -112.3520138889° (W)
07h 44m 50s = 7.7472766704 h
116° 12' 33" = 116.2091500566°
```

$$T_{\text{sky}} = T_{\text{Cont}} + T_{\text{Cas A}} + T_{\text{HI}} + T_{\text{CMB}}$$





Assumptions from this…

- Tcold chosen to be 6.8 to 15 K, a more accurate number might need to include geometry of the shield, and contributions from the sun
- Thot and Tp the ambient air temperature