Design and Hardware Overview of PUEO

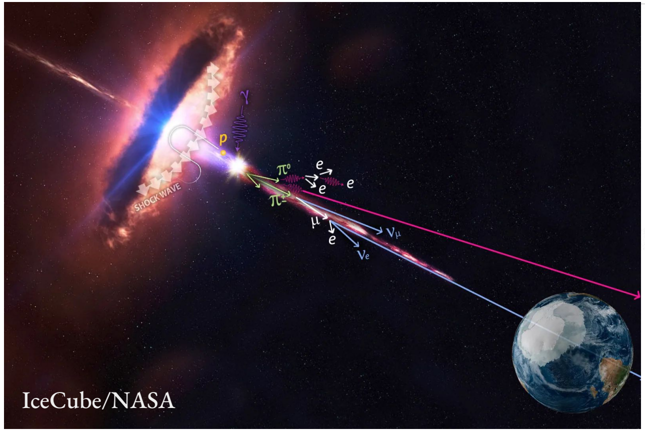
Rachel Scrandis for the PUEO Collaboration

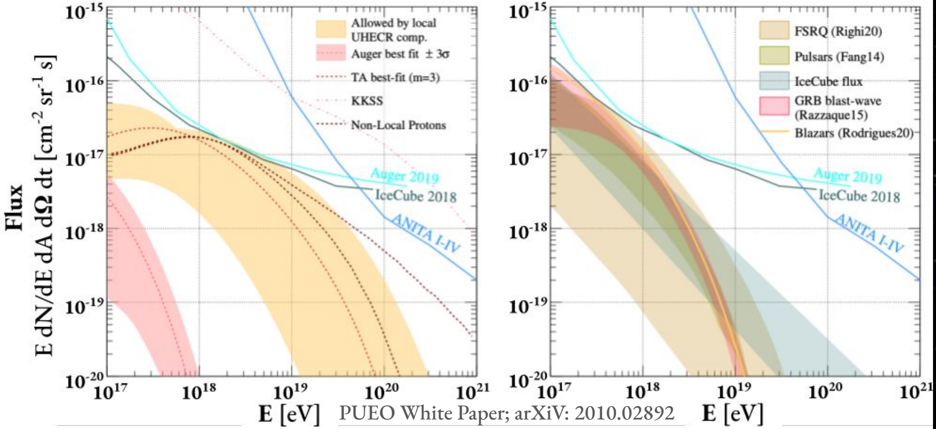
PUEO

TeVPA
Chicago 2024

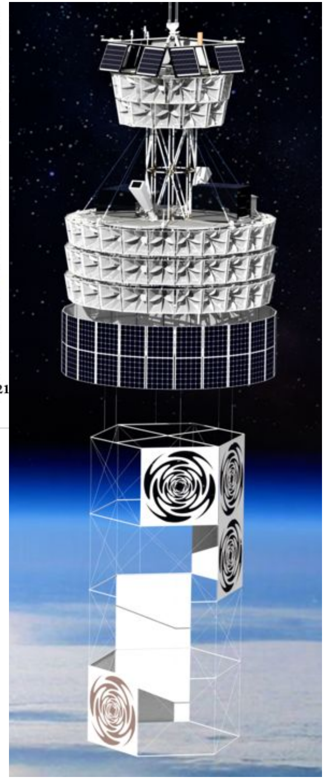
THE UNIVERSITY OF CHICAGO
1890

PUEO's Science Goals





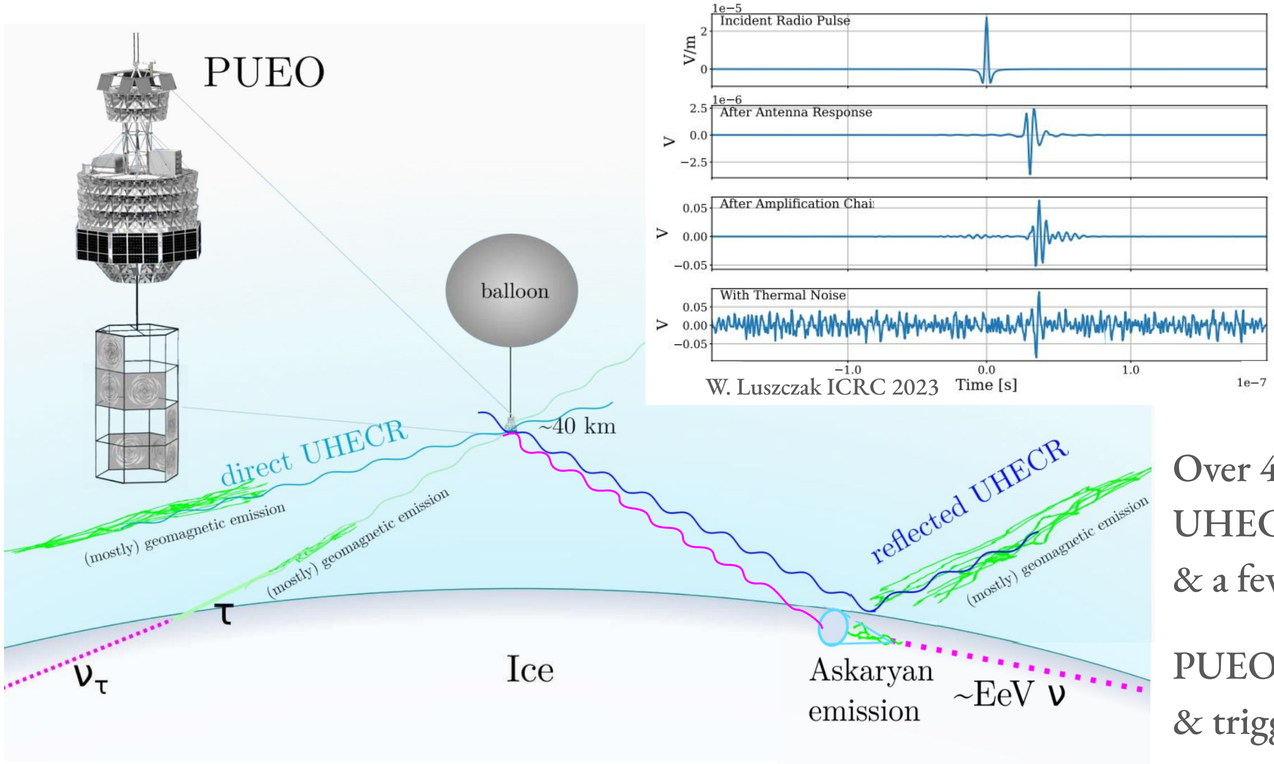
PUEO White Paper; arXiV: 2010.02892



PUEO's goal is to use radio to measure (or set the best limits on) the UHE neutrino flux in order to understand the most extreme environments of our universe

Based off of ANITA heritage, it will leverage the Askaryan emission mechanism to measure these neutrinos

PUEO's Science Signal



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ANITA-IV Recorded Data (O(10^7) events)	
Thermal Noise	~99% of data
Anthropogenic	~0.9% of data
Cosmic Rays	~30 events
Neutrino Candidates	~a few events

A. Ludwig Thesis

Over 4 successful flights, ANITA saw 100s of UHECRs, no excess in neutrino-like events, & a few upward-going air shower candidates

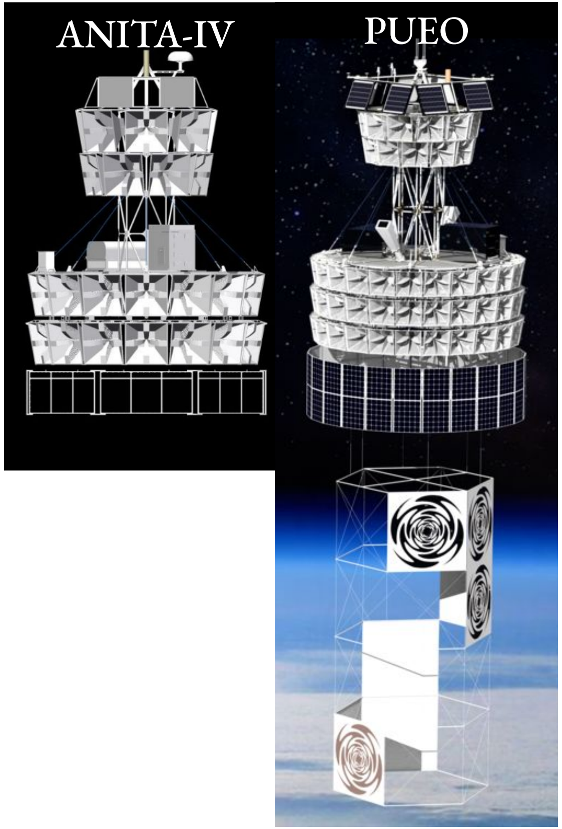
PUEO will improve on background rejection & trigger threshold to increase discovery potential for UHE neutrinos

PUEO Design

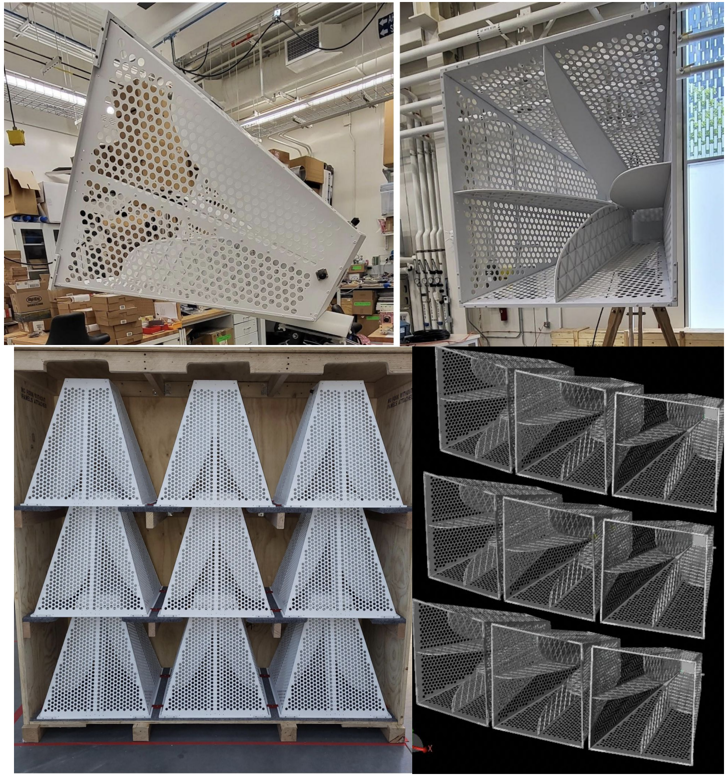
PUEO will be searching for impulsive radio signals in the 300-1200 MHz range and will be capable of reconstructing neutrino direction, energy, and potentially flavor

PUEO will feature:

- 96 quad-ridge horn antennas (192 RF channels)
- 8 sinuous low frequency antennas (16 RF channels)
- Phased array trigger
- Telemetry capabilities
- Navigation suite
- On board power system & housekeeping



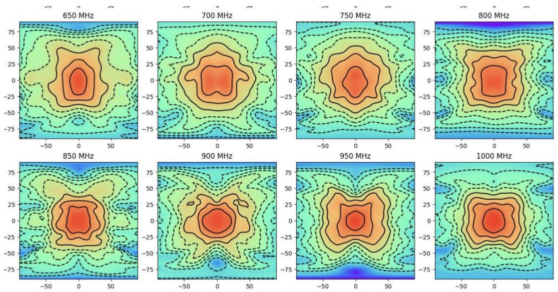
Antennas

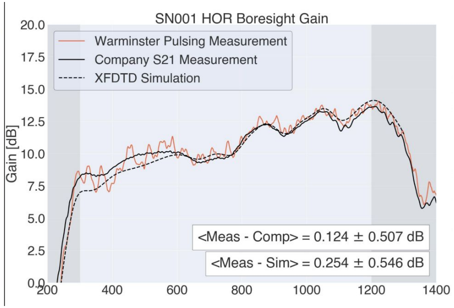


Custom antennas feature (in 300-1200 MHz band):

- Dual polarization
- <-10dB in return loss (S11)
- <-30dB in port isolation (S21)
- ~10dBi boresight gain (ANITA-IV gain: ~8dBi)

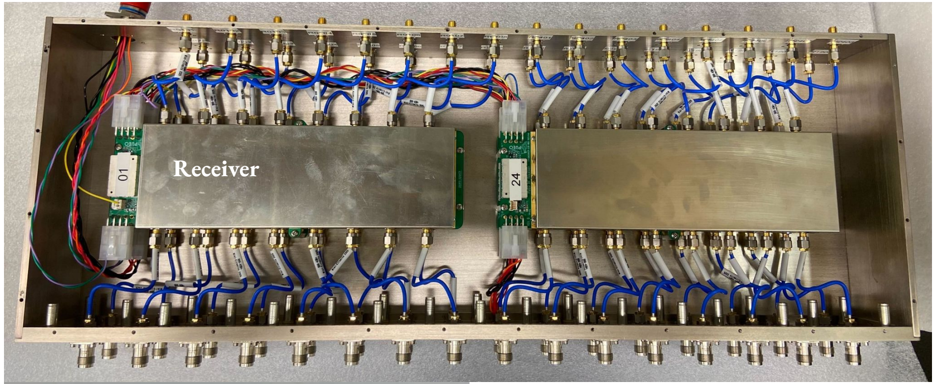
Characterization measurements and sims ongoing

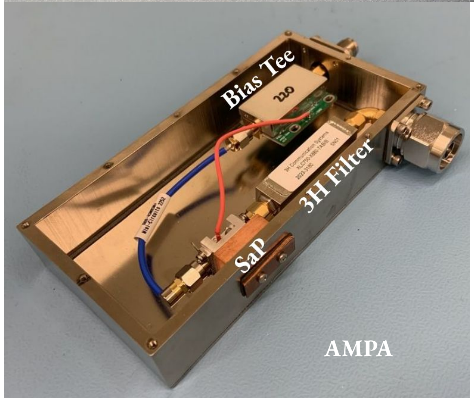




Work by Zack Martin, Scott Mackey, & Natalie Orrantia

RF Chain

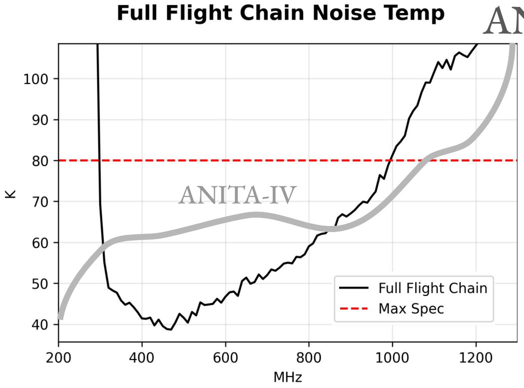


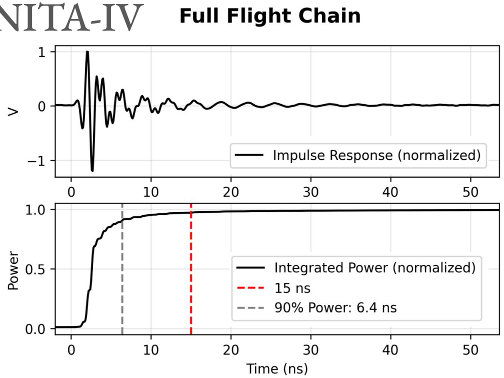


Signal conditioning happens in 2 stages:

1. Antenna Mounted Pre-Amplifier (AMPA) gives ~40dB
2. Octal Receiver (2nd stage amp) gives ~30dB

With cable losses, chain presents 68dB of gain & 23% lower noise temp (inherit chain noise) than ANITA-IV



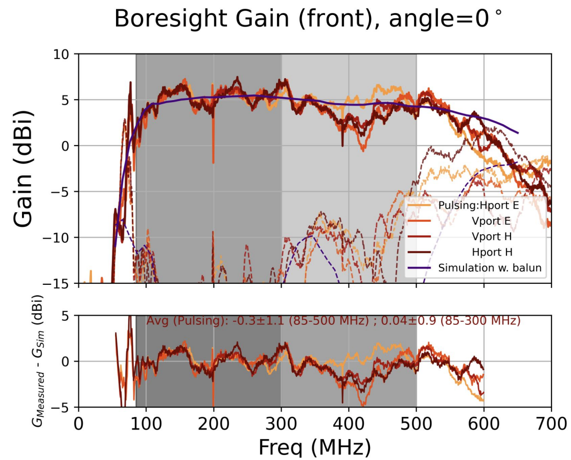


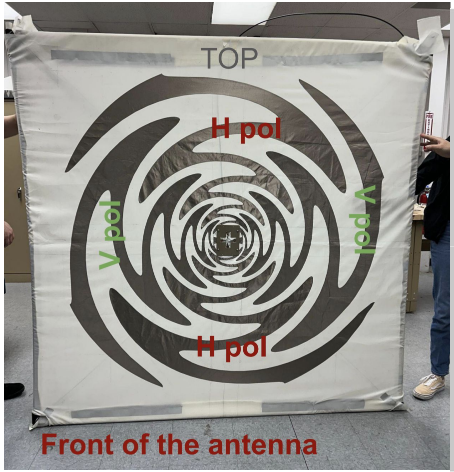
Work by me, Eric Oberla, Peter Gorham, Claire Kaplan, and Tori Ankel

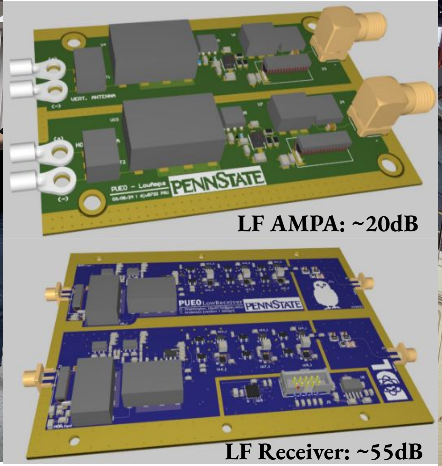
LF Instrument

LF Instrument will target lower frequency air showers (CRs and upgoing Taus). Antennas are sinuous design, sensitive to 50-300MHz.

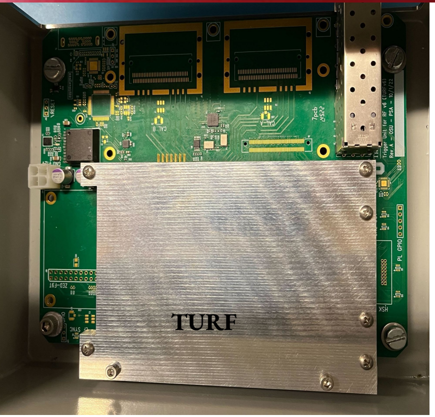
- Conductive fabric (Nylon ripstop coated with Ni/CuAg) on polyester
- ~5dBi boresight gain and 30° beam width
- Will be stowed in gondola during launch, and deployed at float

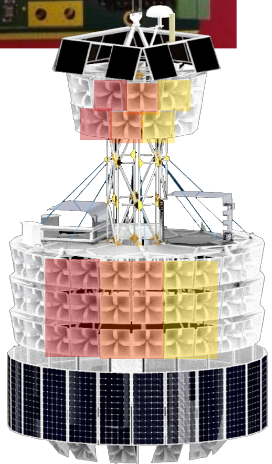






DAQ





Sampling Unit for Radio Frequencies (SURF)

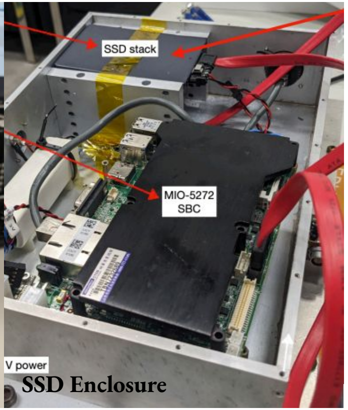
- Uses RFSoCs (x8 ADC @ 3GHz) to digitize 8 RF channels (8 antennas, one pol = 2 phi sectors)
- Conditions signal with FIR low pass filter (boost SNR), 2 biquad notch filters (satellite noise rejection), and 12-to-5 bit conversion (offset & gain control)
- On board FPGA handles beamforming & triggering:
  - L1 Trigger: 100kHz, beam forming with 2 phi sectors (1 SURF)
  - L2 Trigger: 100Hz, beam forming with 4 phi sectors (pulls from neighboring SURF)

Triggering Unit for Radio Frequencies (TURF)

- L3 Trigger: under design (CW elimination, polarization check, etc...)
- Communicates with SFC to record triggered data

Work by Patrick Allison, Lucas Beaufore, Jim Beatty, Taylor Coakley, & Aera Jung

Data Storage & Downlinking

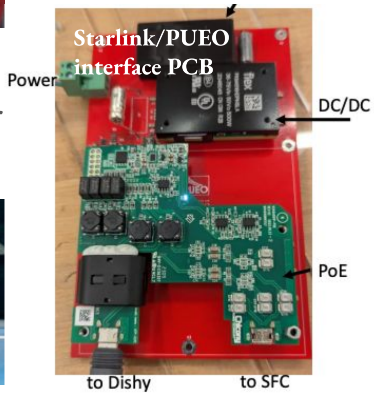


Triply redundant data storage onboard

- 2 HD enclosures (128TB of storage each)
- 1 SSD enclosure (80TB of storage)

Quick connect mounting/demounting for fast takeaway

Starlink used recently on balloon flights→ exploring use for PUEO (after mitigating RFI & thermal concerns)

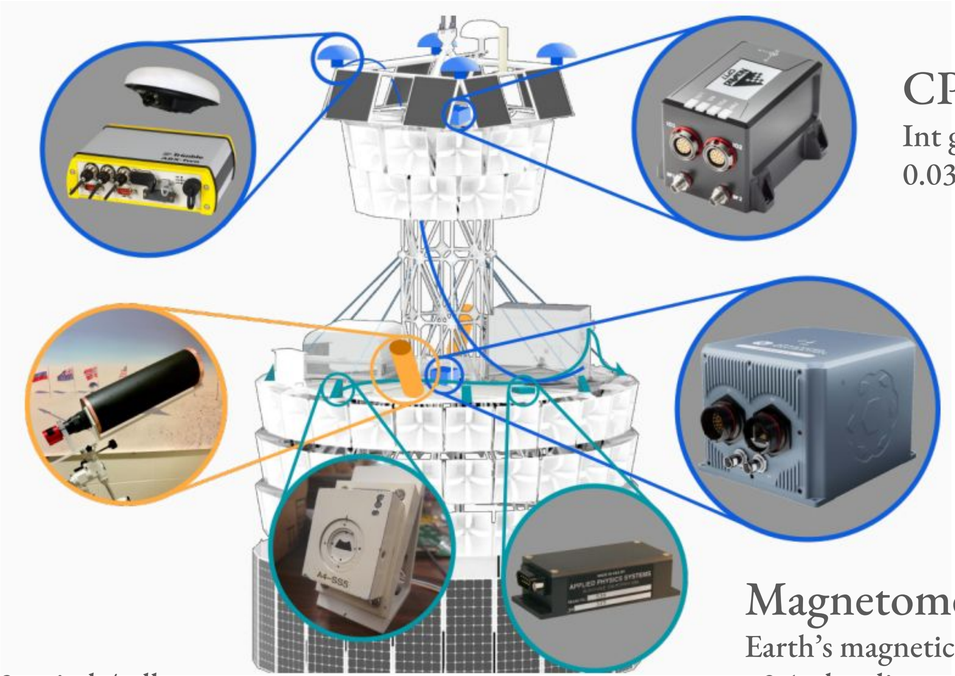


Data downlinking rates dependant on what we decide to use:

- LOS EVTM (up to 12.8 Mbps or so)
- Iridium (255 bytes/every 15M)
- TDRS (6 kbps)
- Starlink (1-40 Mbps downlink)

Work by Keith McBride, Cosmin Deaconu, Connor Godden, TsungChe Liu, Jiwoo Nam, & Natalie Orrantia

Location & Orientation Tracking



ABX2:
Differential GNSS
0.02° heading, 0.075° pitch/roll

CPT7 IMU:
Int gyroscope and accelerometer
0.03° heading, 0.01° pitch/roll

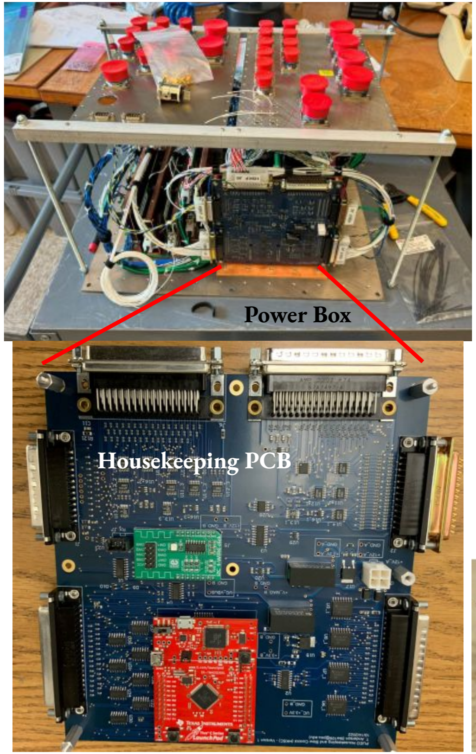
Star Tracker:
Mag <6 stars
0.001° heading, 0.001° pitch/roll

Boreas IMU:
Int gyroscope and accelerometer
0.005° heading, 0.006° pitch/roll

Sun Sensor:
Sun
0.17° heading, ~0.3 ° pitch/roll

Magnetometer:
Earth's magnetic field
~0.1 ° heading, ~0.1 ° - 0.5 ° pitch/roll

Power & Housekeeping

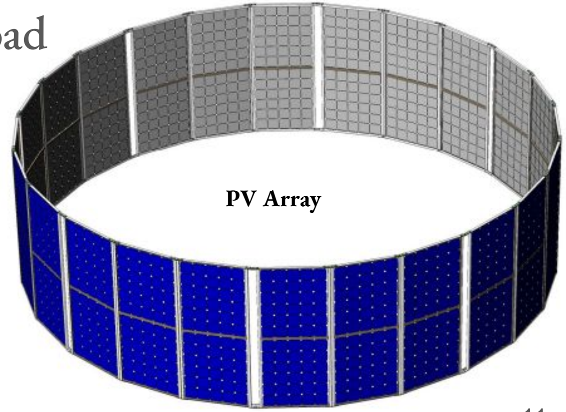


Power comes from PV array→ designed to generate 1800W

- Power box supplies 24V, 12V, 5V, and 4V across payload

Housekeeping board also lives in power box

- Monitors power consumption across payload
- Monitors temperatures across payload
- Toggles on/off RF chain

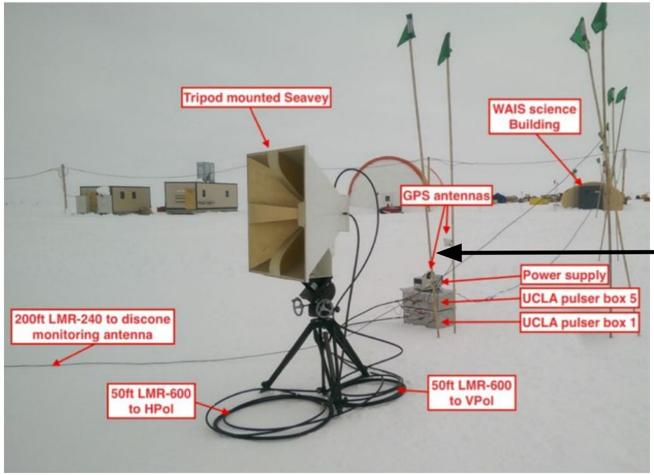


Work by Brian Rauch, Keith McBride, and Zack Martin

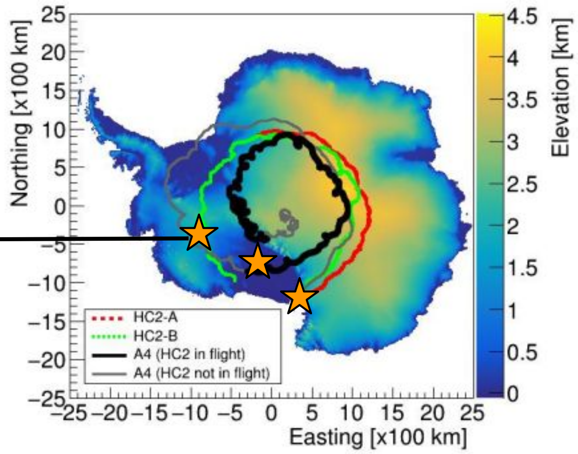
Calibration Plan

PUEO

Ground Calibration

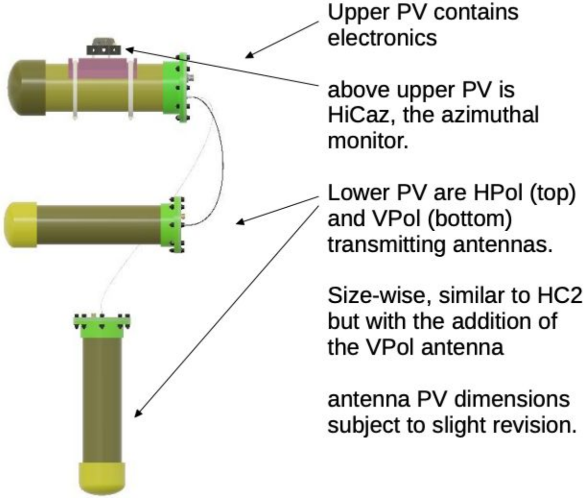


Field stations along PUEO path that pulse as payload flies overhead



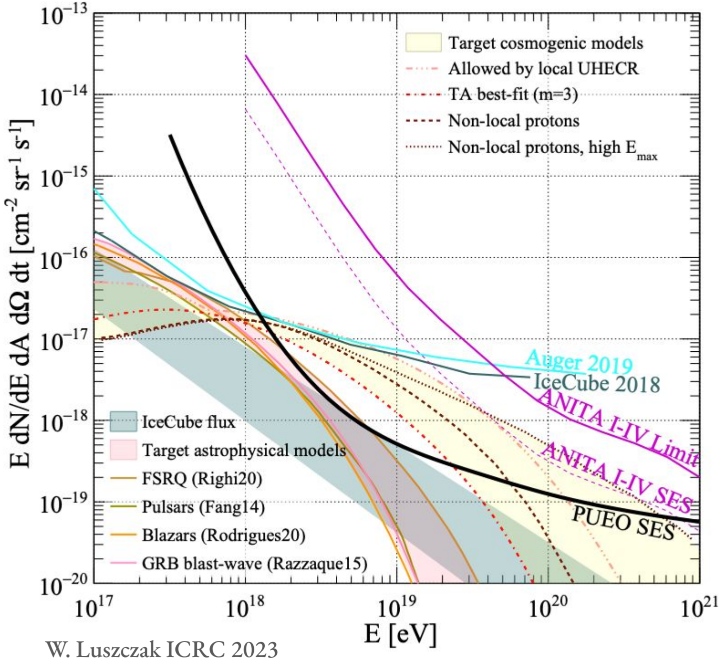
Work by Steven Prohira, Steph Wissel, Julien Alfaro, Shoukat Ali, Dave Besson, Kenny Couberly, Rob Young, & Andrew Zeolla

High-altitude Calibration



Small hand-launched balloons that follow main payload

Outlook



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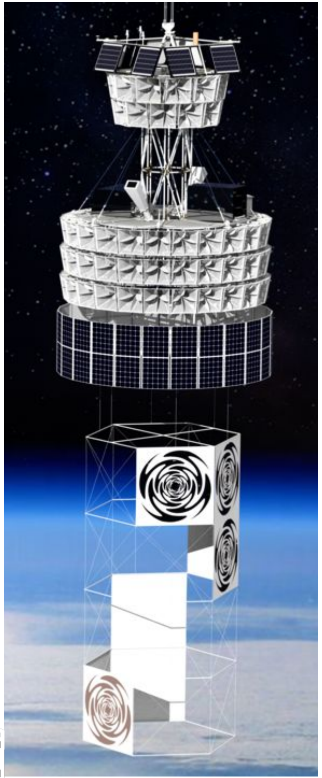
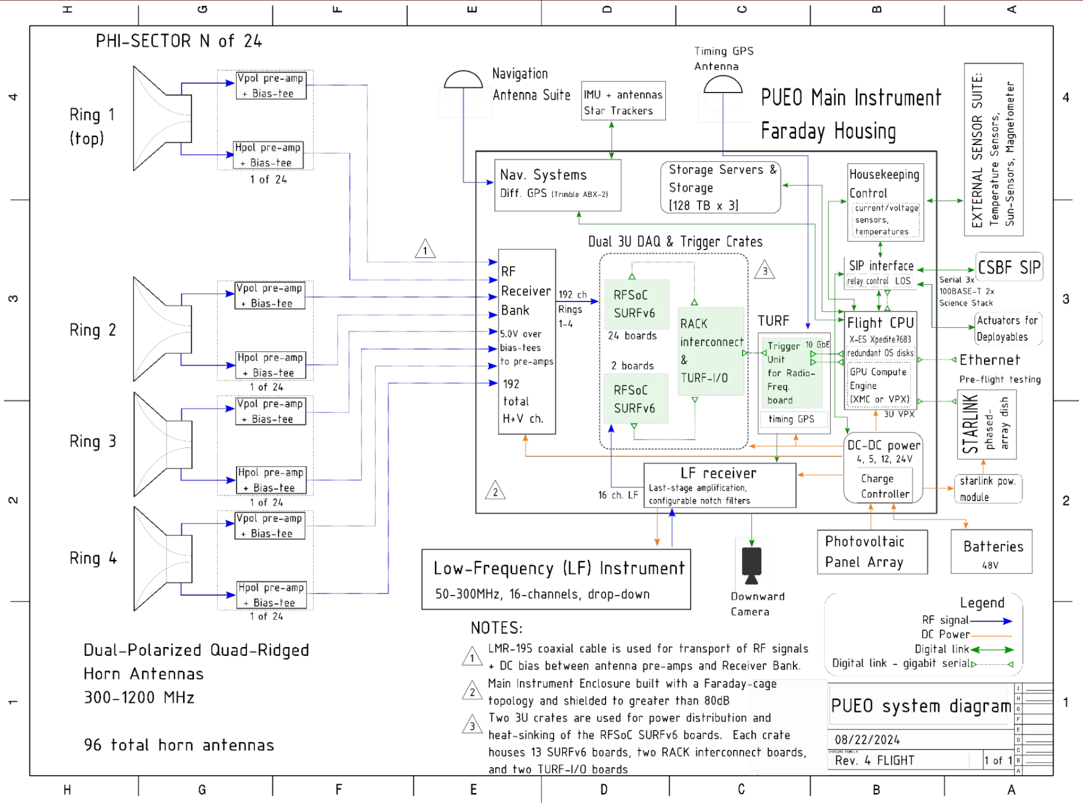


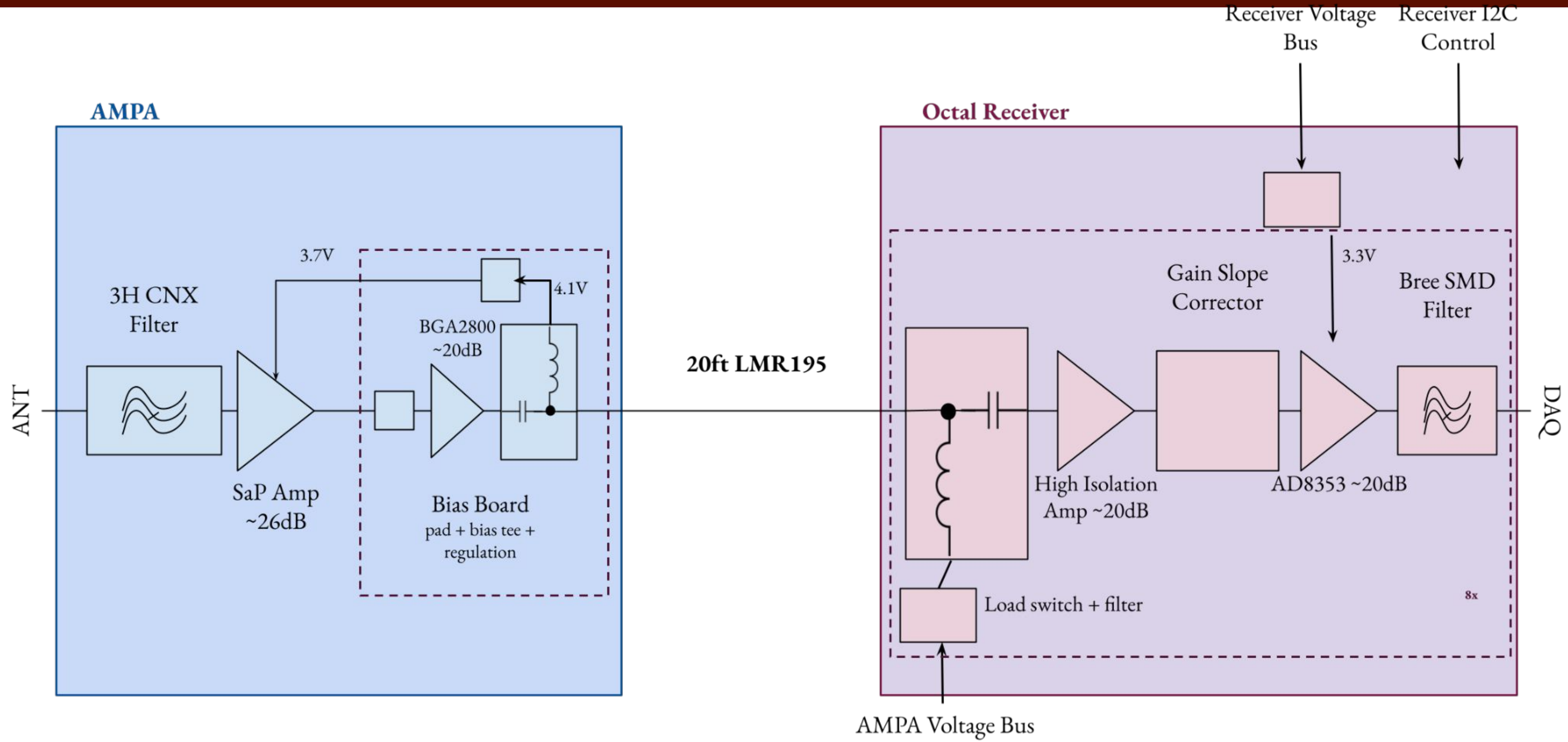
We gratefully acknowledge NASA Awards #80NSSC20K0775 and #80NSSC20K0925.

Extra Slides

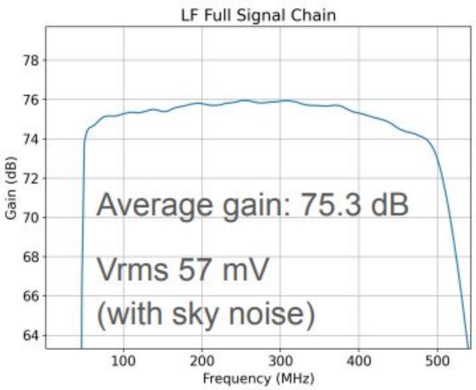
Full System Diagram

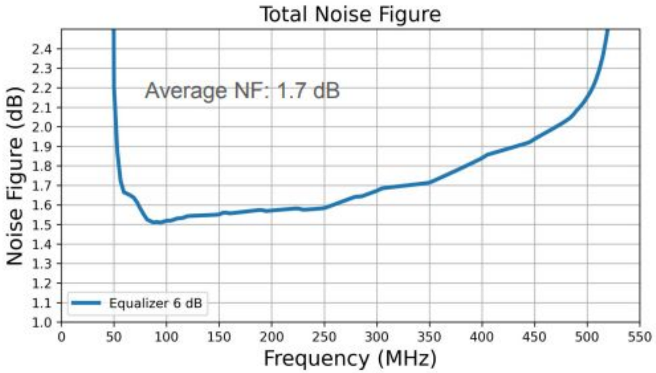


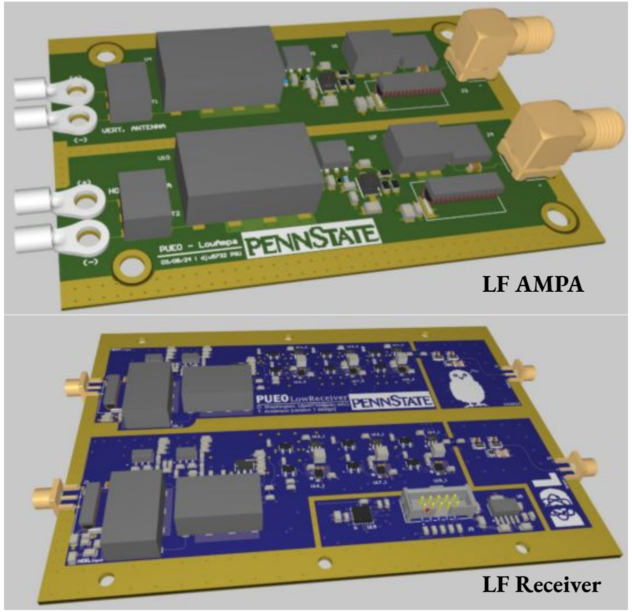
RF Chain Block Diagram



LF RF Chain





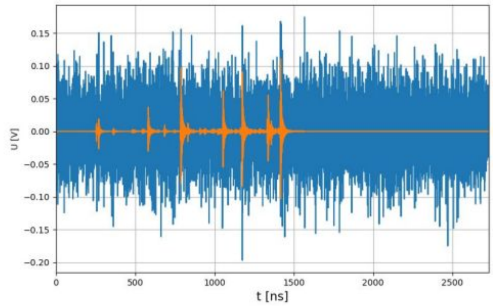


Work by Daniel Washington

LF signal conditioning happens in two stages

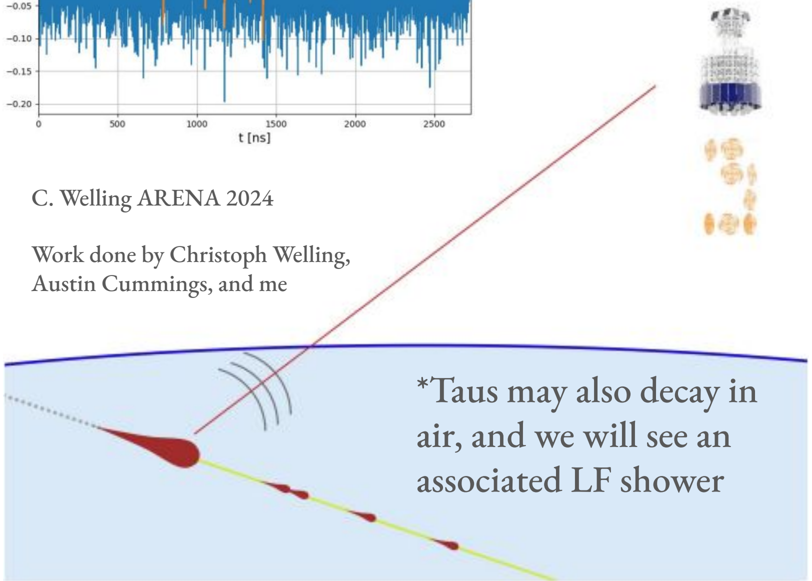
- LF AMPA mounted directly behind antenna gives ~20dB
- LF Receiver gives ~55dB

Flavor Reconstruction



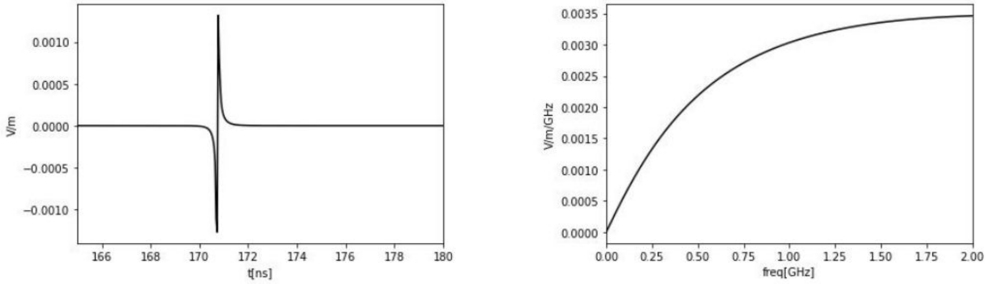
C. Welling ARENA 2024

Work done by Christoph Welling, Austin Cummings, and me

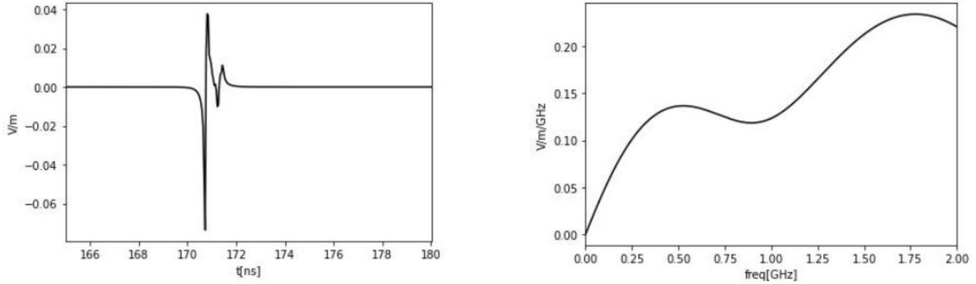


*Taus may also decay in air, and we will see an associated LF shower

Hadronic shower



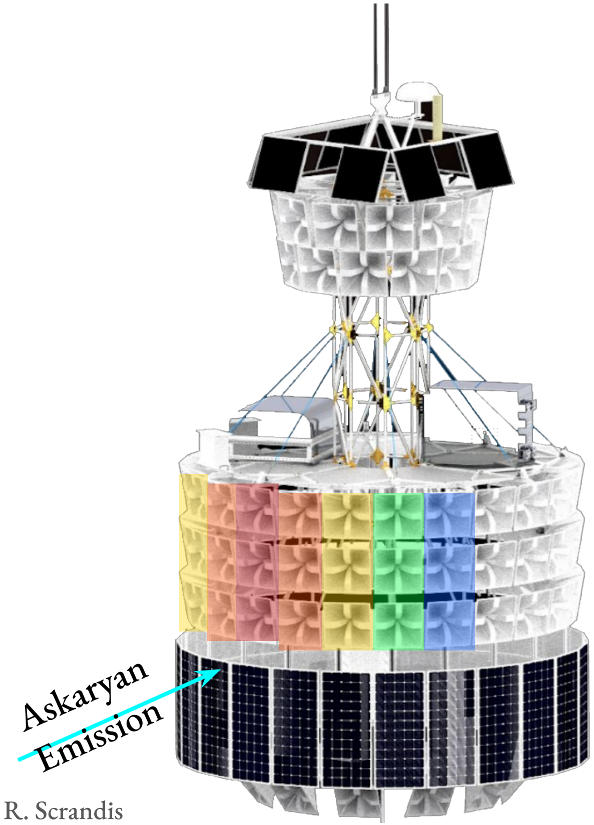
Hadronic + EM shower

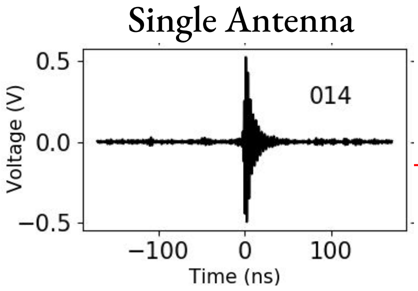


Phased Array Triggering

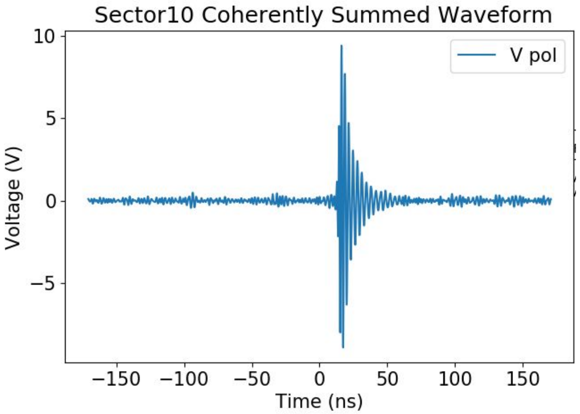
On board, preset arrival directions will be checked by applying relevant time delays and summing each channel in a sector

- If any of the beams (arrival directions) passes some voltage threshold, event will pass the trigger
- This beam forming + coherent summing (summing each channel) will help reject thermal noise triggers (SNR goes as √N(ant))





Best Guess Direction



DAQ Block Diagram

Signal moves from right to left

LF digitizing and L1/L2 triggering happens on independent SURF, and speaks to the global trigger with an OR logic

TURFIO is between SURF and TURF; it synchronizes clocks, collects data, and buffers it

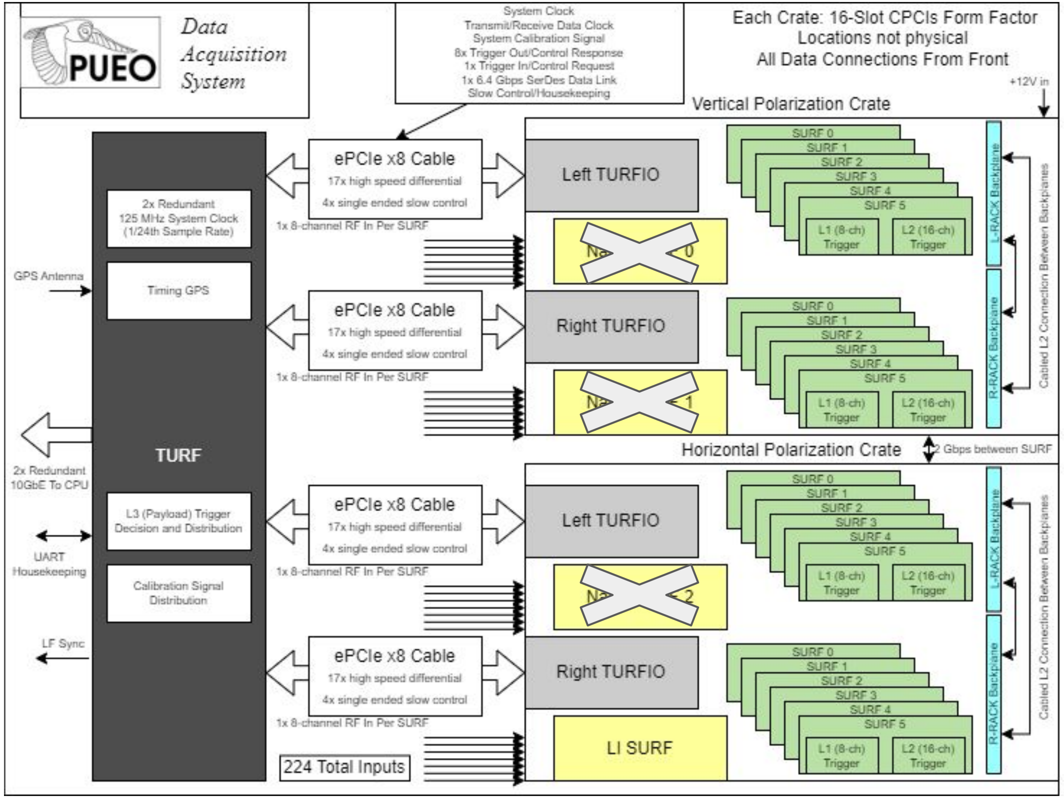


Figure by Patrick Allison

DAQ Hardware Specs

SURF: Trenz TE0835 with a Xilinx ZU47DR RFSoC

- FPGA Package: E1156 (35 x 35 mm)
- Engine: Quad-core Arm Cortex-A53 MPCore up to 1.3GHz
- 8 RFADCs with 4.096 GSPS

TURFIO: Xilinx Artix-7 FPGA

TURF: Xilinx Zynq Ultrascale+ MPSoC

Nav Suite Block Diagram

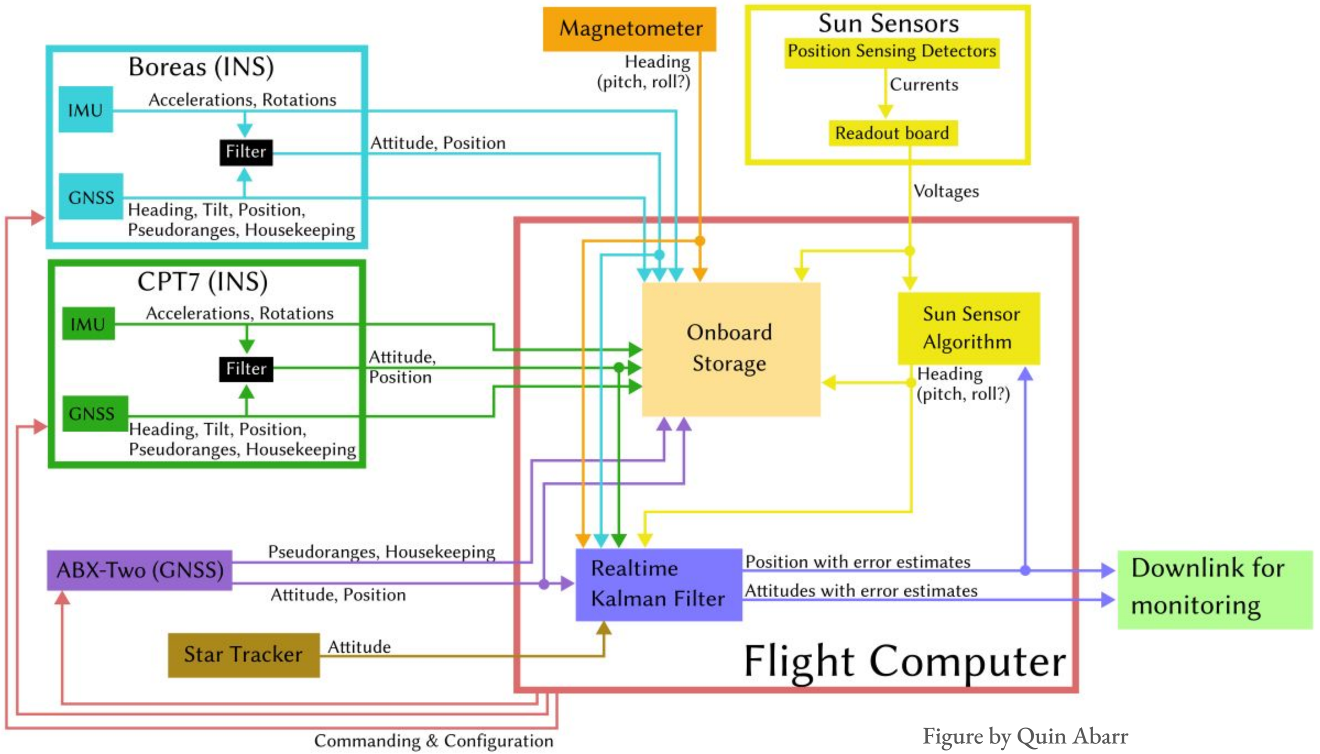


Figure by Quin Abarr

Power Block Diagram

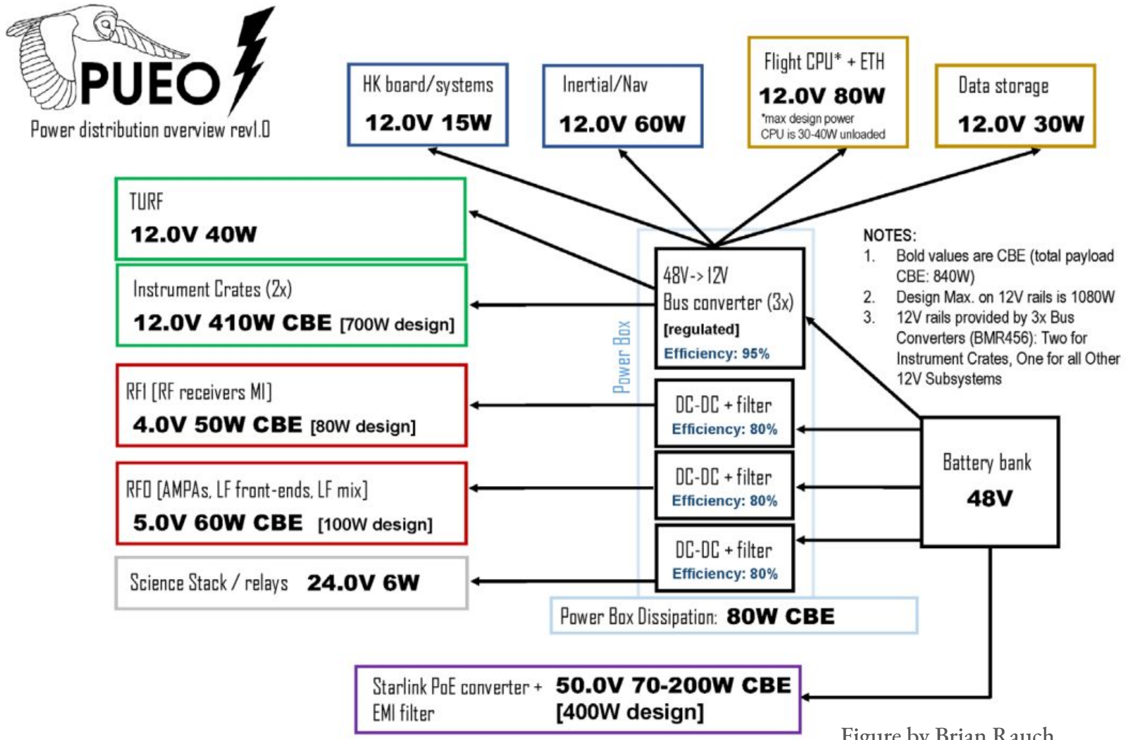


Figure by Brian Rauch