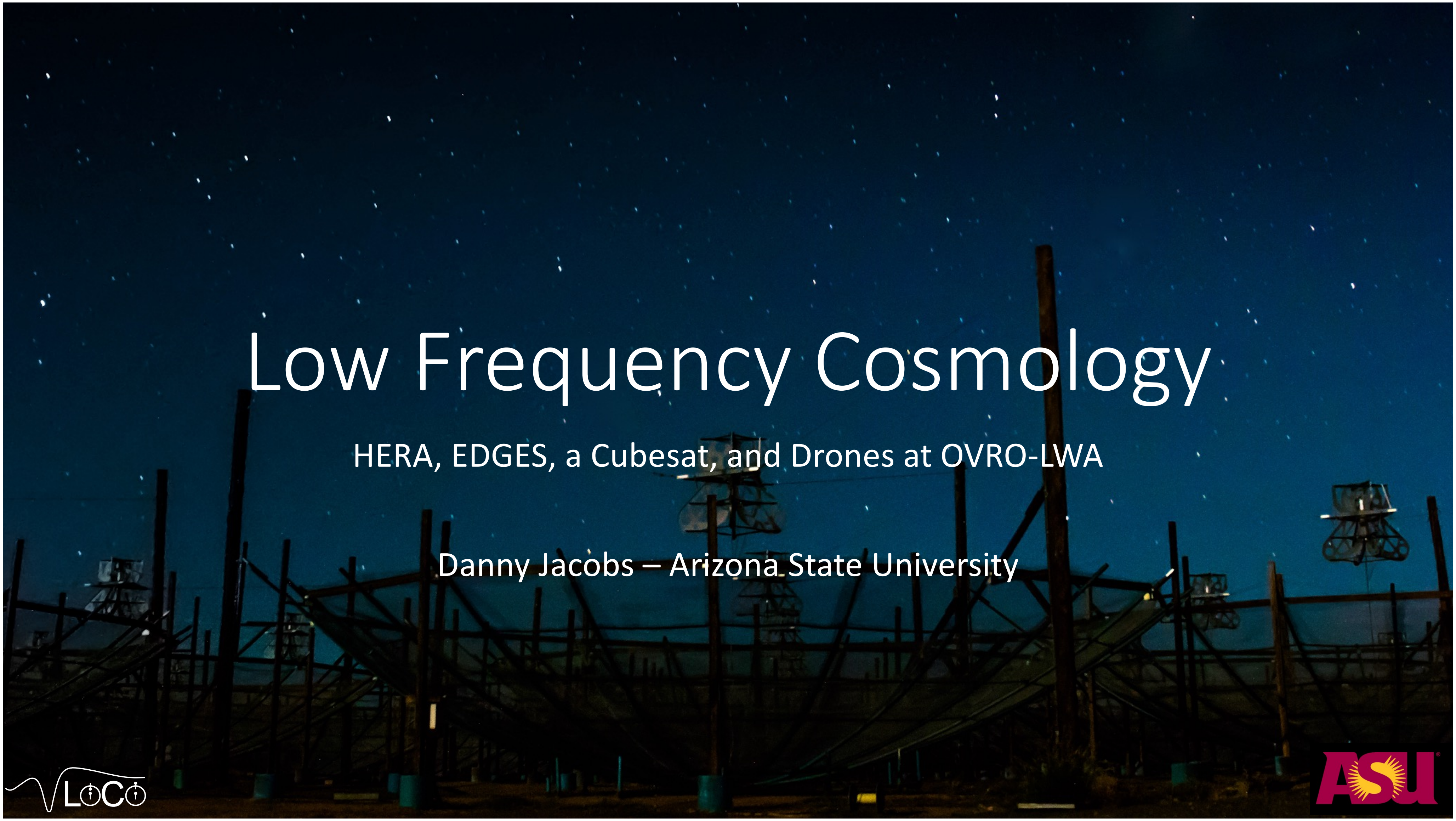


Low Frequency Cosmology

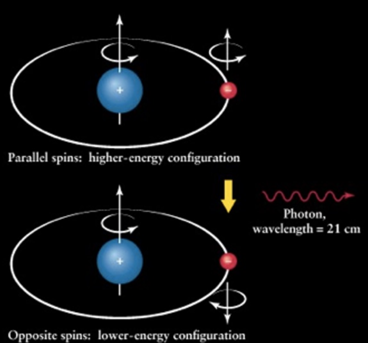
HERA, EDGES, a Cubesat, and Drones at OVRO-LWA

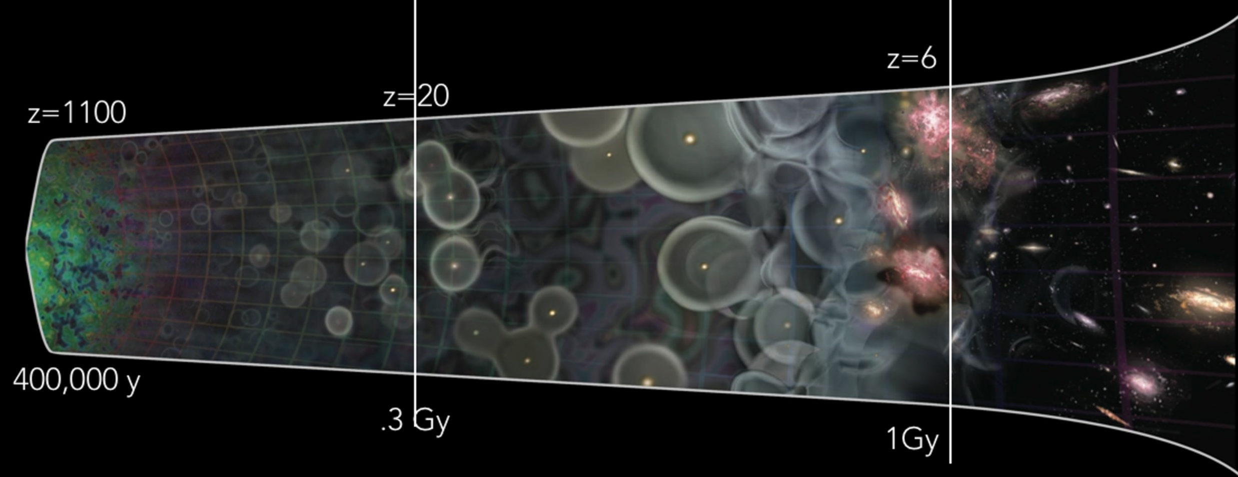
Danny Jacobs – Arizona State University

Pre-Reionization
First stars activate 21cm line with Lyalpha
Visible in absorption

Reionization
Tau, As, $\sum m_\nu$,
first galaxies, supermassive blackholes

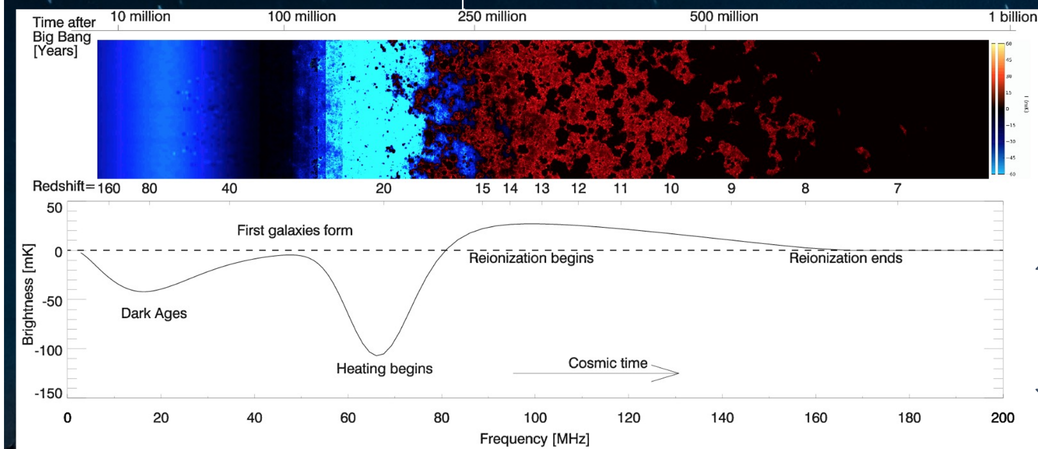
Post-Reionization
dark energy equation of state





Observables

Fluctuations



20mk

200mK

Total Power

3D Power Spectrum vs redshift

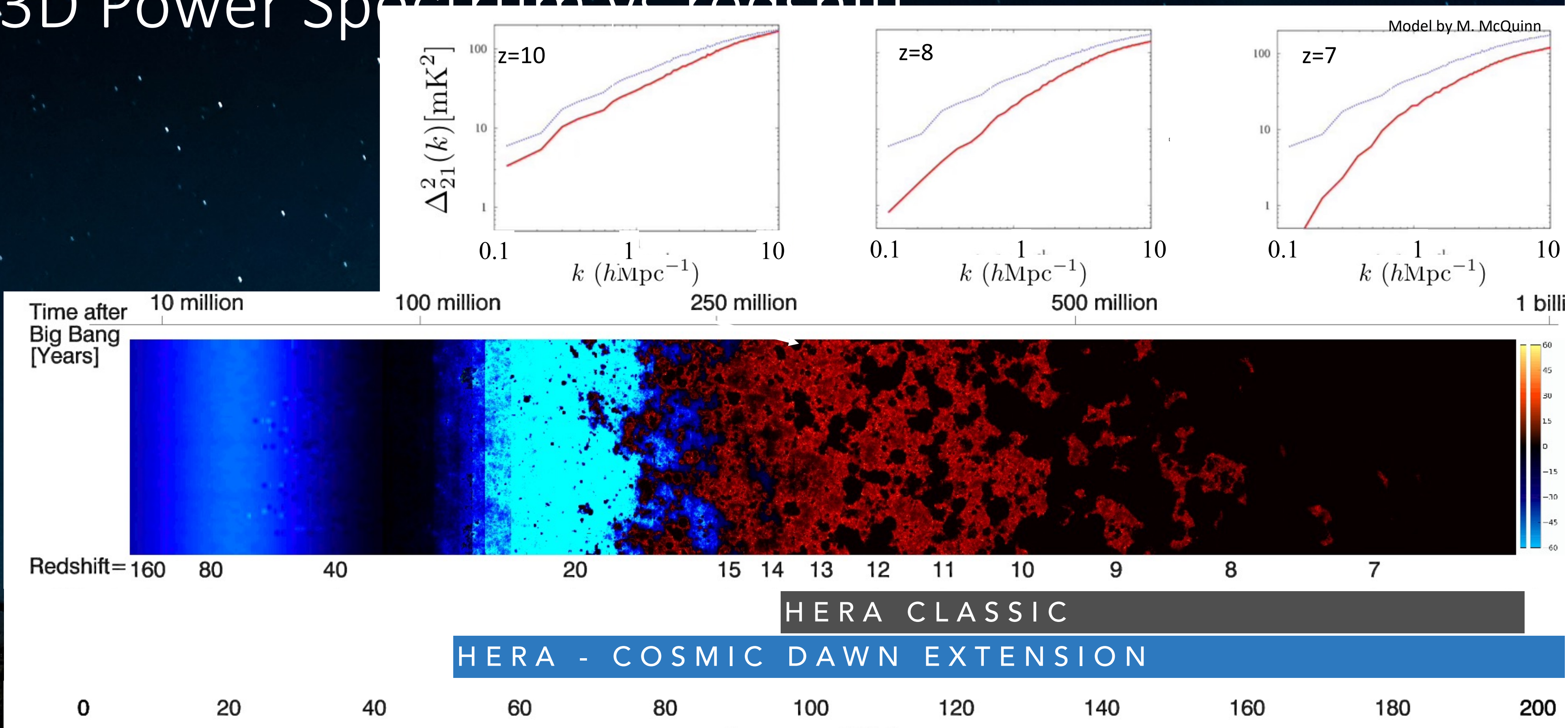


Figure Adapted from Pritchard and Loeb 2012

HERA Phase 1

- 70/350 antennas operational
- RF system inherited from HERA
- 75 ohm coax
- sleeved dipole feeds
- 2k channel correlator (ROACH2 + GPU)
- 100 – 200MHz (13 < z < 5.5)
- Testing new active balun design

Phase 1

Phase 2

HERA Collab et al 2022

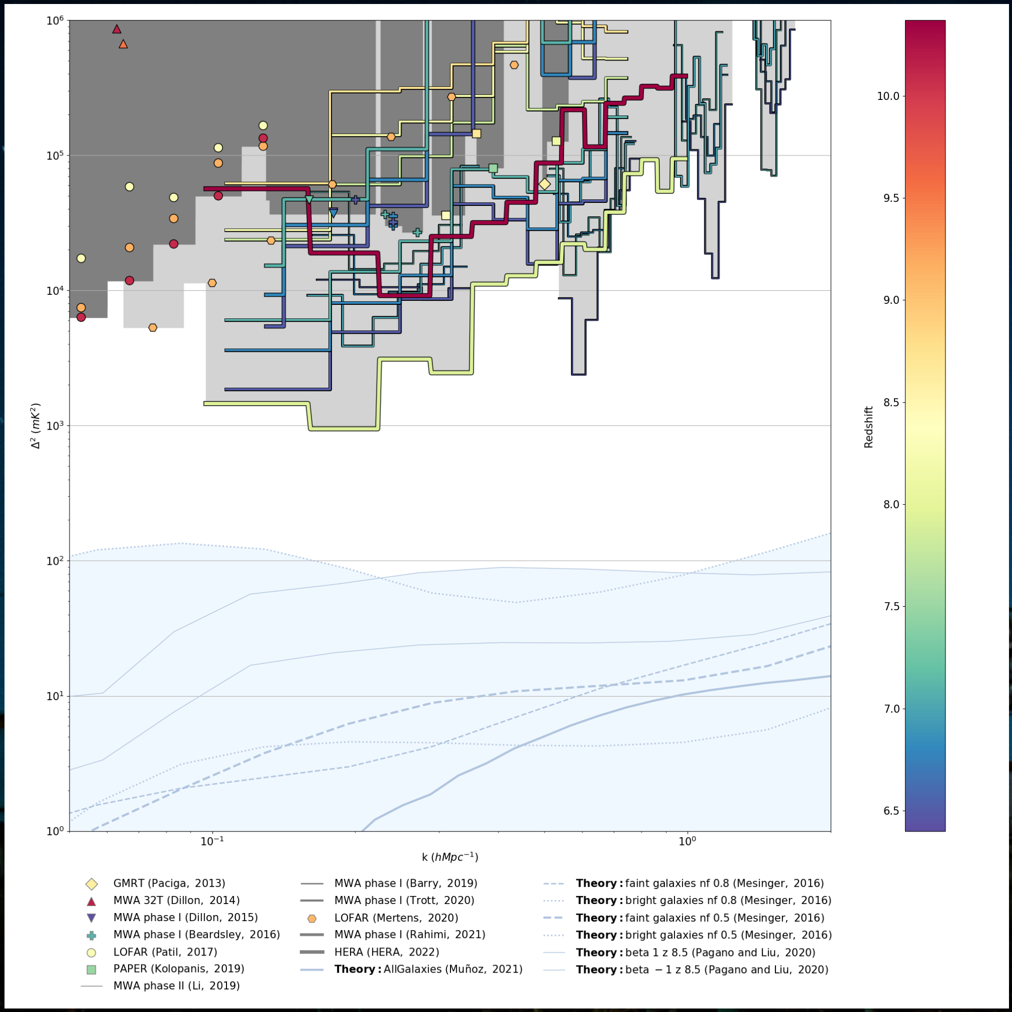
Phase 1 system

Three weeks of data

Crosstalk filtering

Full Forward instrument model

2022ApJ...925..221A



HERA Collab et al 2023

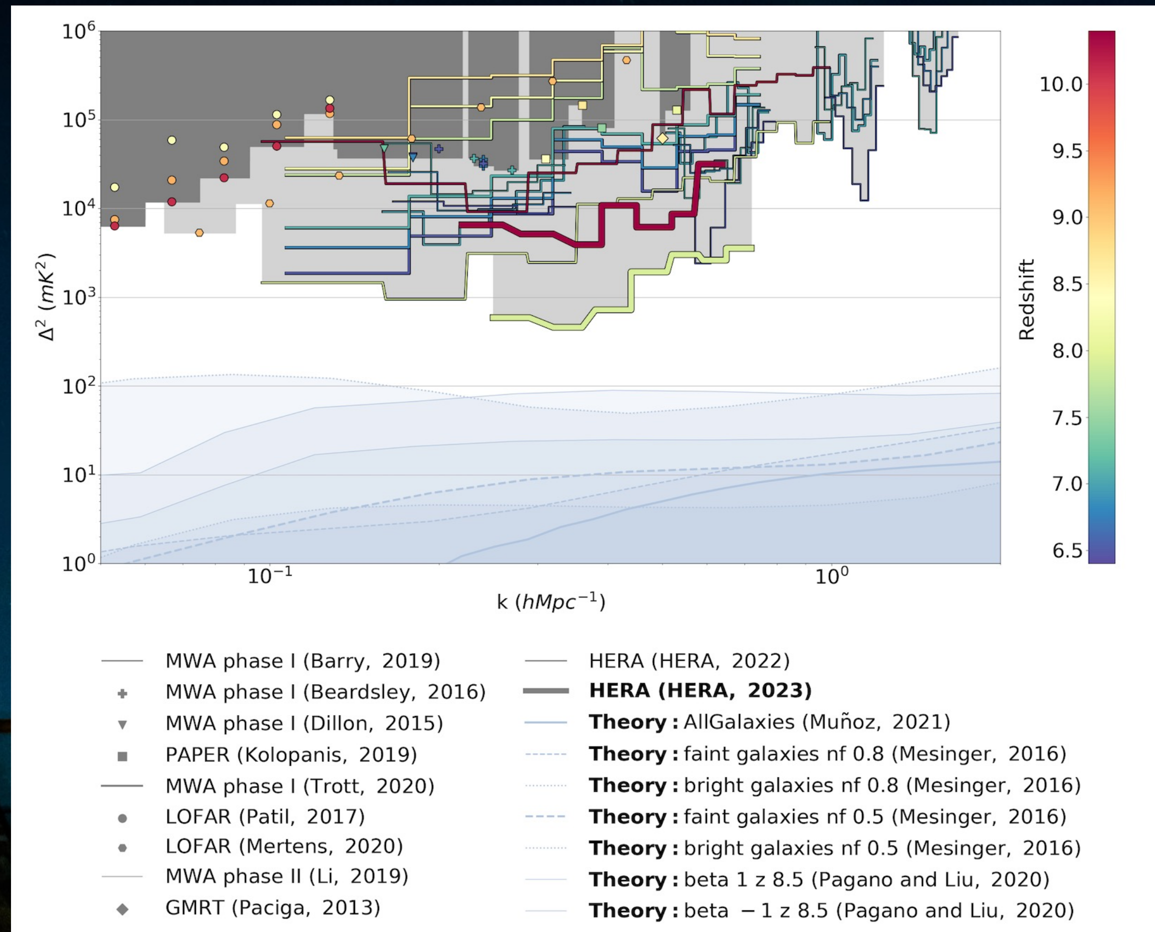
Phase 1 system

Analysis similar to previous

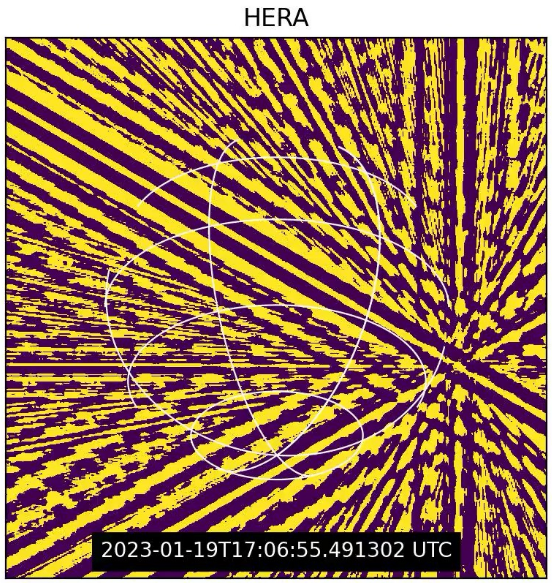
Four months of data

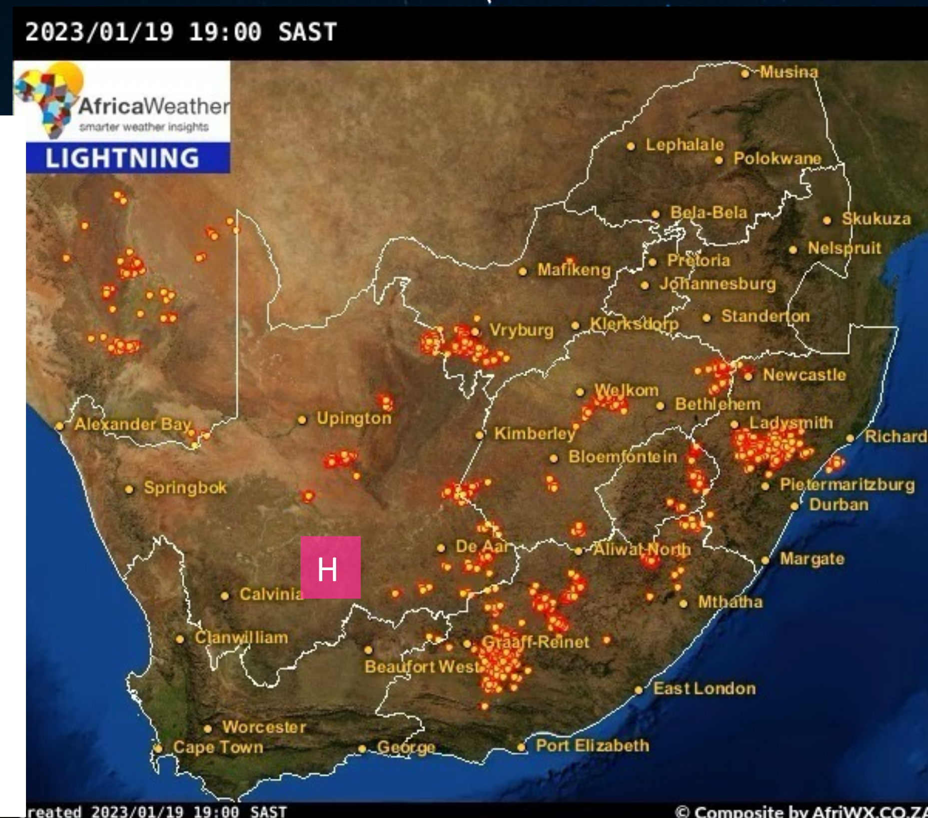
2023ApJ...945..124H

Further constrains cool reionization models



Lots of Lightning in South Africa!



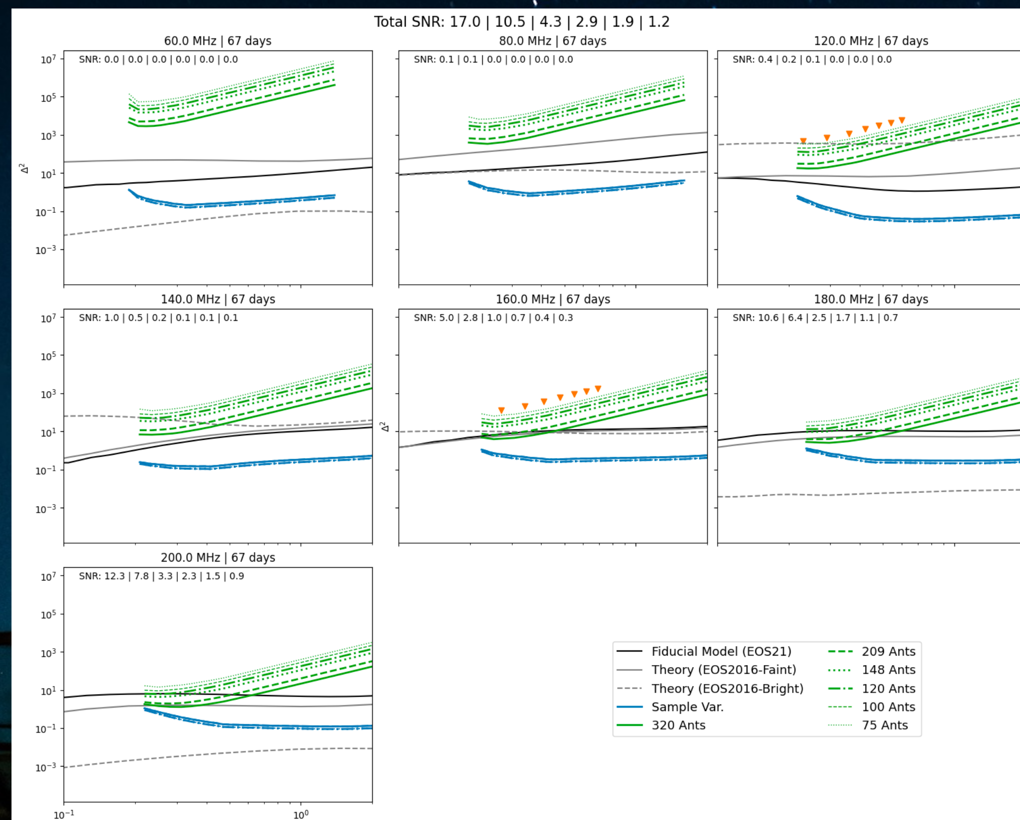


See Heligenstein & Jacobs, HERA Memo 121
reionization.org/science/memos/

2022-2023 Season Sensitivity

Season probably had ~120 good antennas.

Might still recover more as analysis continues



Steven Murray (ASU)

HERA Headlines in 2022-2023

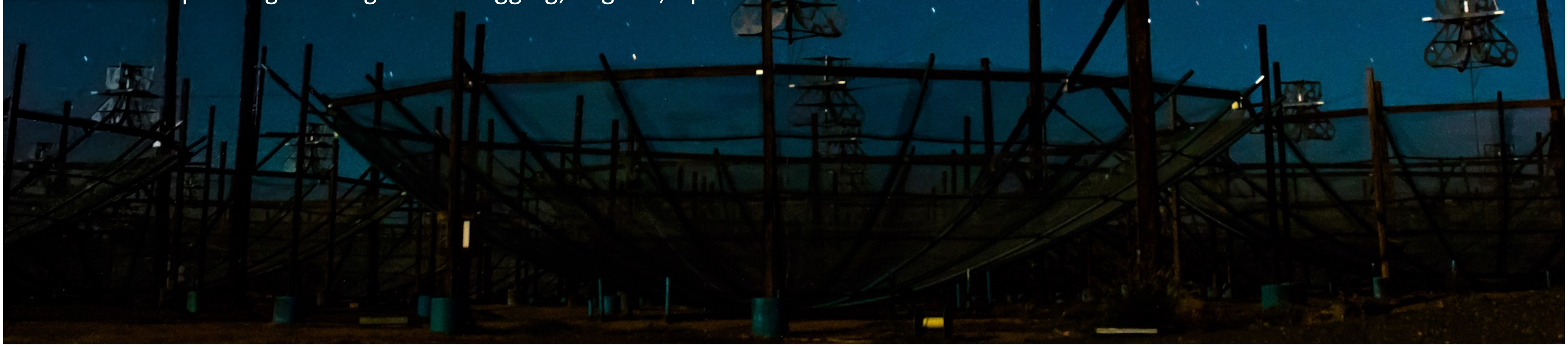
HERA Collab et al, ApJ 2022 – First Major results - 2 weeks of Phase 1 data
HERA Collab et al, ApJ 2023 – Second round of results – 6 months of Phase 1 data

Analysis

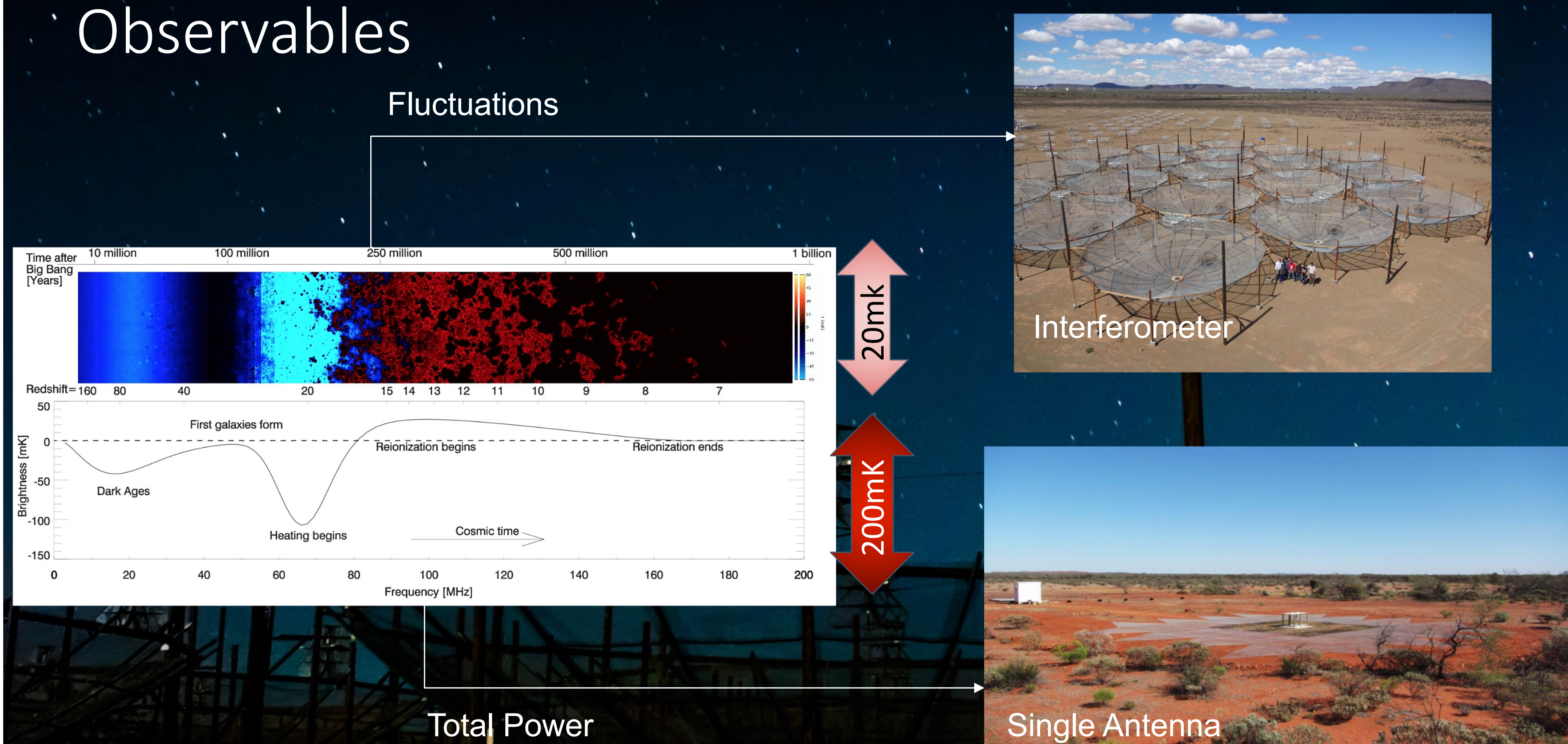
- Direct Optimal Mapmaking, Xu, ApJ, Oct 2022
- Bayesian Systematic Jacknives, Wilensky, MNRAS, Feb 2023
- Window functions, Gorce, MNRAS, March 2023
- Inpainting to mitigate RFI flagging, Pagano, April 2023

Instrumental

- Solved a big Common Mode problem!
- Lightning
- Mutual coupling

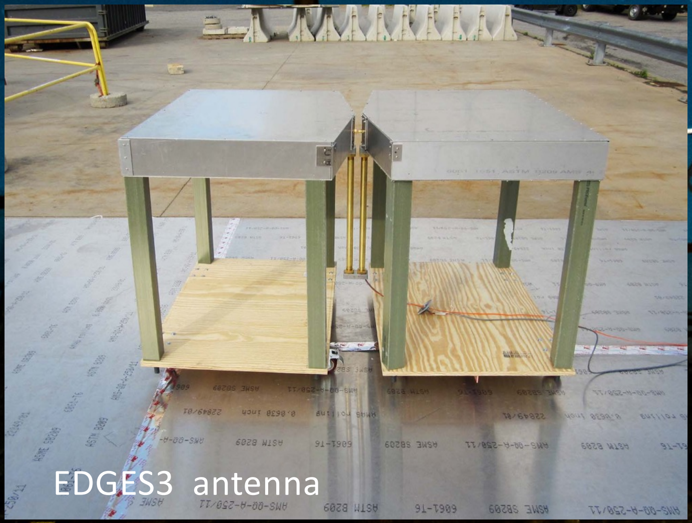


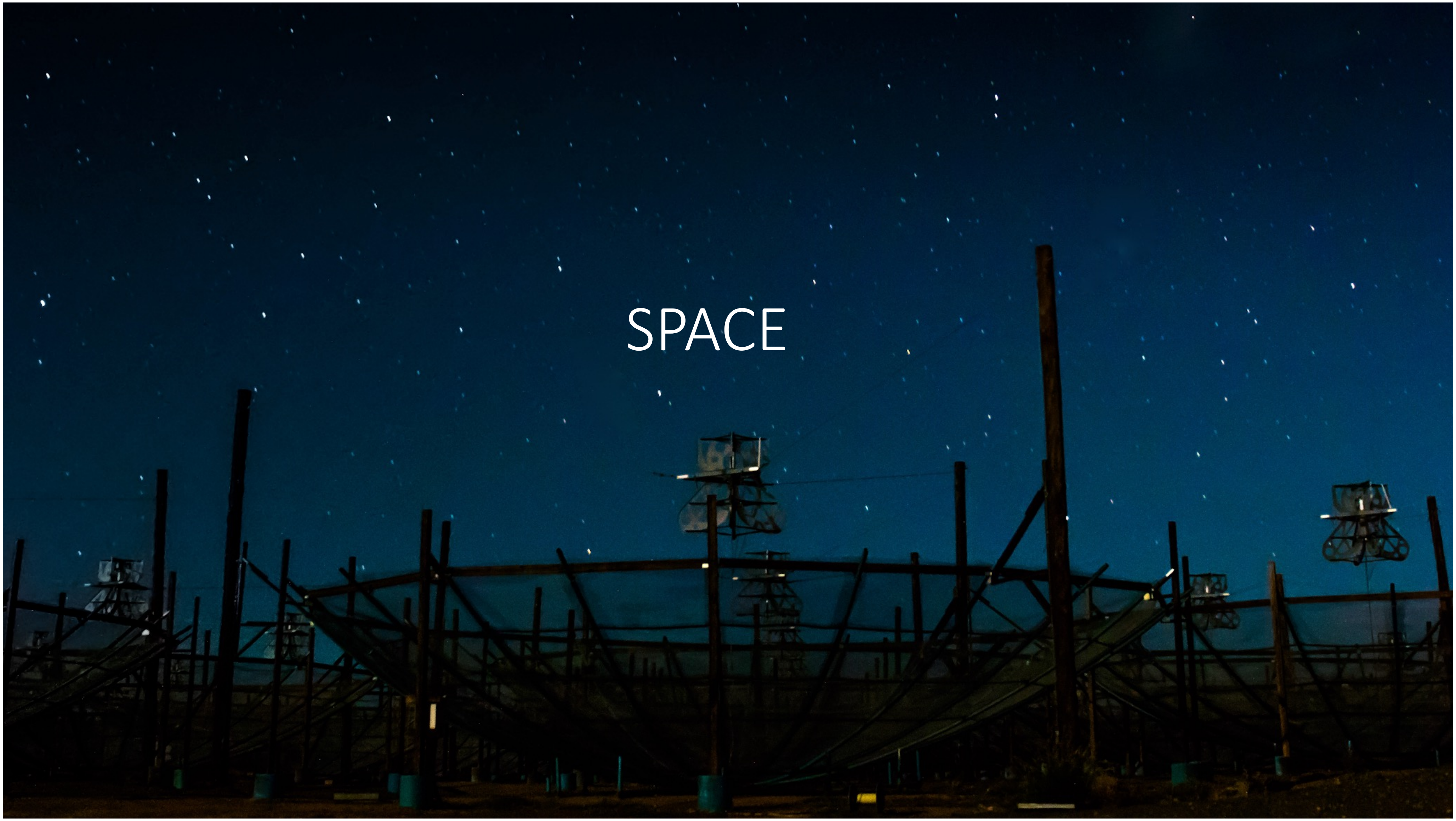
Observables



EDGES headlines

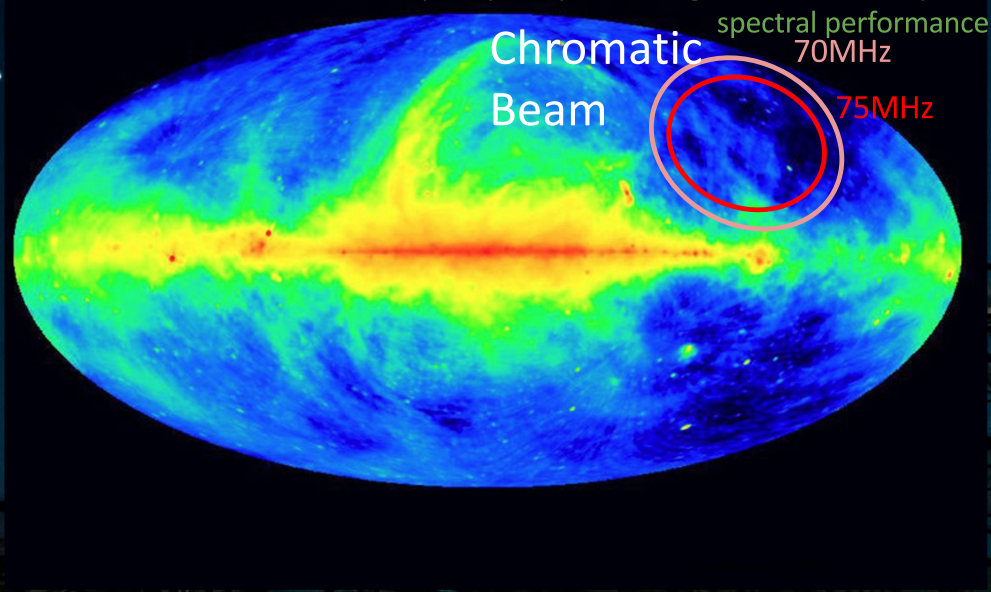
- Large Ground plane – Mid 2022
- First season of EDGES3 – End 2022
- Ground plane extension for mid-band complete – Mid 2023



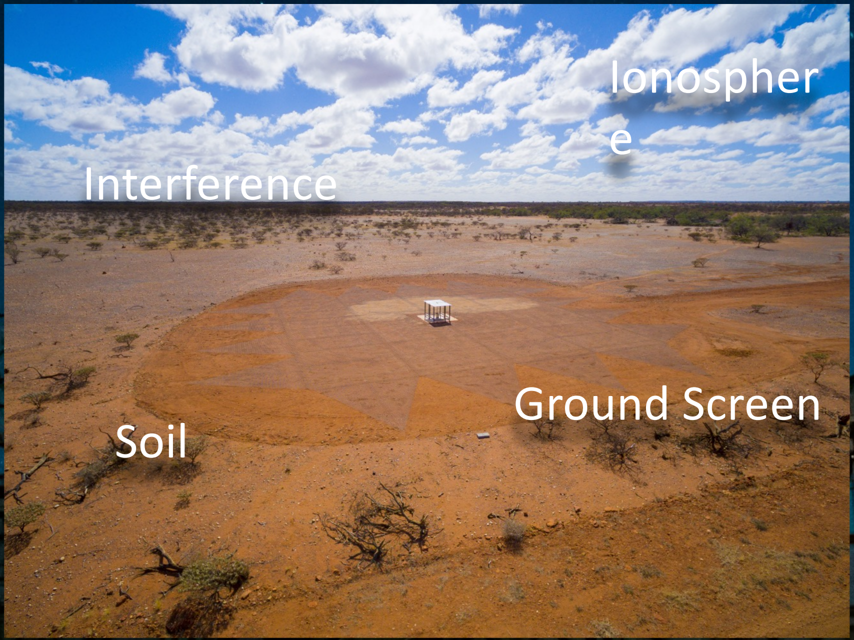

SPACE

Global Experiment Challenges

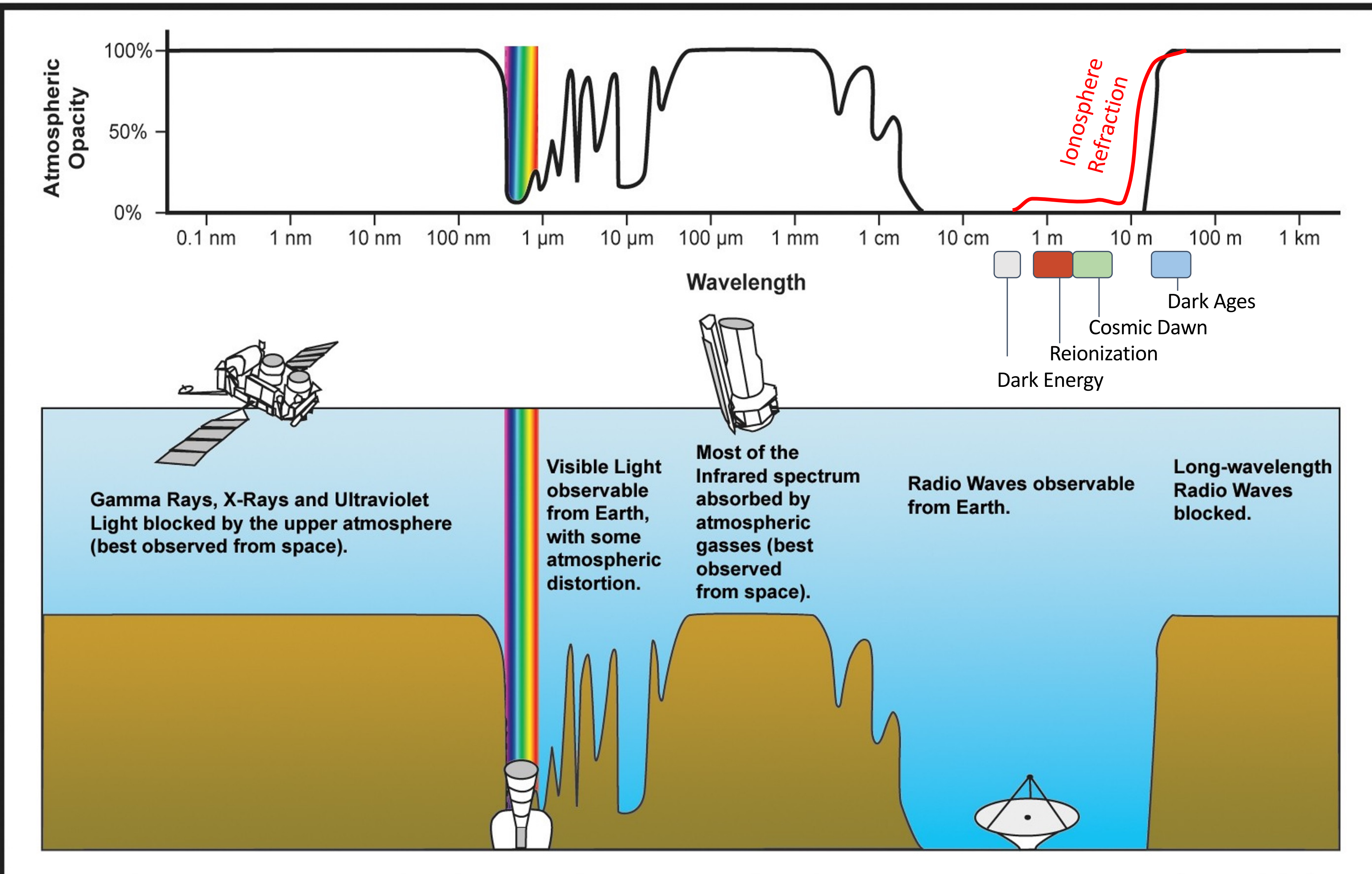
Antenna Beam:
Beam uncertainty couples spatial foreground uncertainty into spectral performance



Bright Foreground:
Difficult to measure independently of background



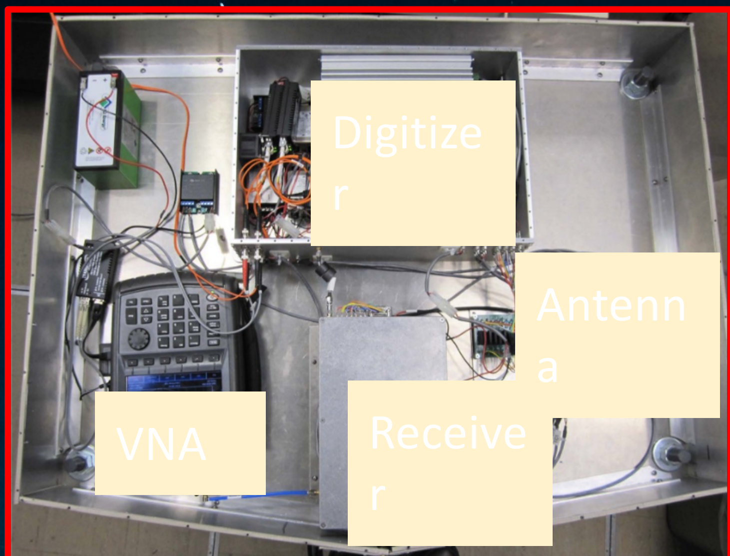
Antenna:
Terrestrial environment difficult to control



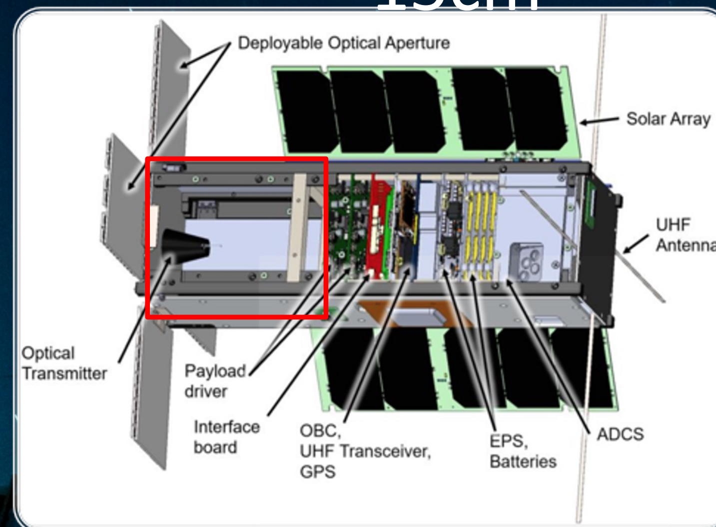
Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Ionosphere Refraction
Dark Ages
Cosmic Dawn
Reionization
Dark Energy
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.

Miniaturization for Space (SWaP)

~1m



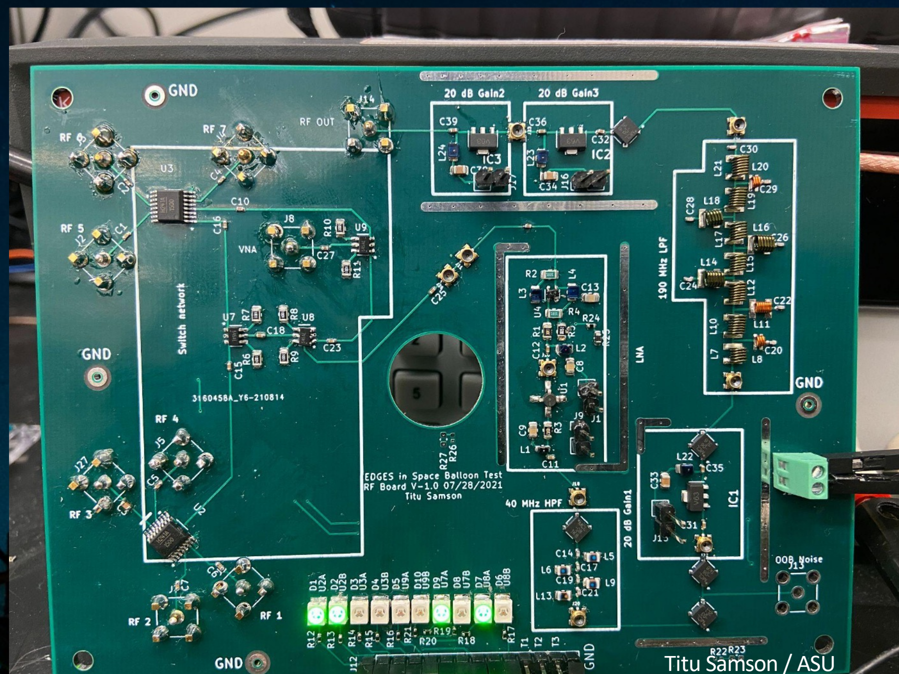
~15cm



EDGES3 Prototype 2020

3U Cubesat

Single board prototype



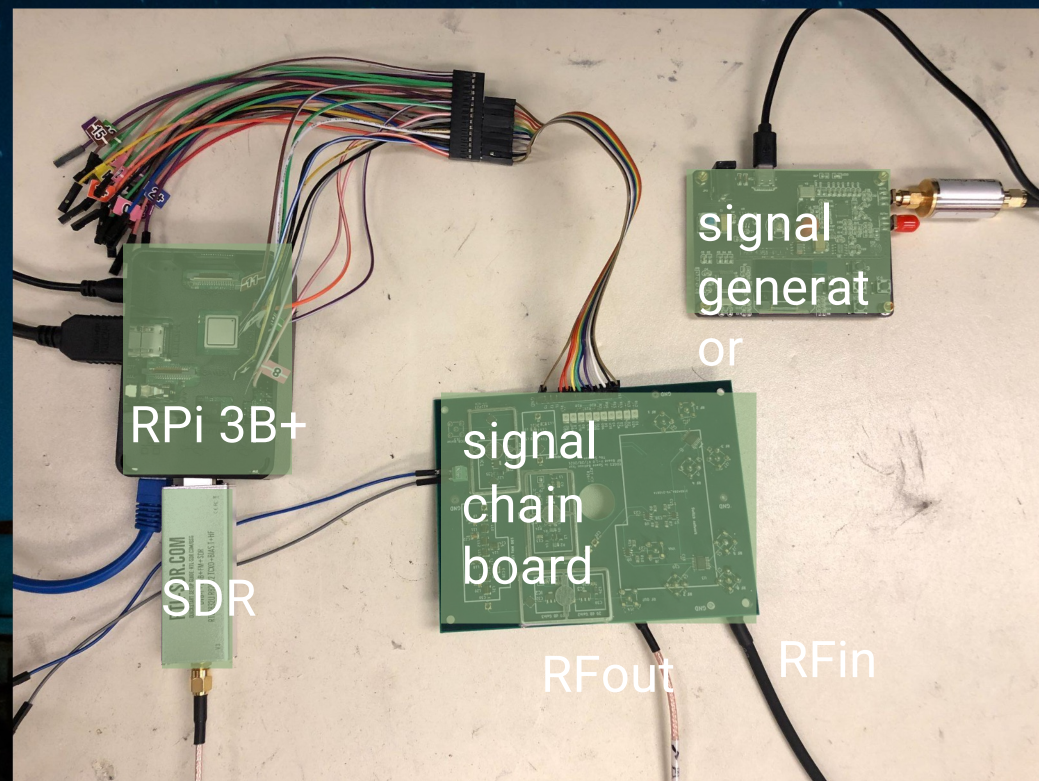
Benchtop integration setup

Raspberry Pi + RTL SDR Recorder

- Extremely low power and mass

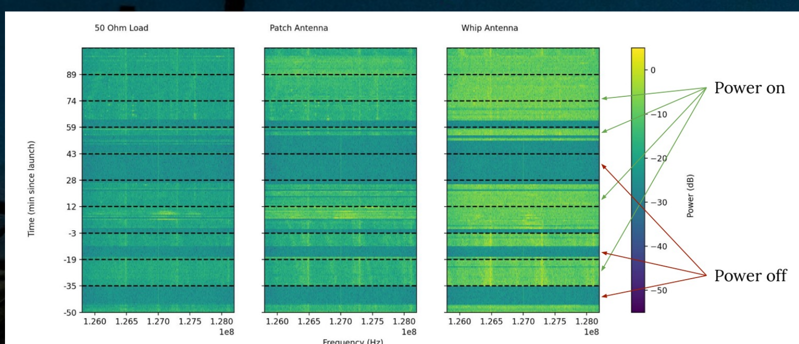
USB Battery Pack power source not shown.

Total mass < 2kg.

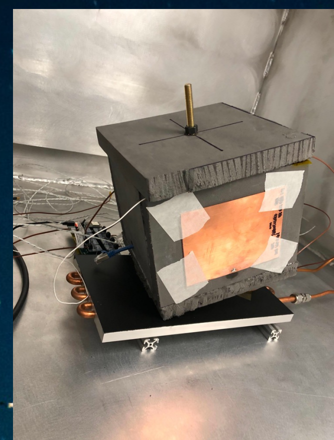


Balloon Tests:

- Pretesting: thermal vac, EMI
- Balloon testing
  - Space time for receiver board
  - Systems integration testing
  - Practical Thermal testing



Thermal Vac Test
Sep 2022

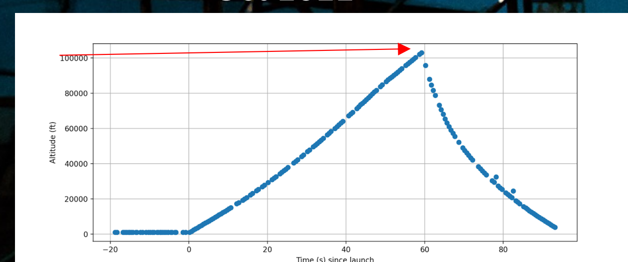


Thermal Vac Test
Sep 2022

~100k ft

Flight 1
Oct 2022

Flight 2
Feb 2023

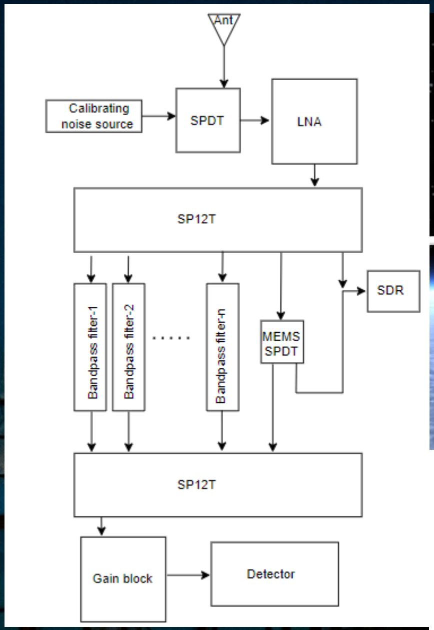


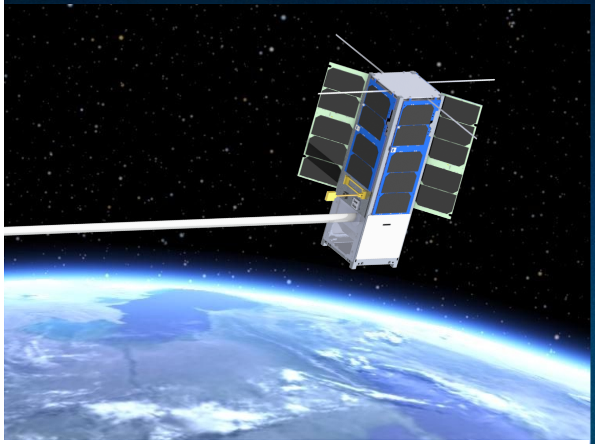
Orbital Test as Secondary payload on DORA

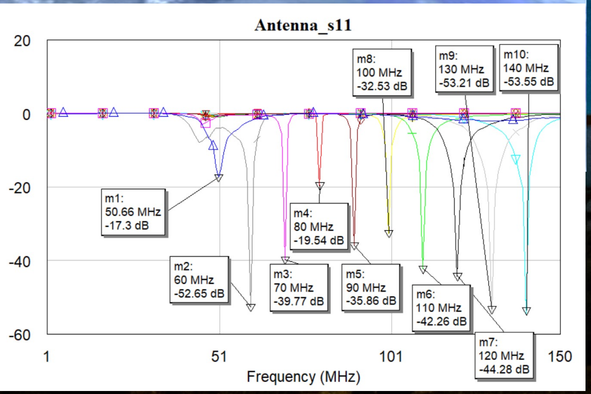
- DORA = Deployable Optical Receiver Array
- Widefield multi-party 1Gb communications
- Funded by NASA Smallsat Technology Partnerships program

Orbital Test as Secondary payload on DORA

- Goal 1: Test Compact Receiver
- Analog filterbank:
  - 50MHz to 120MHz in 20MHz chans
- SDR Spectrometer
  - RTL SDR, 2MHz instantaneous
- Tape Measure monopole

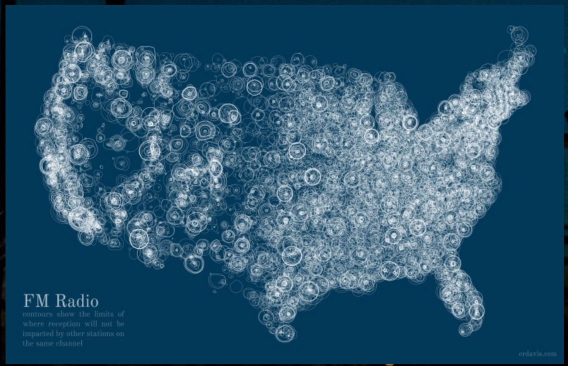


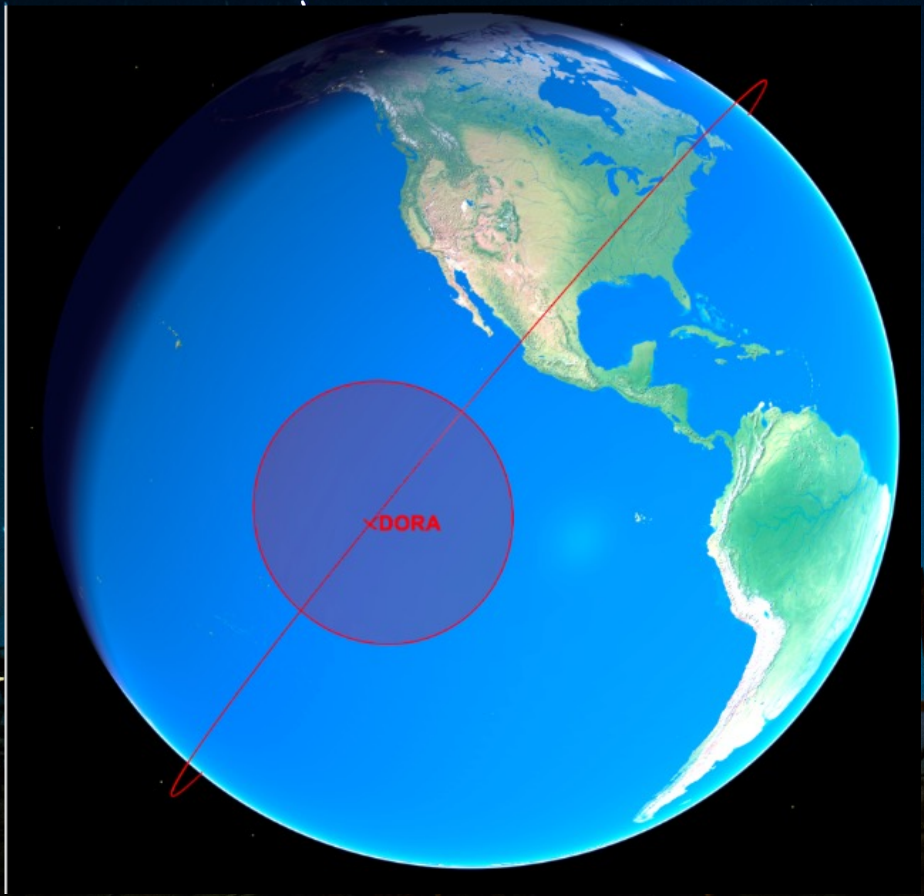




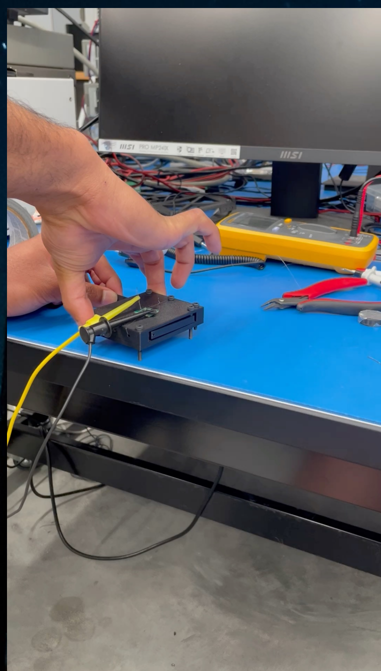
Orbital Test: Goal 2

- LEO tracks cover lots of ground
- Horizon isn't *that* far away
- Are there quiet spots?
- Goal: Map RFI

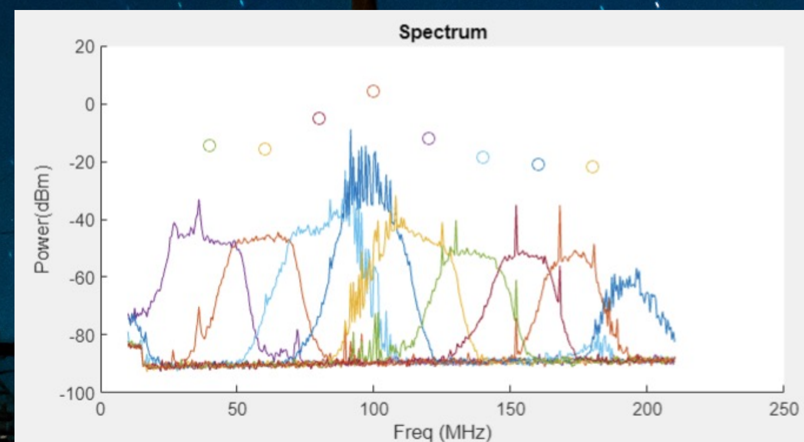




DORA RF testing

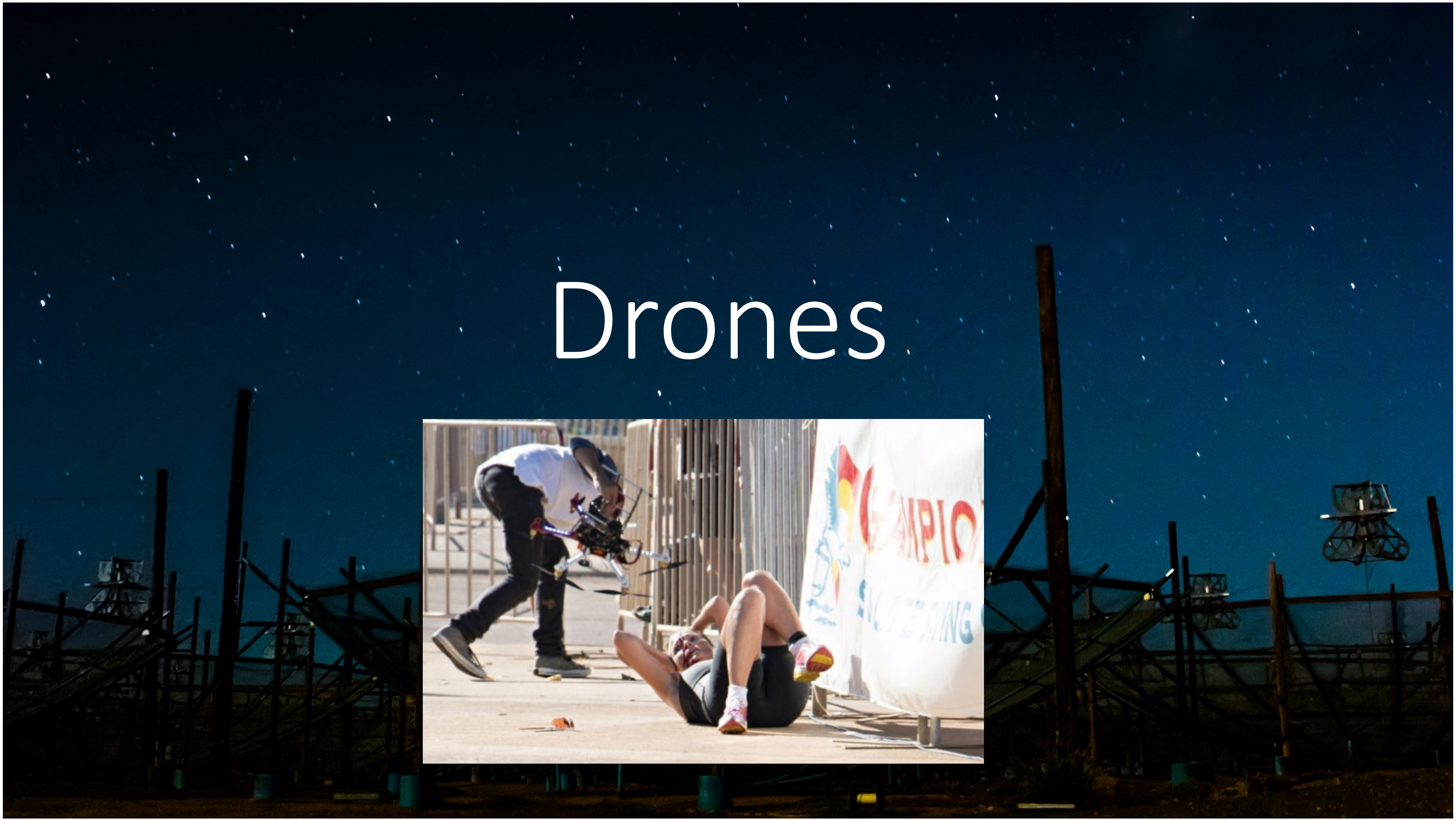


Deployable 4m ¼ whip Antenna

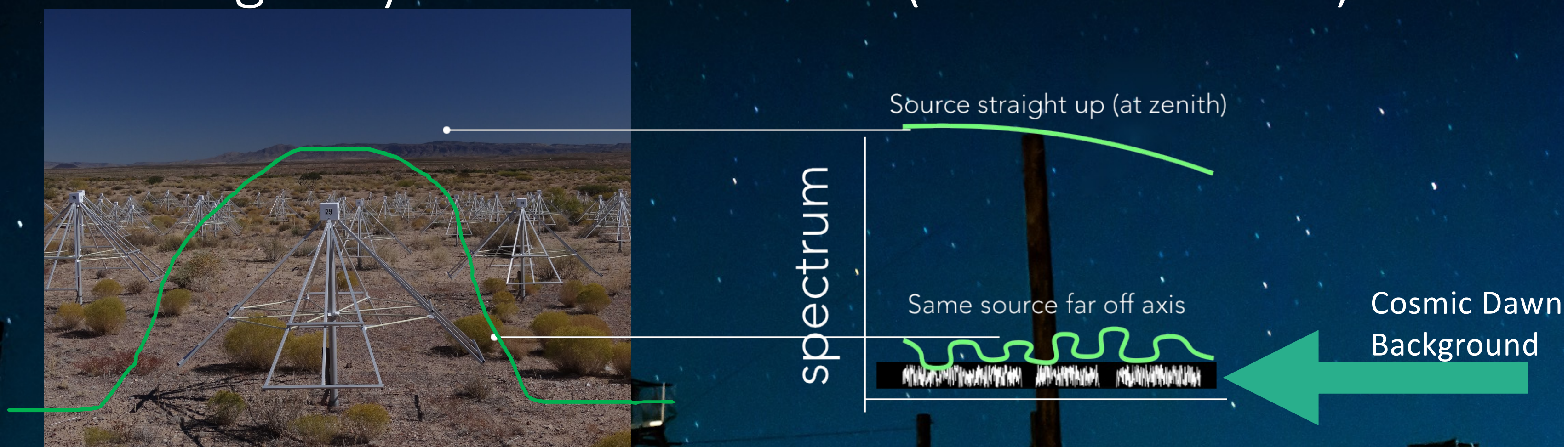


Coarse and fine spectrometer

Drones



Beam Knowledge key for Cosmic Dawn (and other stuff)

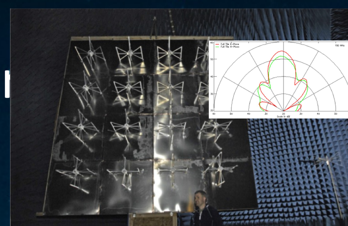


Requirement: Accurate map of in-situ beam pattern to 1% in FWHM, 10% outside (Ewall-wice et al 2017)
Wide bandwidth (ex HERA at 50-250MHz, EDGES Low 60-90MHz)

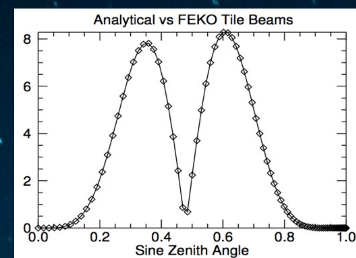
Work supported by the NSF CAREER program

A (Brief) History of Beam mapping

- Anechoic Chamber
- Range testing
- E&M models
- Sky sources
- Satellites
- Helicopters (real or
- **Drones**



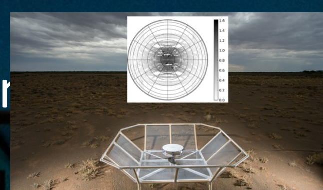
MWA Tile Anechoic Chamber (MIT/Lincoln Labs)



Precision Simulation

Source: Bob Wilson

Ben McKinley



Pober et al, AJ, 2012, v143

PAPER Antenna, Sky Sources (Jacobs/Pober et al)

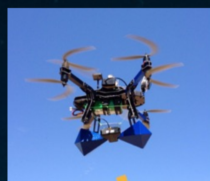
Neben et al. Radio Science, 2015, vol 50

MWA Tile, Satellite Constellation (Neben et al)

Source: Bob Wilson

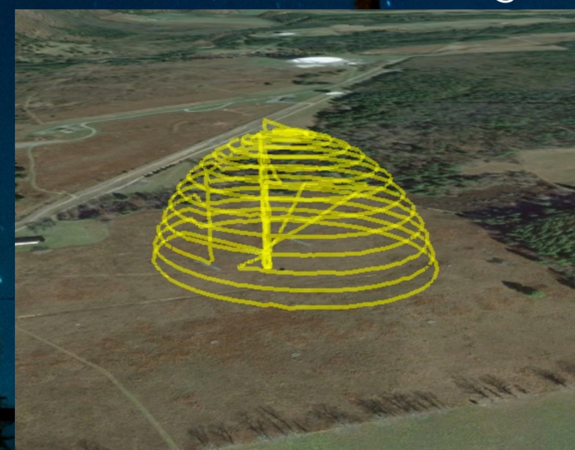
Penzias and Wilson, Detection of CMB

Drone Beam Mapping



Transmits known Calibration signal

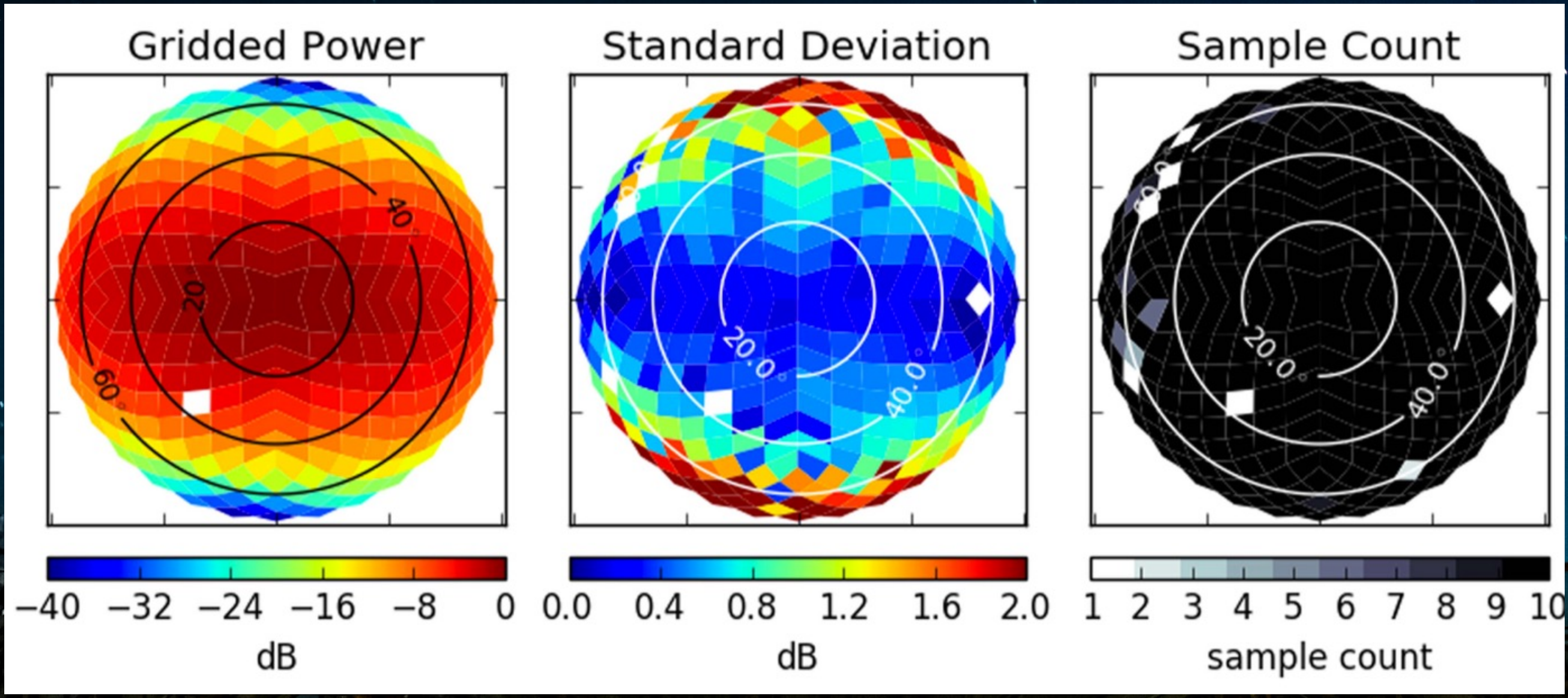
Complete spatial coverage



Requirement:
Map beam voltage pattern to better than 1% to horizon.

record amplitude as a function of GPS position

Best Demonstrated Dipole Map



Jacobs et al, PASP, 2017

Beam Mapping at OVRO LWA

2023 OVRO LWA Beam Mapping Campaign

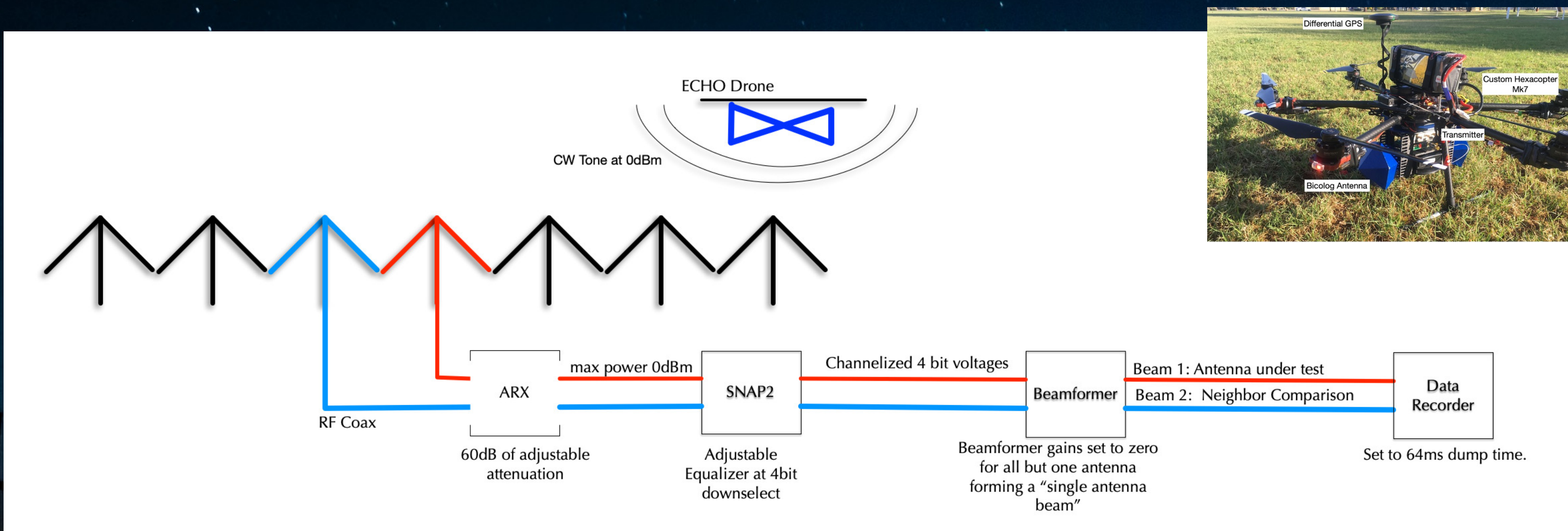
Goals

- Test array setup with active calibration transmitter
- Needs:
  spectra from one antenna, <100ms dump time, 100% duty cycle
- Demonstrate transmitter-array integration
- Field time for drone system.
- Inspect and use LWA antennas
- Stretch goals
  - Measure drone interference
  - Make beam map

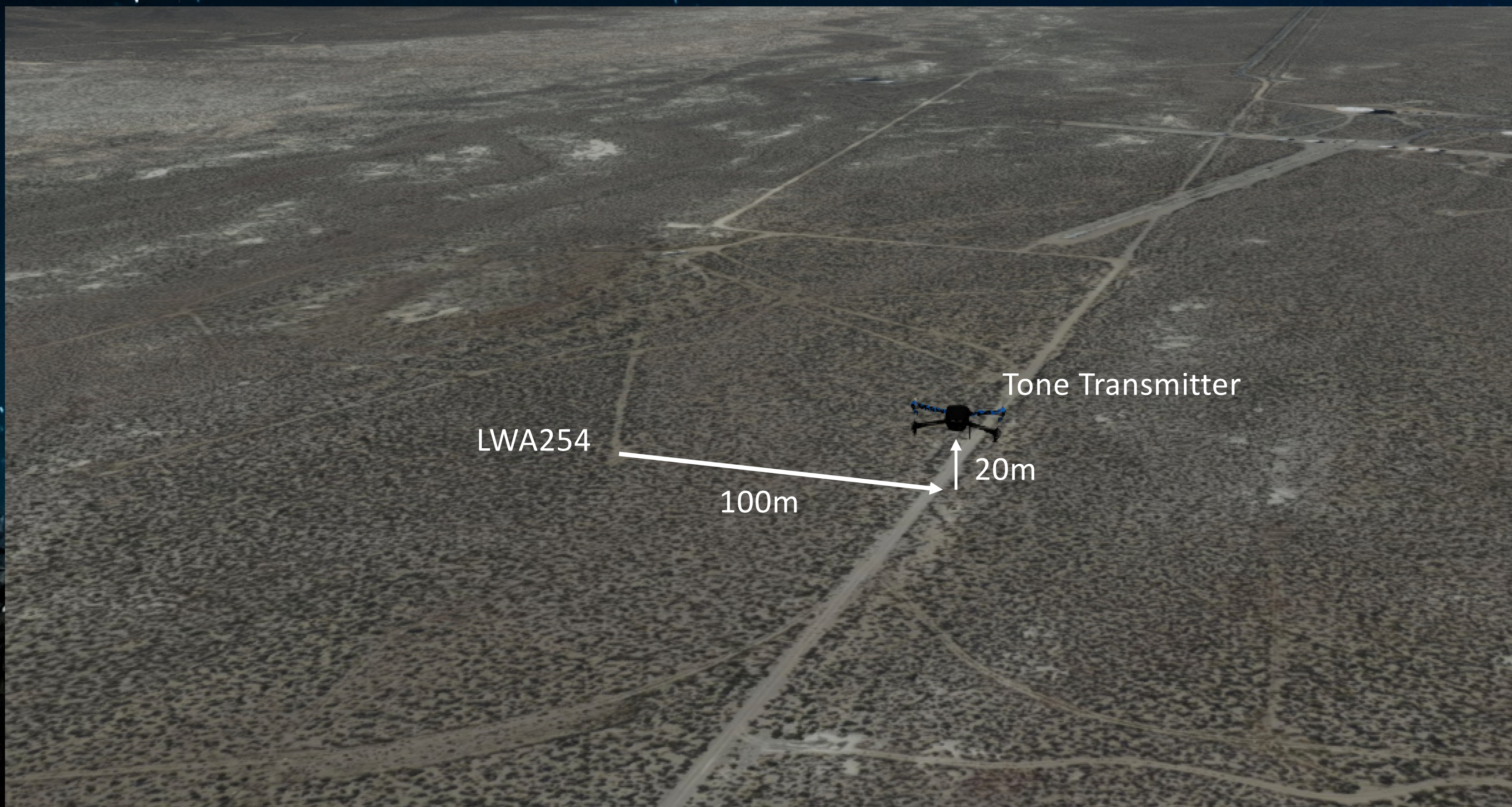
23 May 2023

24 May 2023

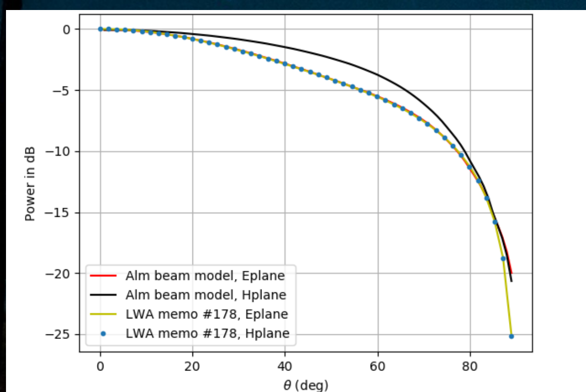
Setup


ECHO Drone
CW Tone at 0dBm
Differential GPS
Custom Hexacopter Mk7
Transmitter
Bicolog Antenna
max power 0dBm
ARX
SNAP2
Channelized 4 bit voltages
Beamformer
Beam 1: Antenna under test
Beam 2: Neighbor Comparison
Data Recorder
RF Coax
60dB of adjustable attenuation
Adjustable Equalizer at 4bit downselect
Beamformer gains set to zero for all but one antenna forming a "single antenna beam"
Set to 64ms dump time.

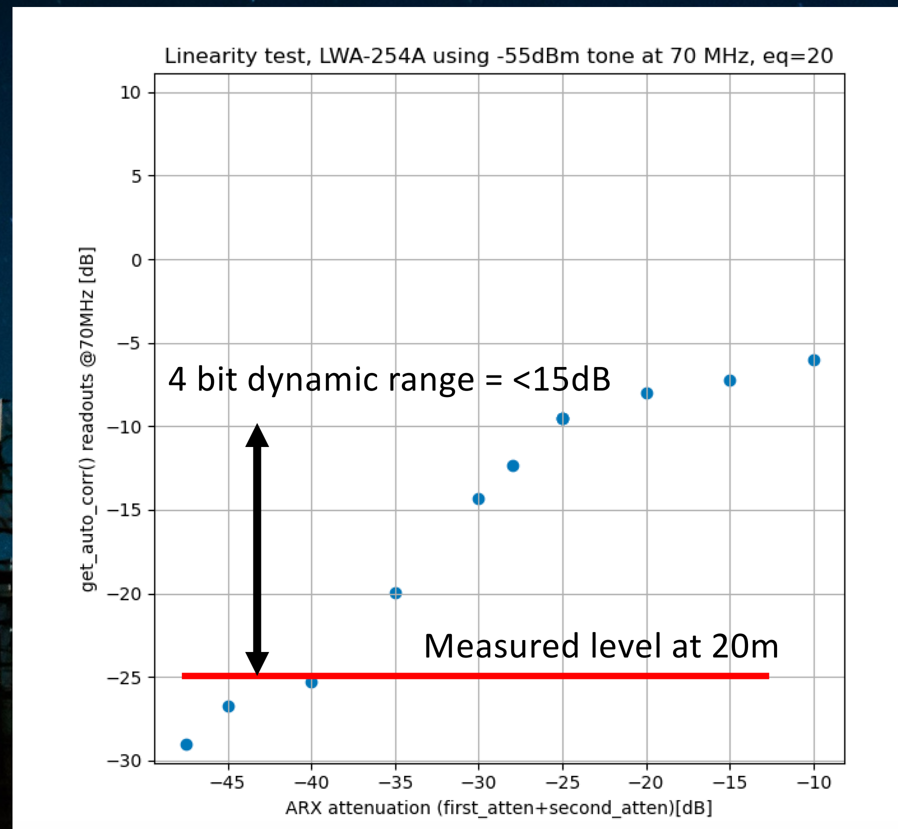
Range Test



Range Test



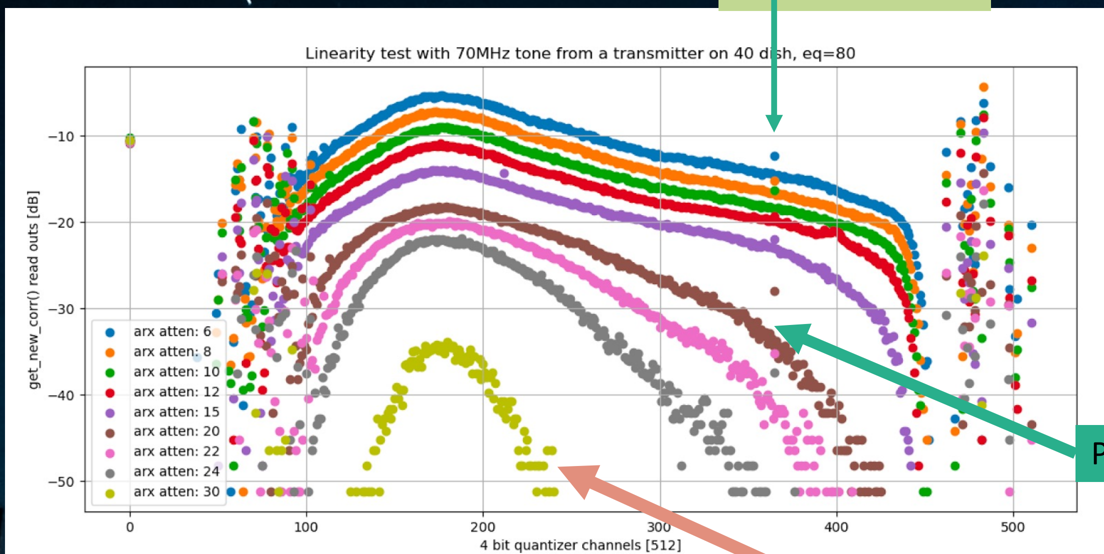
Plot by Mrudula Gopalkrishna



Plot by Akshatha Vydula

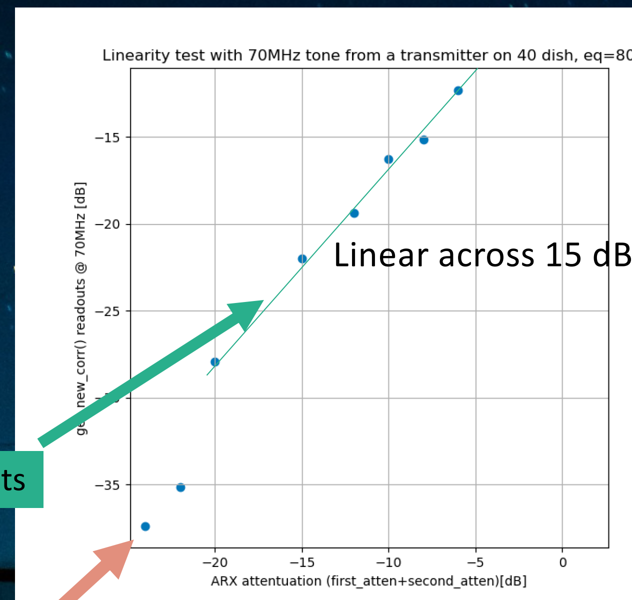
Check our control of nonlinearity with a more distant transmission

Transmitter tone



Plots by Akshatha Vydula

4x higher equalization to account for increased distance



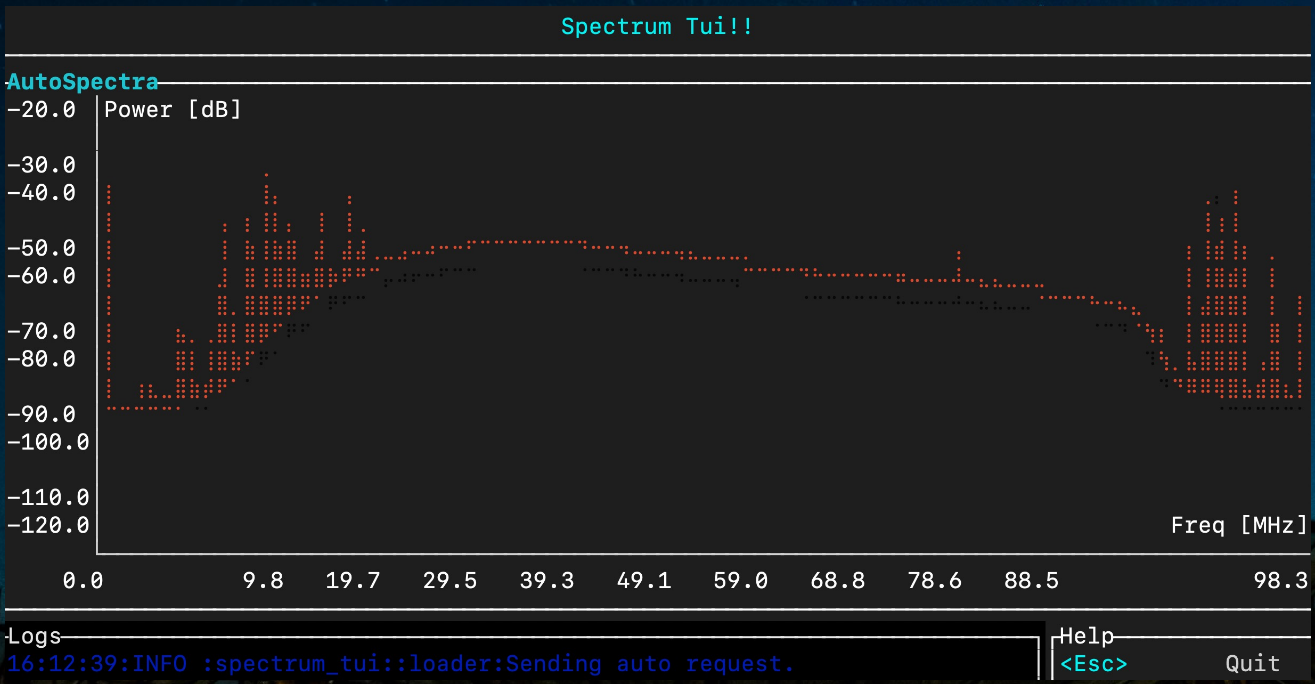
Linear across 15 dB

Plenty o bits

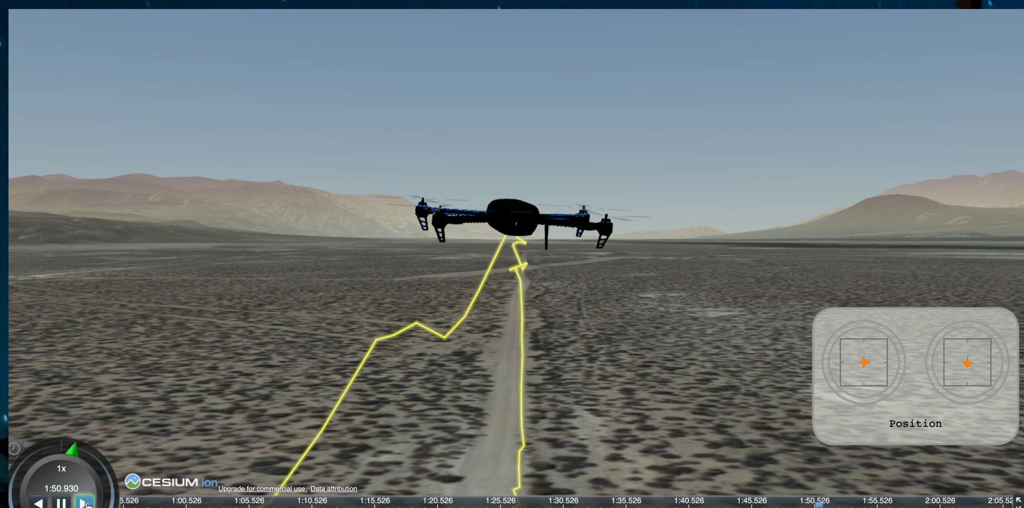
Not enough bits

Mark Hodges holds transmitter on catwalk of 40m. Range 1100m

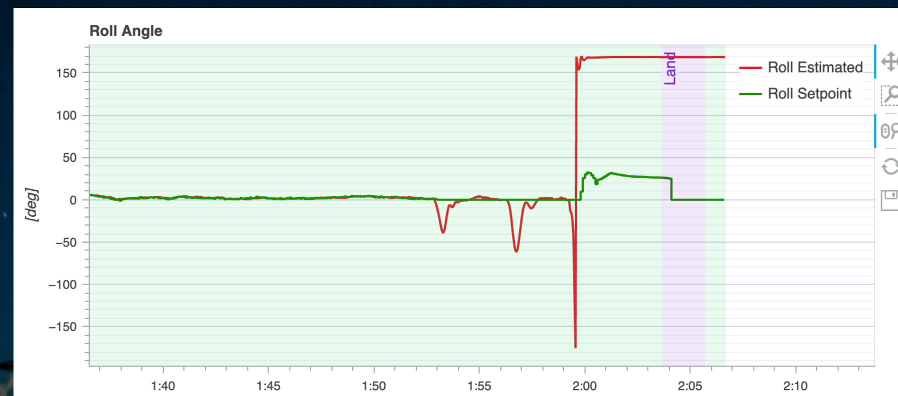
Matts Awesome terminal spectrum monitor

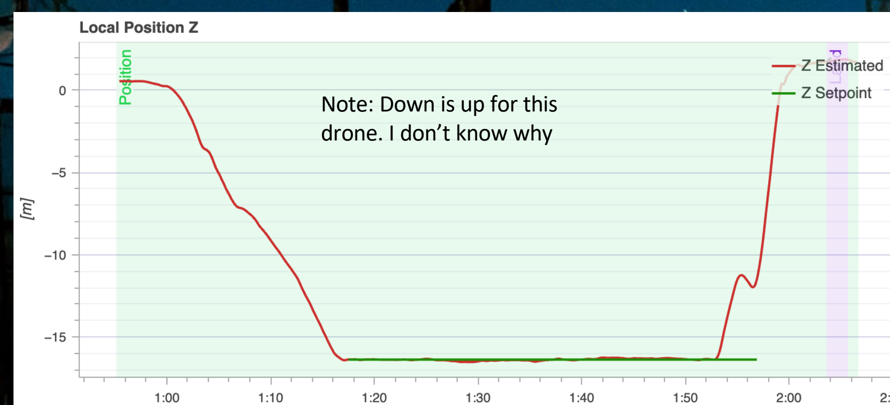


A Premature Descent

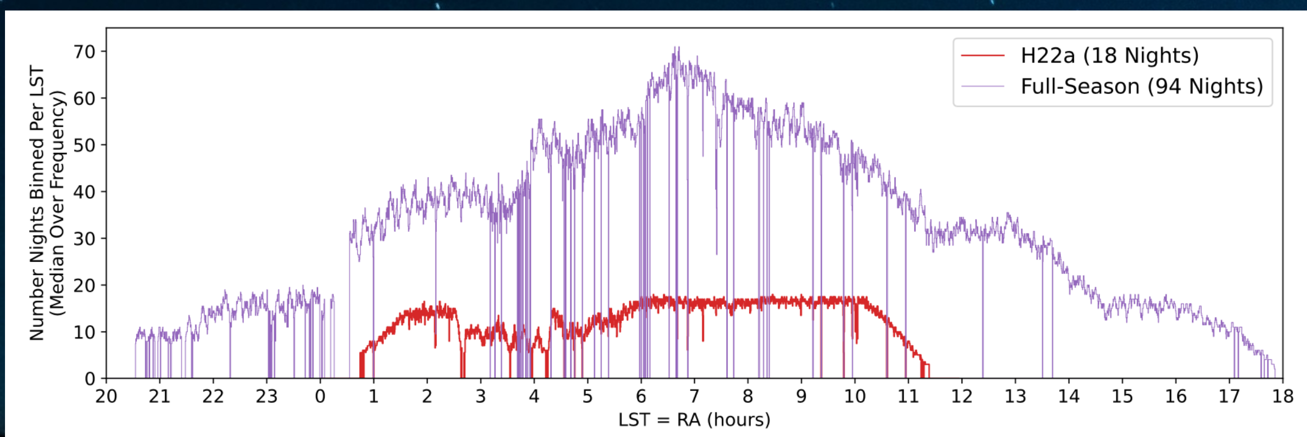


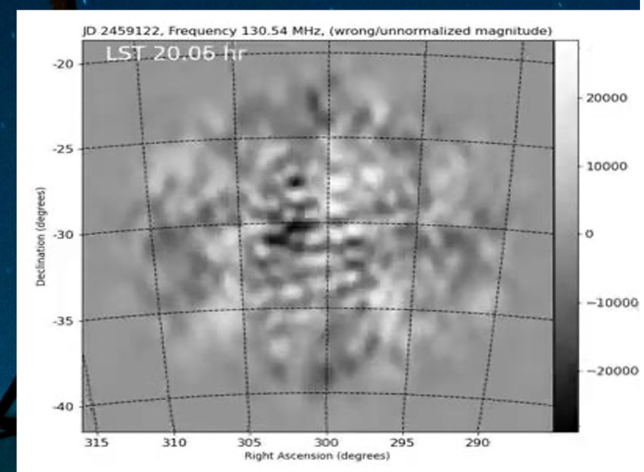
May 25 2023 – Drone C Incident log





Extended Phase 1 Analysis

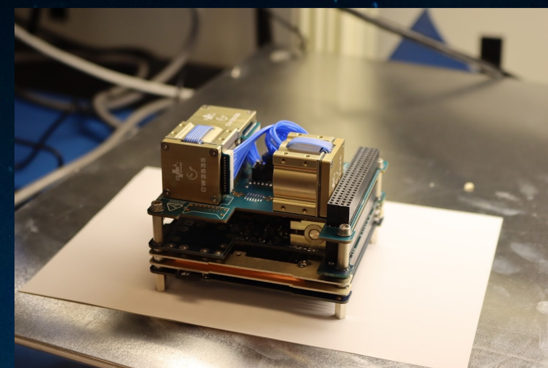




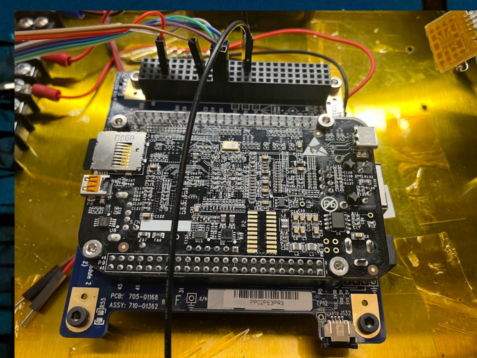
HERA Collab 2023 - ApJ

DORA Status

- Selected for NASA Rideshare Flight
- Expected Launch Jan 2025

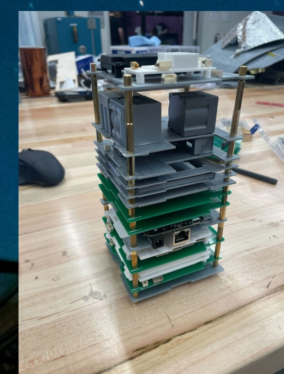


Attitude Control from CubeSpace



Custom embedded linux system with applications in Rust

https://github.com/ASU-cubesat/loco-linux



Mechanical Mockup for cable design