Calibration Challenges

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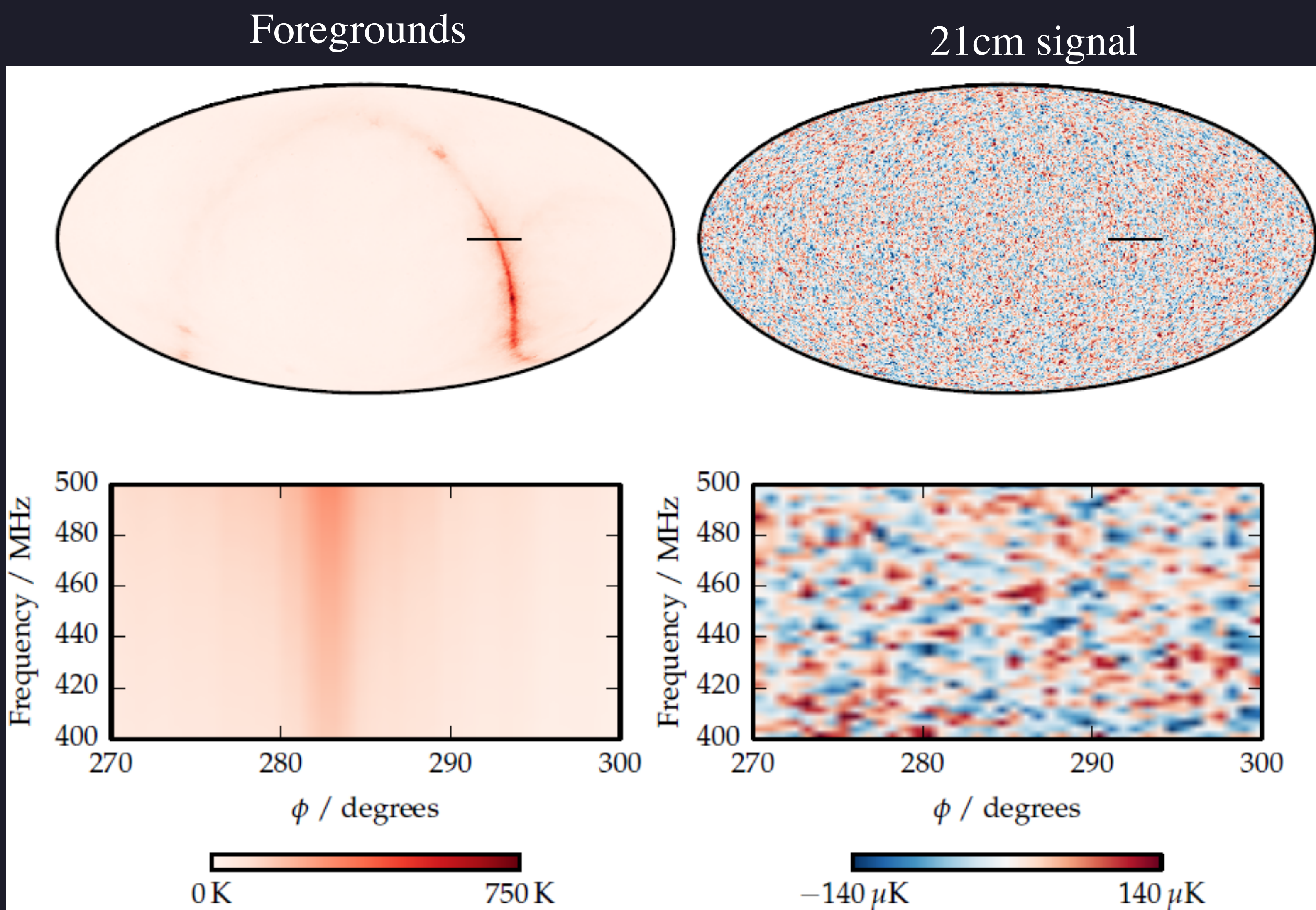
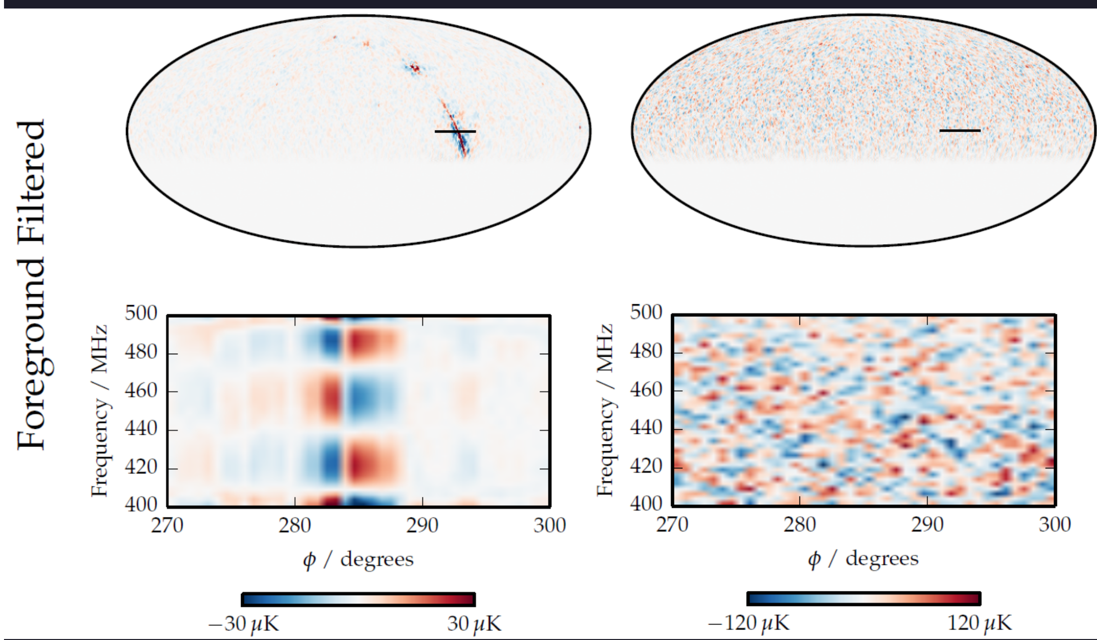
Foregrounds



Shaw et al. 2015

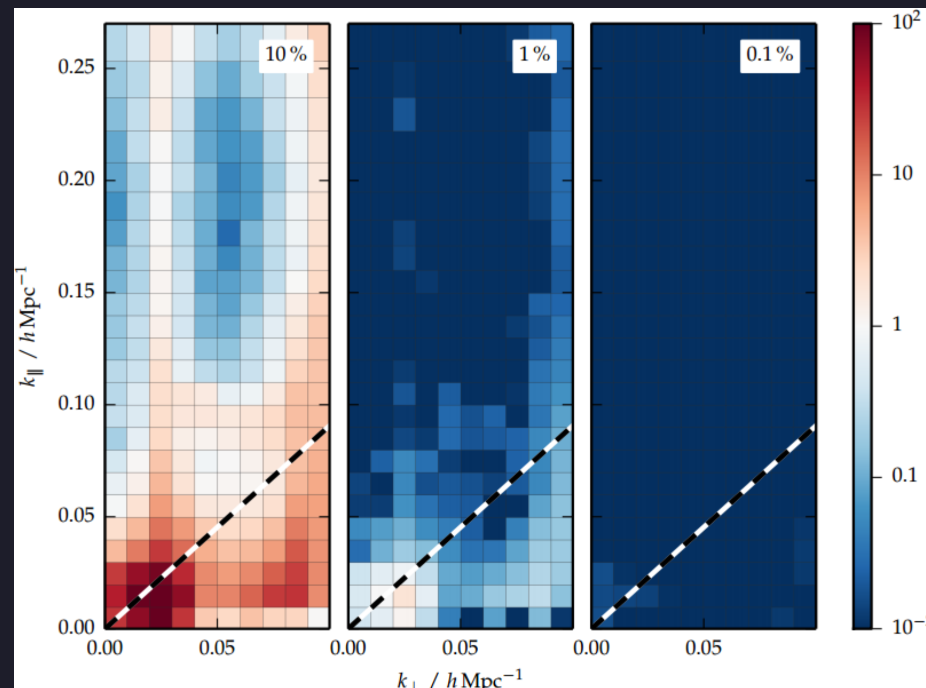
Foregrounds



Filtered Foregrounds

Filtered
21cm signal

Error in Power spectrum
due to % error in gain



Shaw et al. 2015

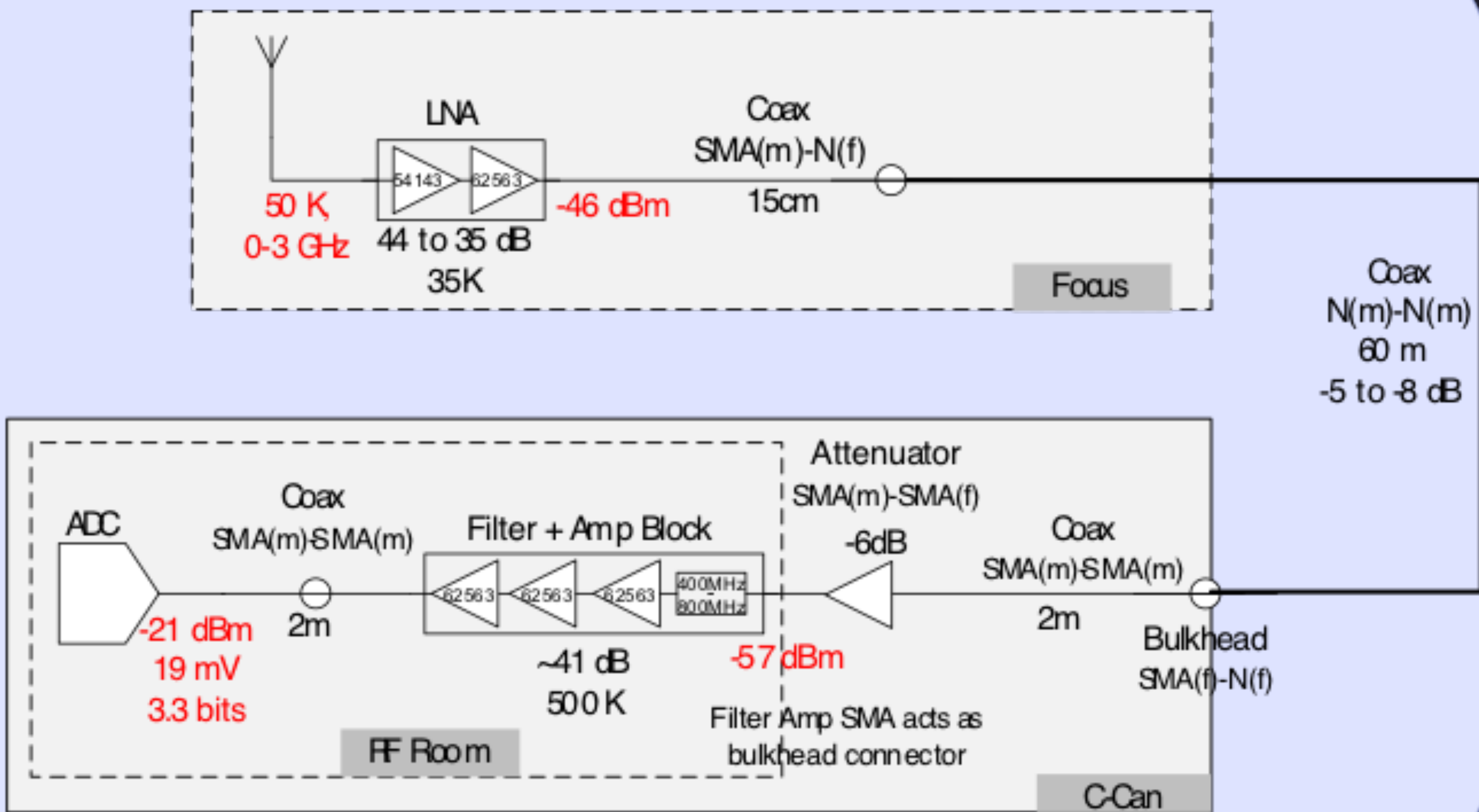
Requirements

- Beam Calibration to better than 0.1%
- Complex Gain target better than 1% (Shaw et al. 2015)
  - ~0.3% amplitude
  - ~0.003 Radian phase
- Redundant Baseline compression or FFT Beamforming will require Real-time Calibration

Redundant Baseline Calibration

- Requires baselines to be actually redundant.
- Corr-cal
  - Imperfect Sky model + nearly redundant baselines

Analog System



Temperature Stability

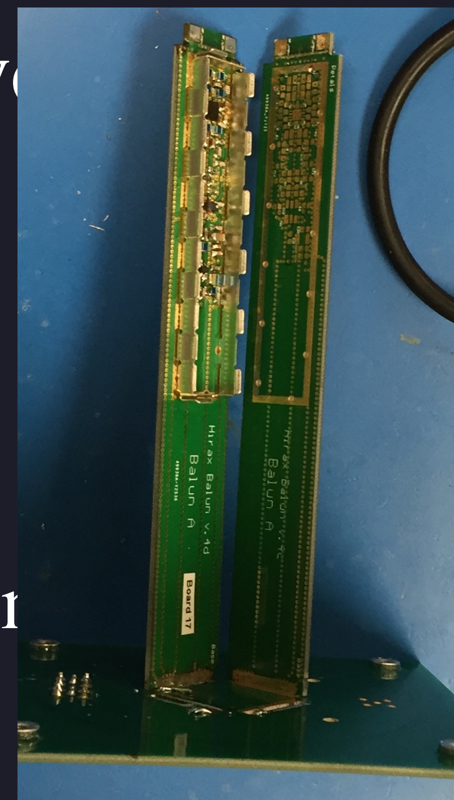
- Current analog amplifier chains have

  ~0.2 % / °C amplitude variation

- Maintain to 1°C
  - Measure and model temperature to rer

    variation

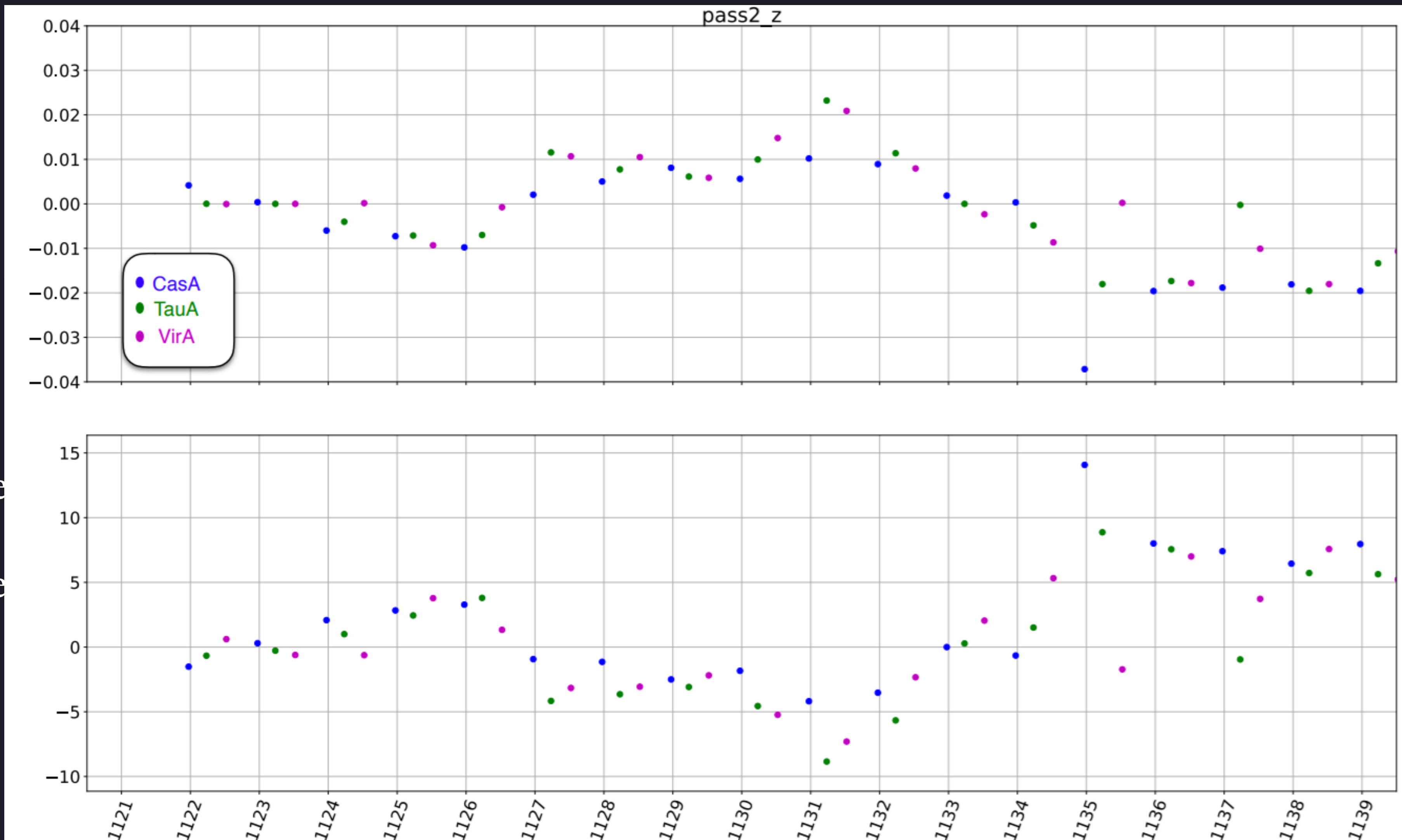
- Analog chain phase
  - Cable lengths change ~10-50ppm/ °C ~20ppm/



Measure Gain Variations

Amplitude

Ambient Temperature °C

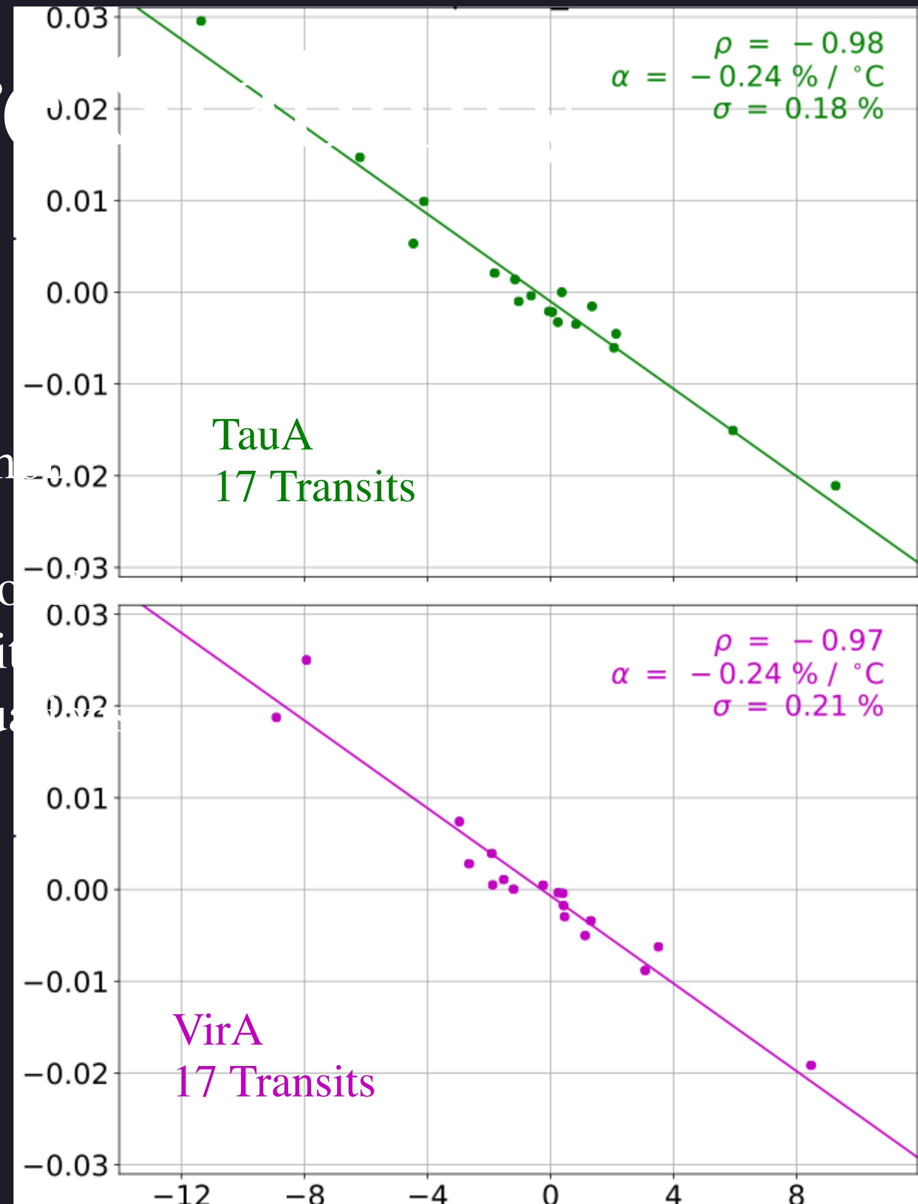


Credit: Seth Siegel

CHIME Pathfinder Temperatur…

- Thermal Model to remove common mode amplitude fluctuations.

  Approaching the ~0.5% amplitude stability



Credit: Seth Siegel

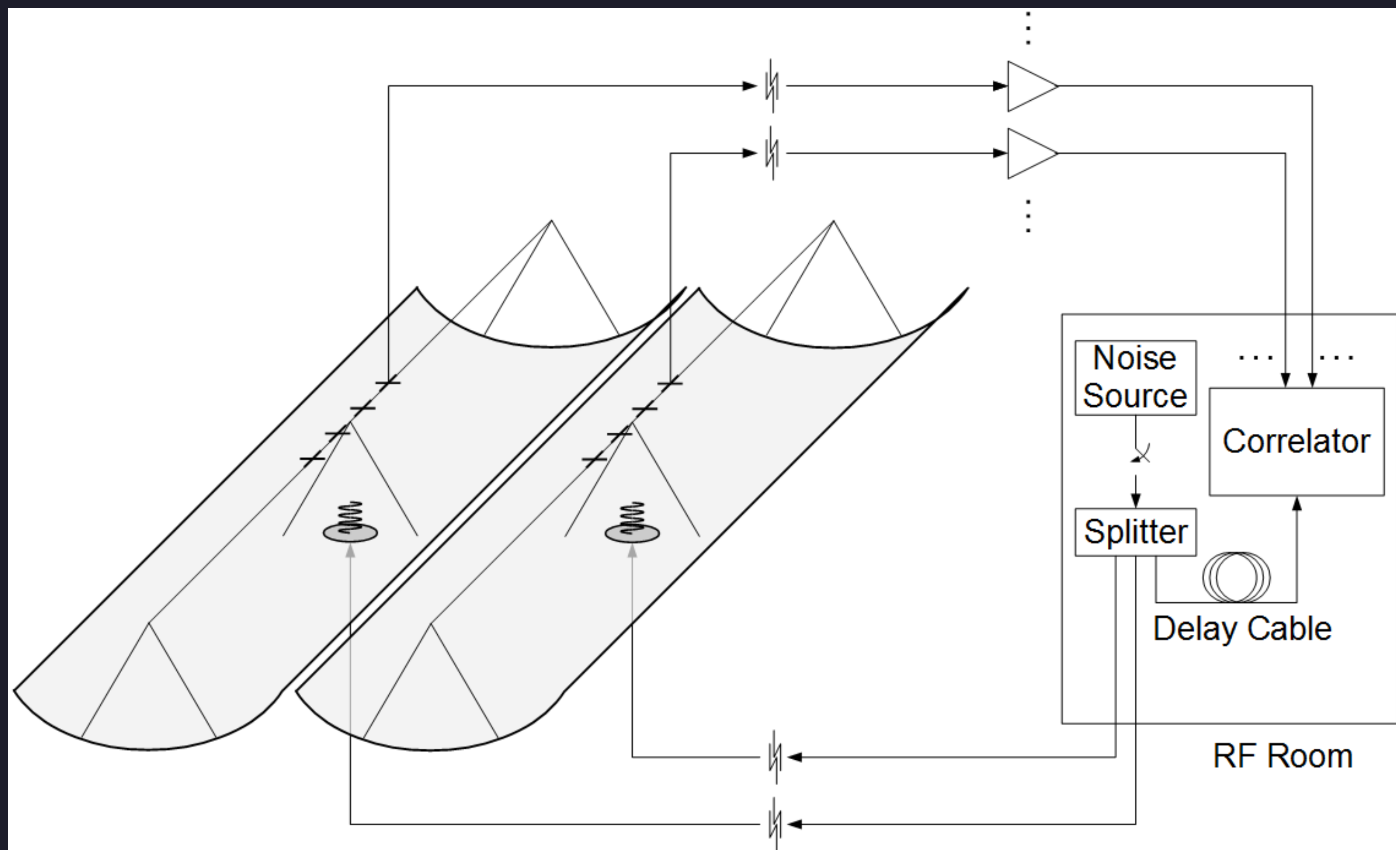
Tsource - Tcal [°C]

Add Temperature Stabilization

- Heater and/or TEC:
  - Maintain ~ 20-40°C
- Digital electronics at focus
- Measure each amplifier and transmission system

Broadband Signal Injection

- Broadband Injected Signal
- Measured by Correlator



Gain Calibration Visibilities

$$\mathbf{V}_{\mathrm{on}}^{\mathrm{meas}} = \mathbf{g}\mathbf{g}^{\mathrm{H}}\sigma_s^2 + \mathbf{G}\mathbf{V}^{\mathrm{sky}}\mathbf{G}^{\mathrm{H}} + \mathbf{N}_{\mathrm{on}}$$

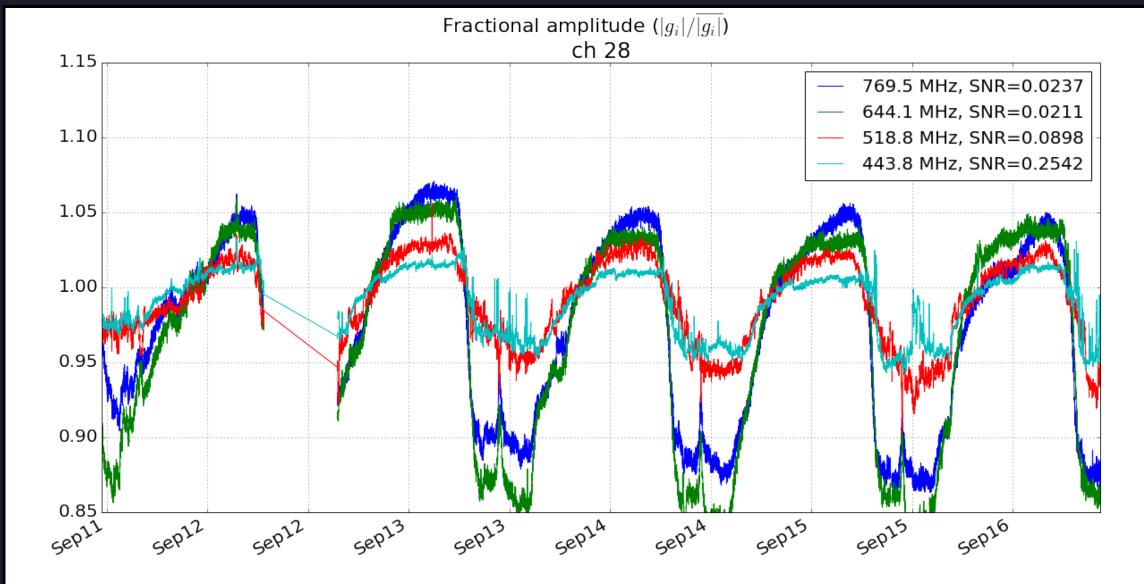
$$\mathbf{V}_{\mathrm{off}}^{\mathrm{meas}} = \mathbf{G}\mathbf{V}^{\mathrm{sky}}\mathbf{G}^{\mathrm{H}} + \mathbf{N}_{\mathrm{off}}$$

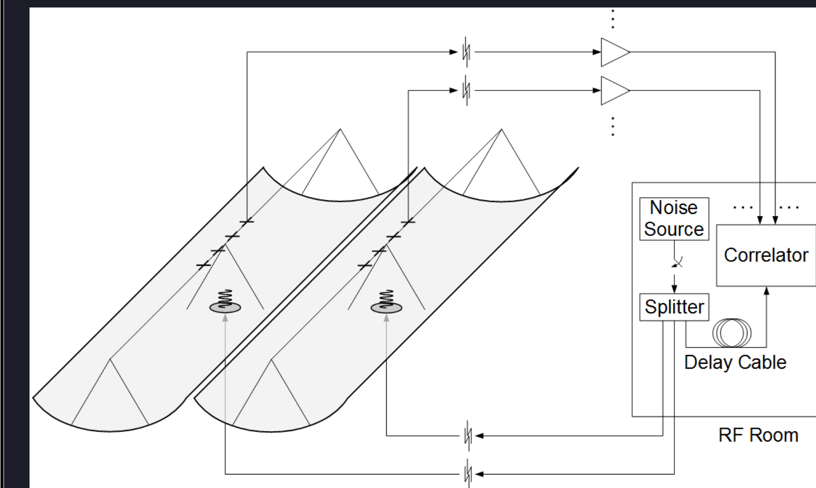
Broadband Signal Injection

$$\frac{\Delta \mathbf{V}^{\mathrm{meas}}}{\sigma_s^2} = \mathbf{g}\mathbf{g}^{\mathrm{H}} + \frac{\Delta \mathbf{N}}{\sigma_s^2}$$

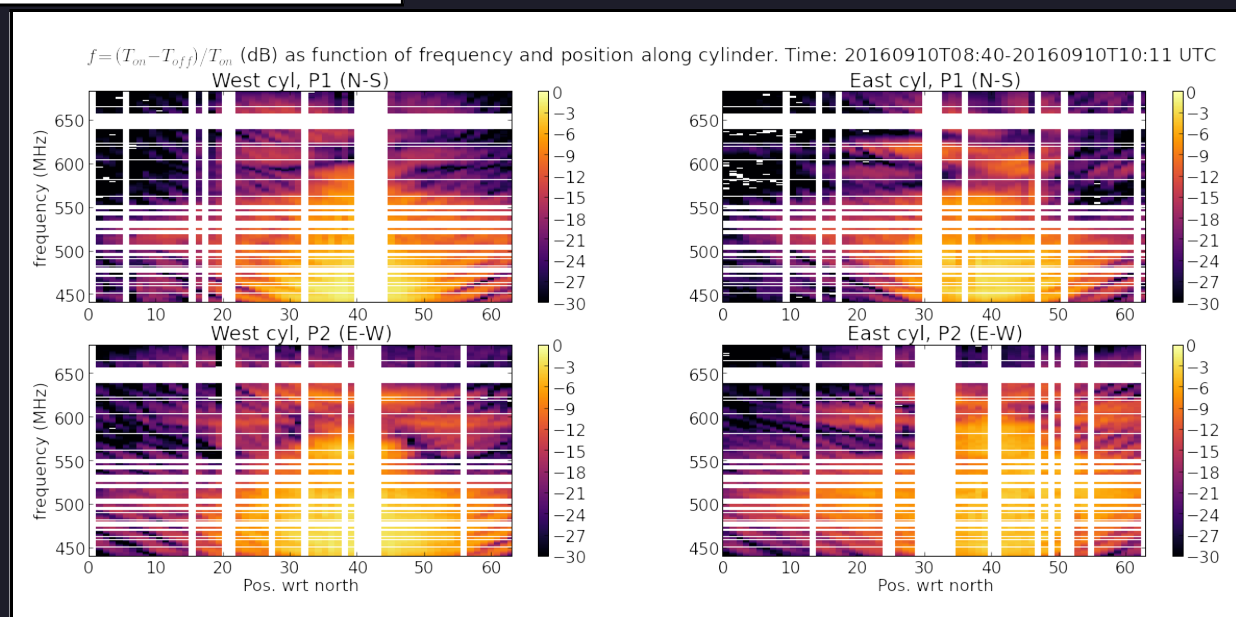
$$\hat{\mathbf{g}} = \underset{\mathbf{g}}{\operatorname{argmin}} \left\| \frac{\Delta \mathbf{V}^{meas}}{\sigma_s^2} - \mathbf{g}\mathbf{g}^{\mathrm{H}} \right\|_F^2 = \sqrt{\lambda_{\max}}\, \mathbf{u}_{\max}$$

Broadband Signal Injection





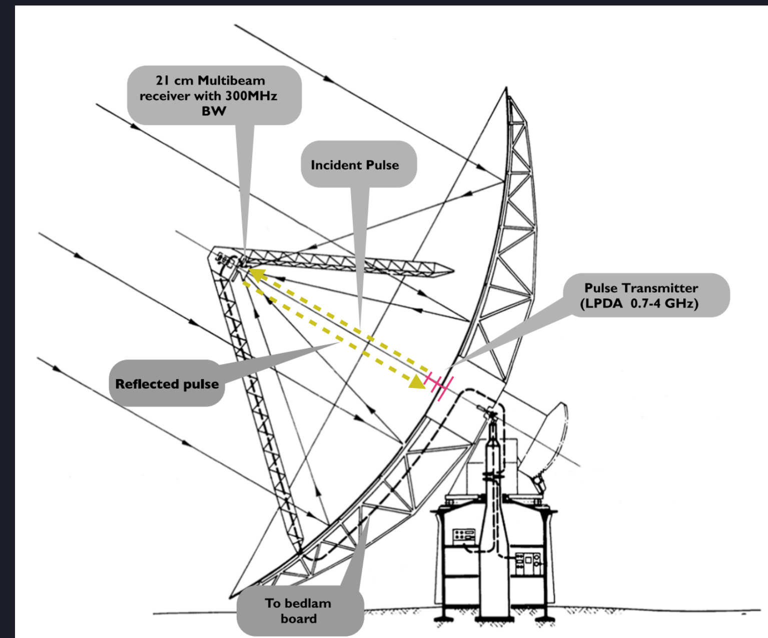
- Calibration to the 1% level.
- Injection system must be stable and uniform



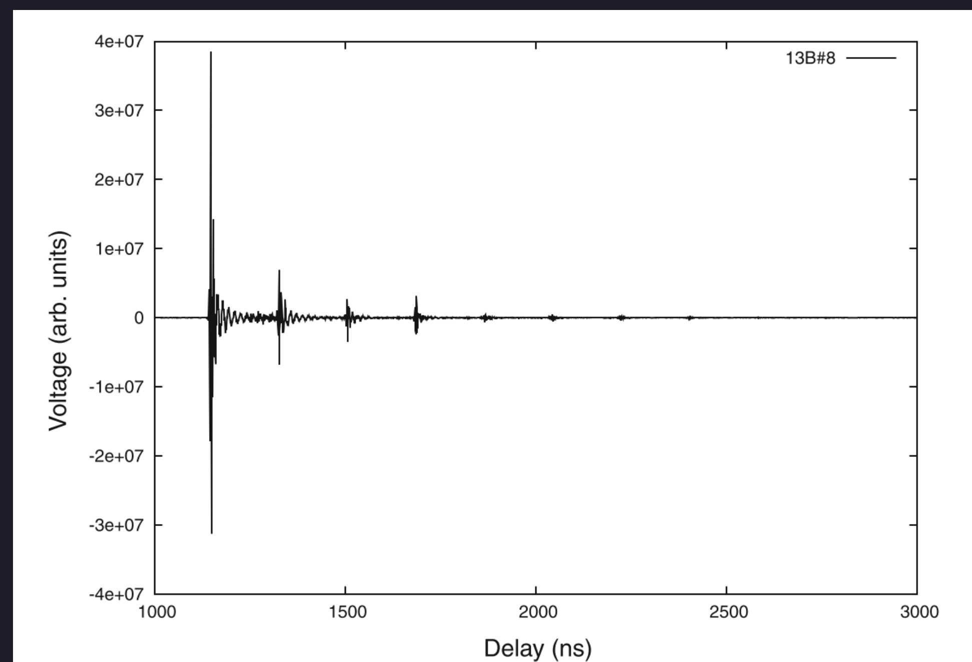
Credit: Juan Mena

Pulse Injection

- Instead of broadband noise, inject < ns pulse
- Measure in time domain.
- “Strong Signal”, synchronize and blank

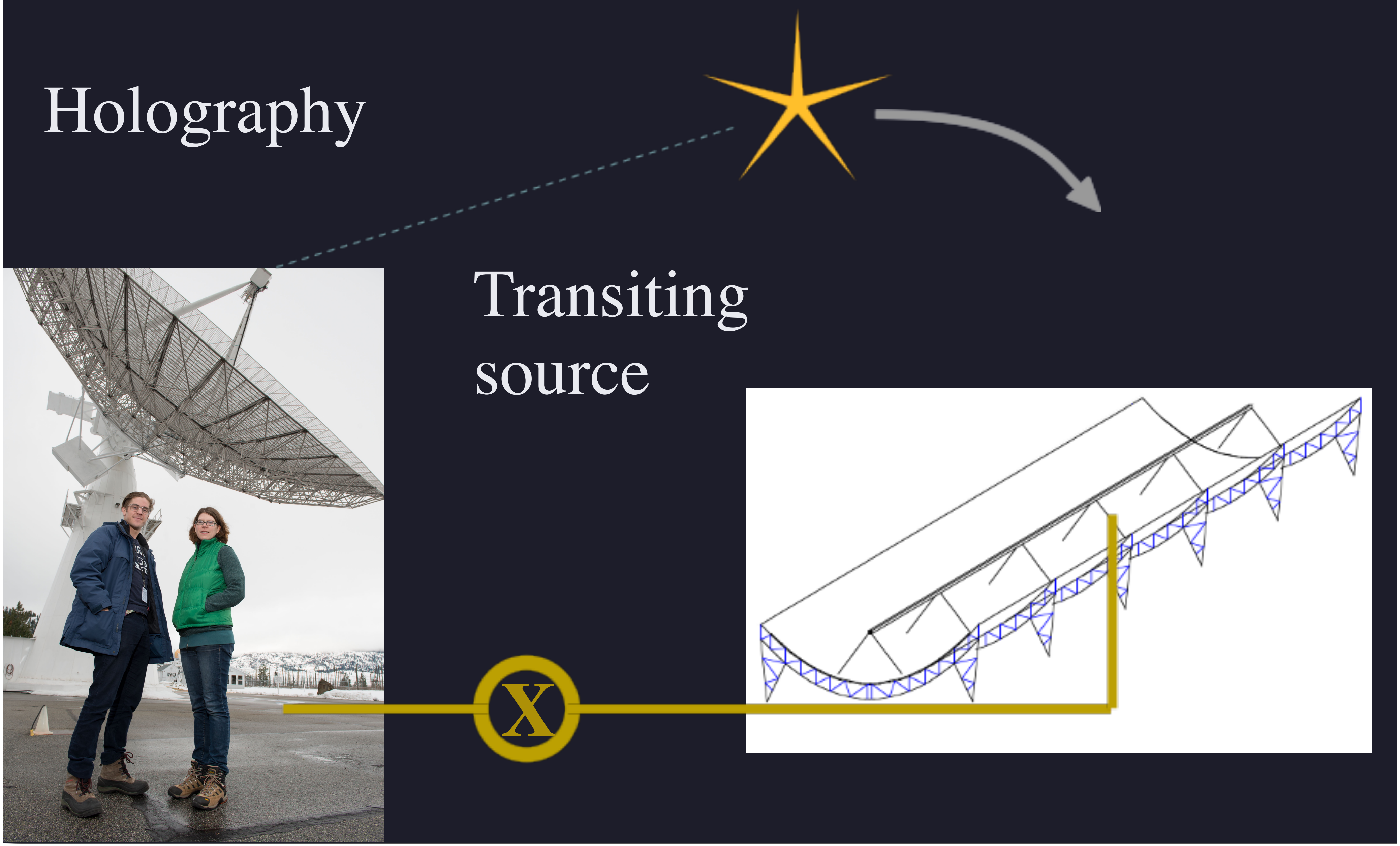


Patra et. al. 2017



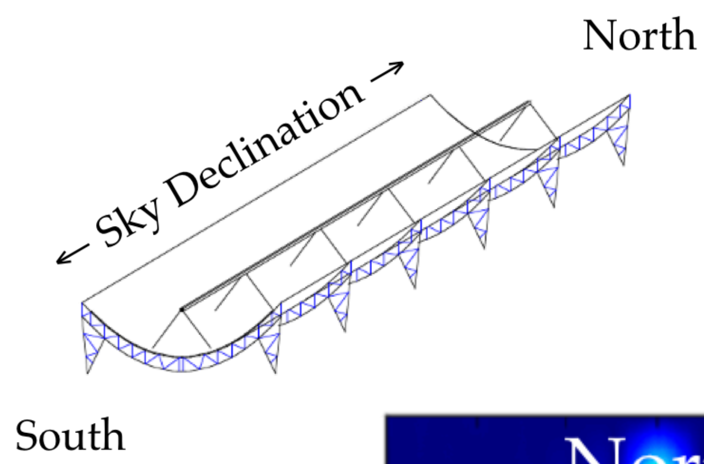
Patra et. al. 2017

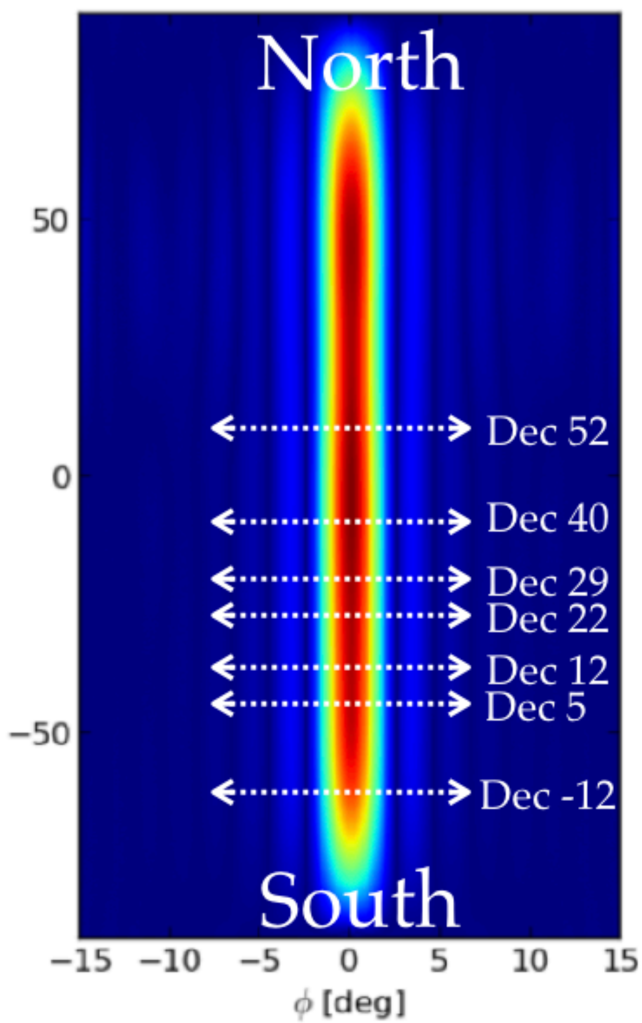
Beam Calibration

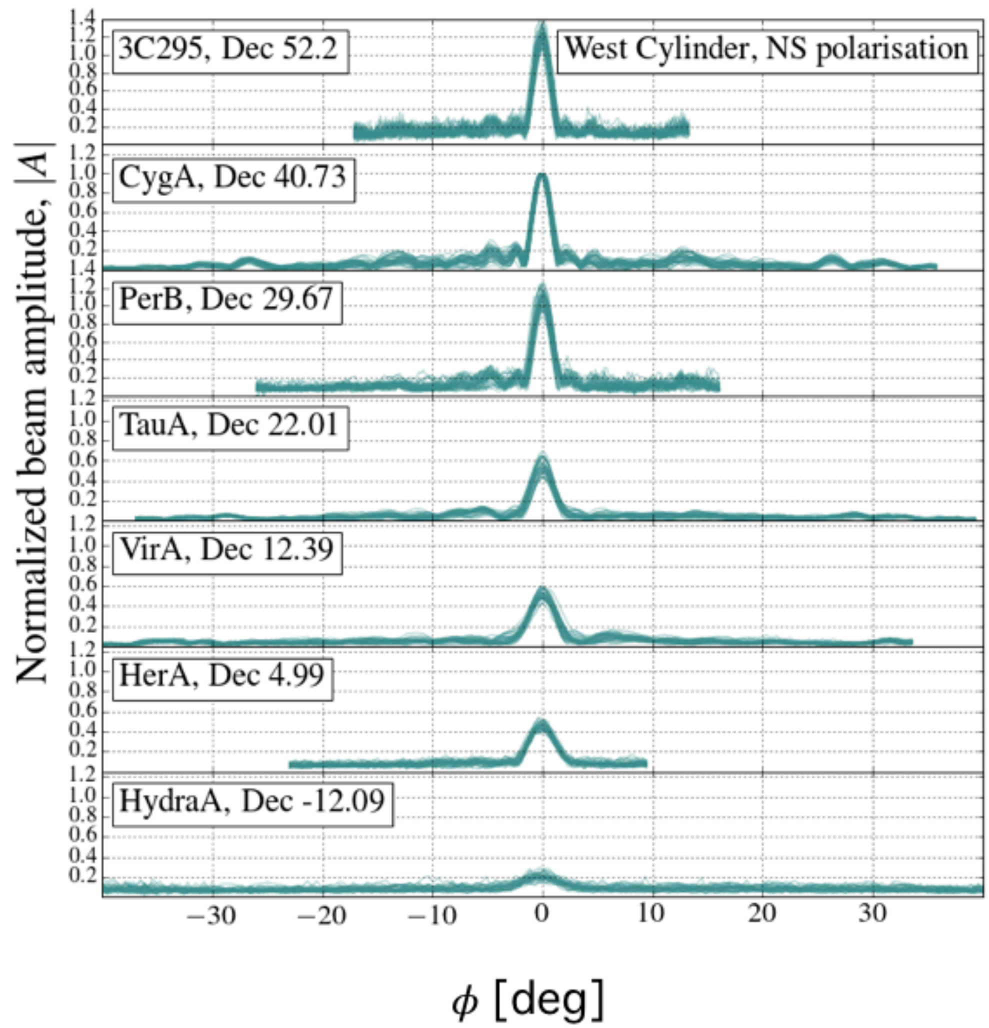


Holography

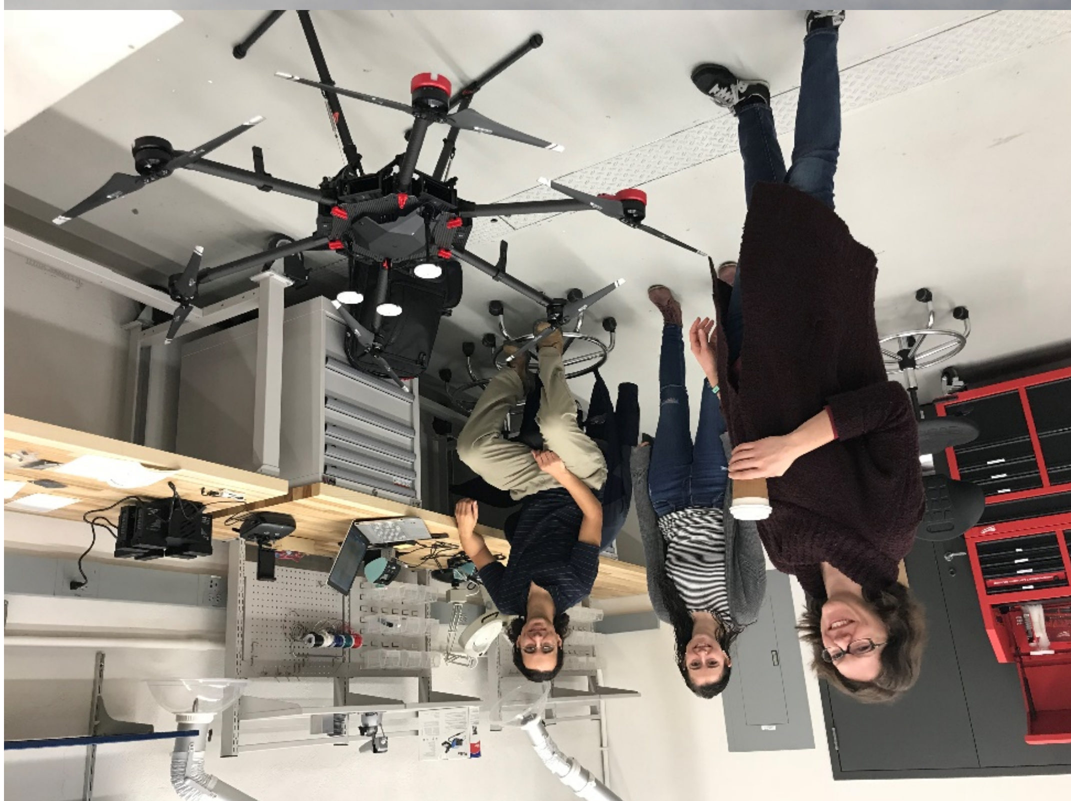
Berger et al 2016



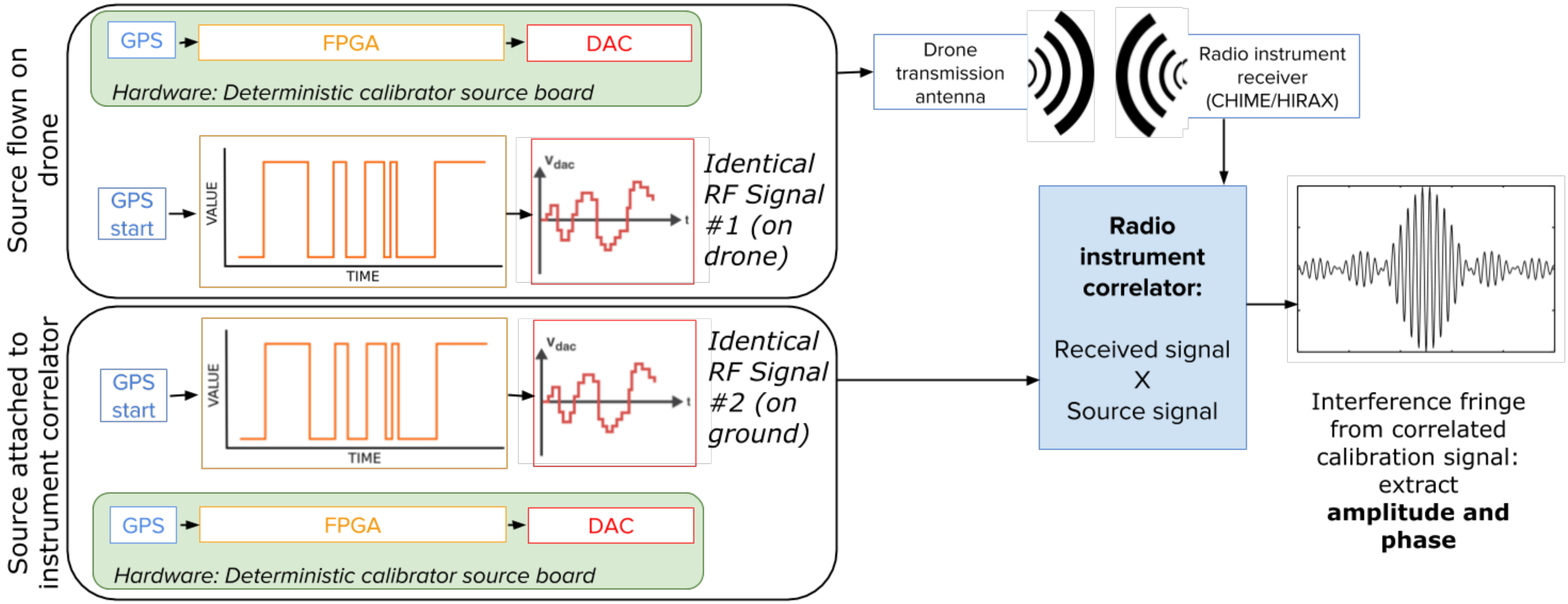


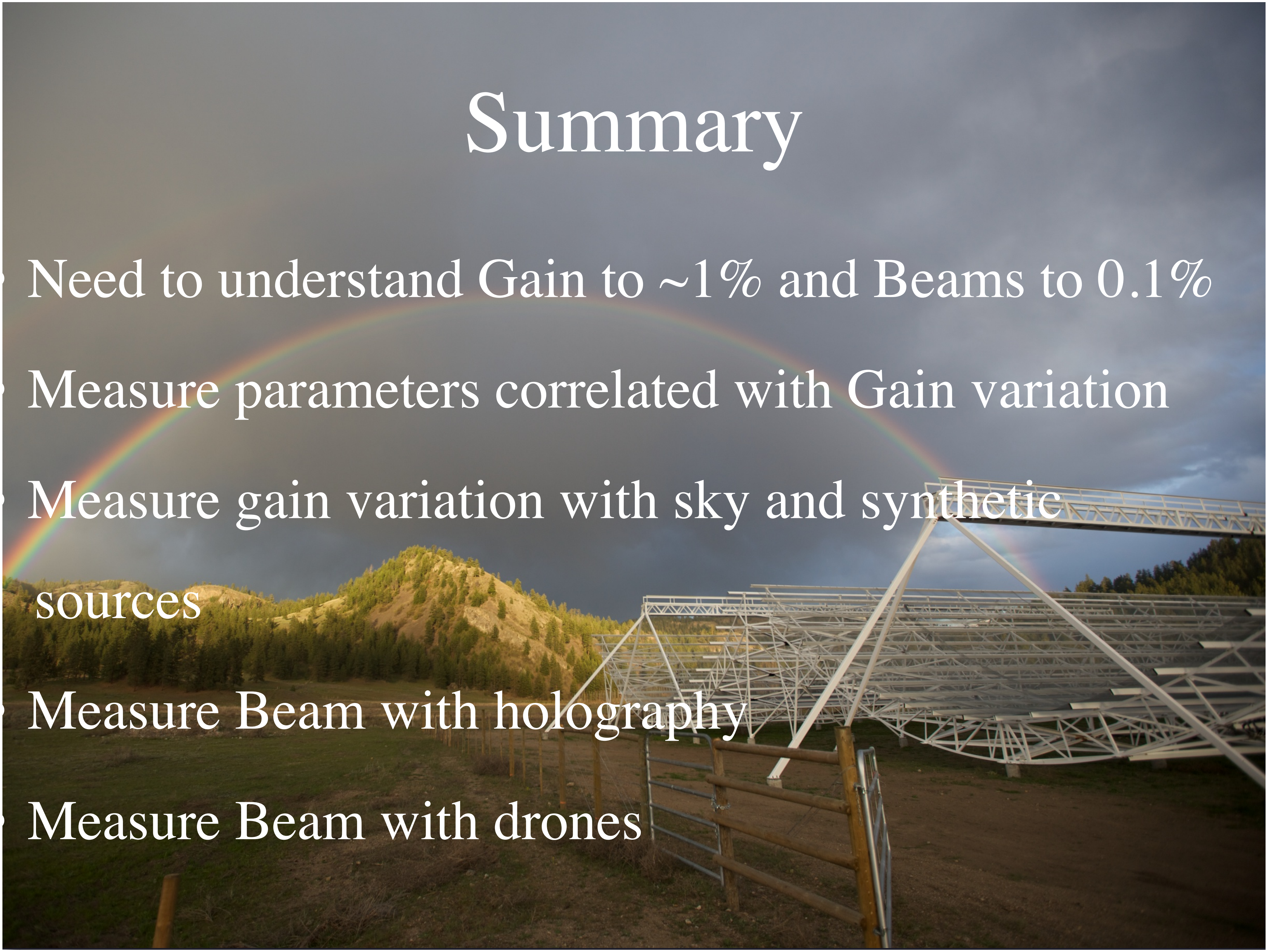


Drone Calibration



Improved Calibration Source

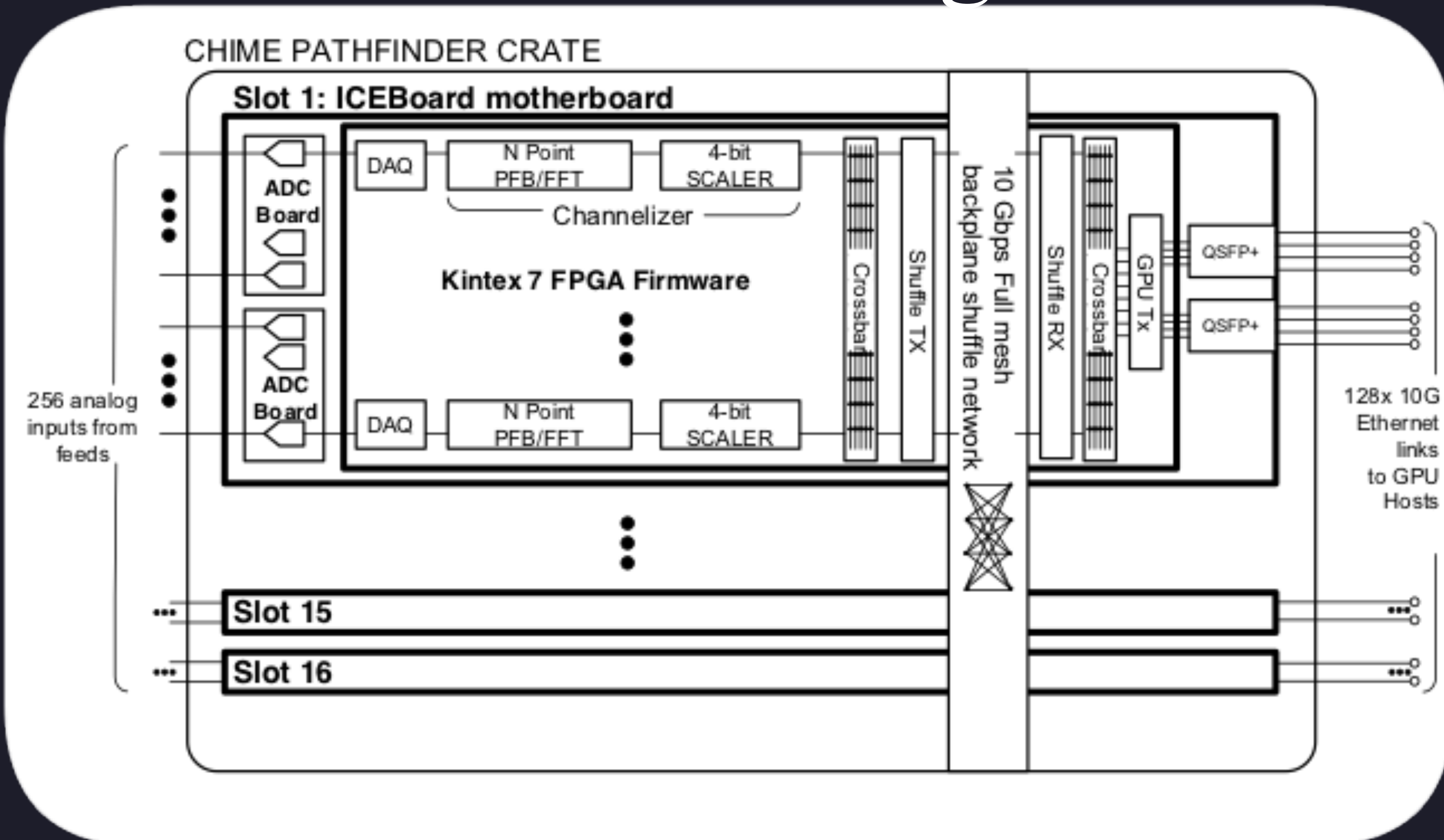




Summary

- Need to understand Gain to ~1% and Beams to 0.1%
- Measure parameters correlated with Gain variation
- Measure gain variation with sky and synthetic sources
- Measure Beam with holography
- Measure Beam with drones

Correlator F-Engine and Networking



Correlator F-Engine

Two
Gbit
Ethernet

Digital signals come in/out the back

Custom Backplane
Power, clock, timestamp
Board inter-connect

9U VME Front-
panel

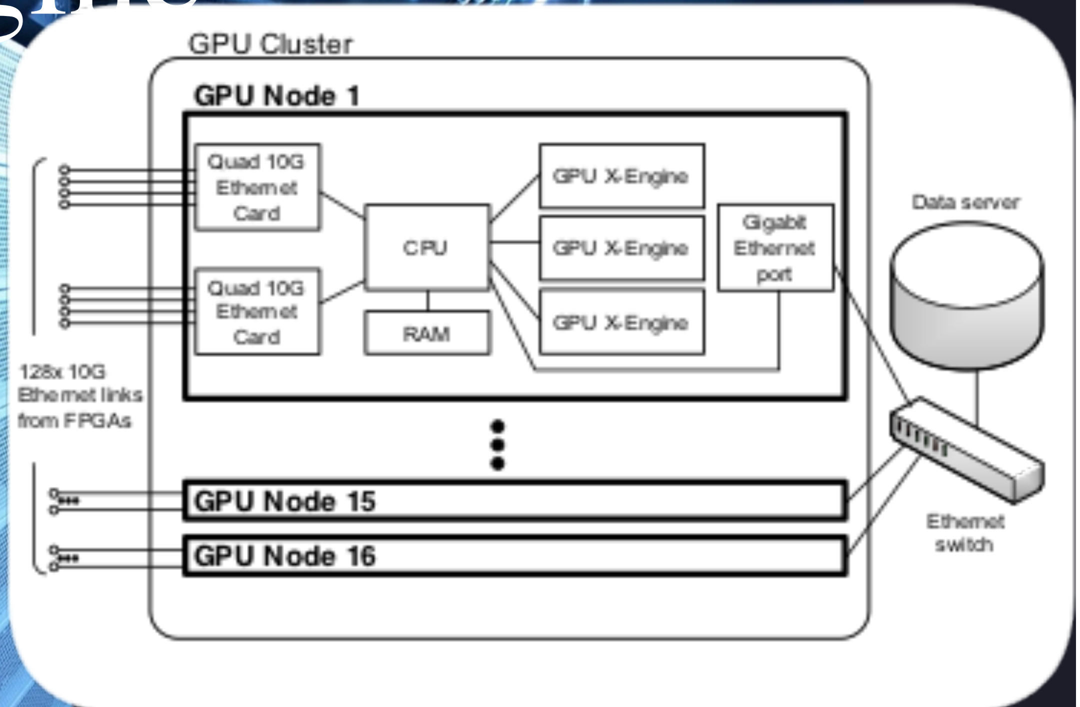
Two FMC
Mezzanines

Correlator – X Engine

GPU

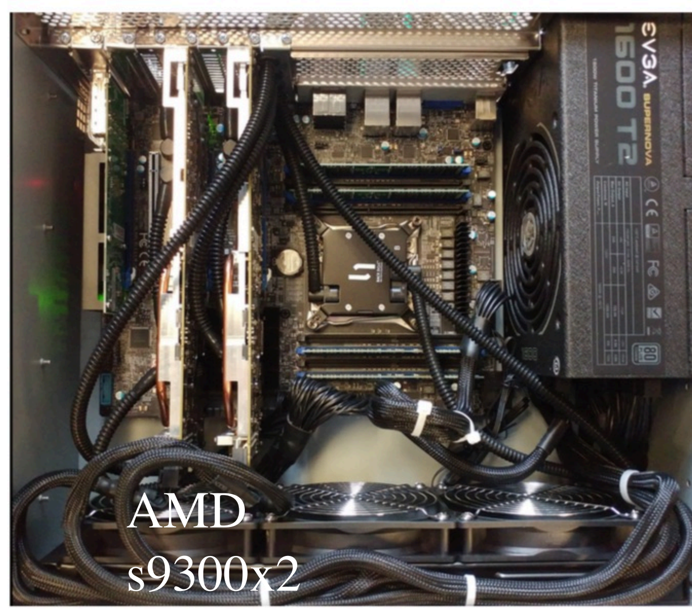
Pathfinder: 13T complex MAC/s

CHIME: 840 T MAC/s



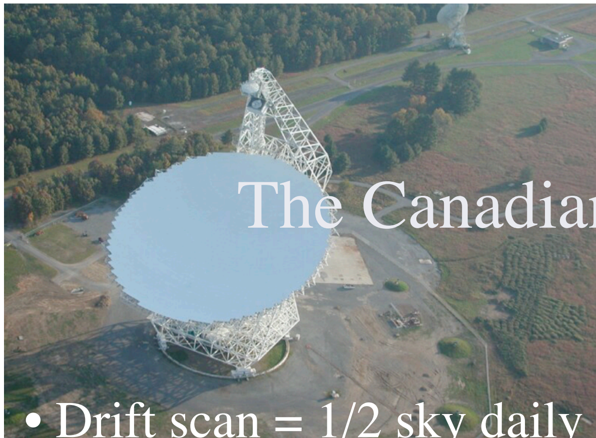
- FRB FFT Beamformer
- Pulsar Beamformer


Denman et al. 2015

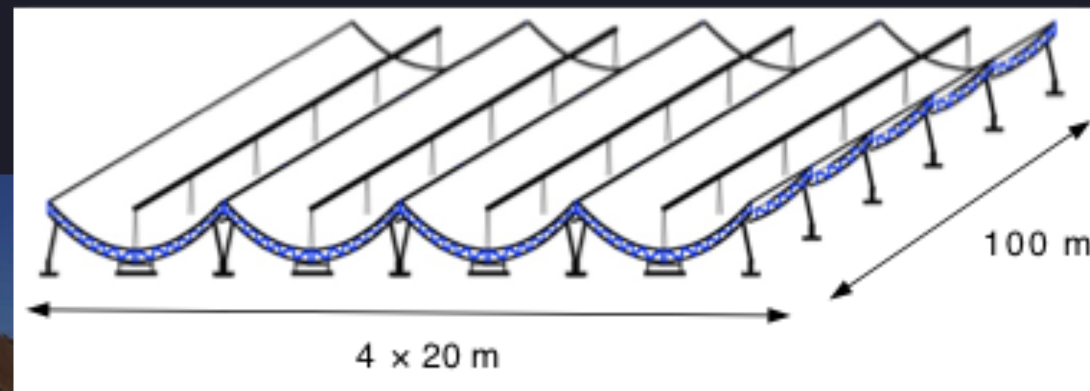


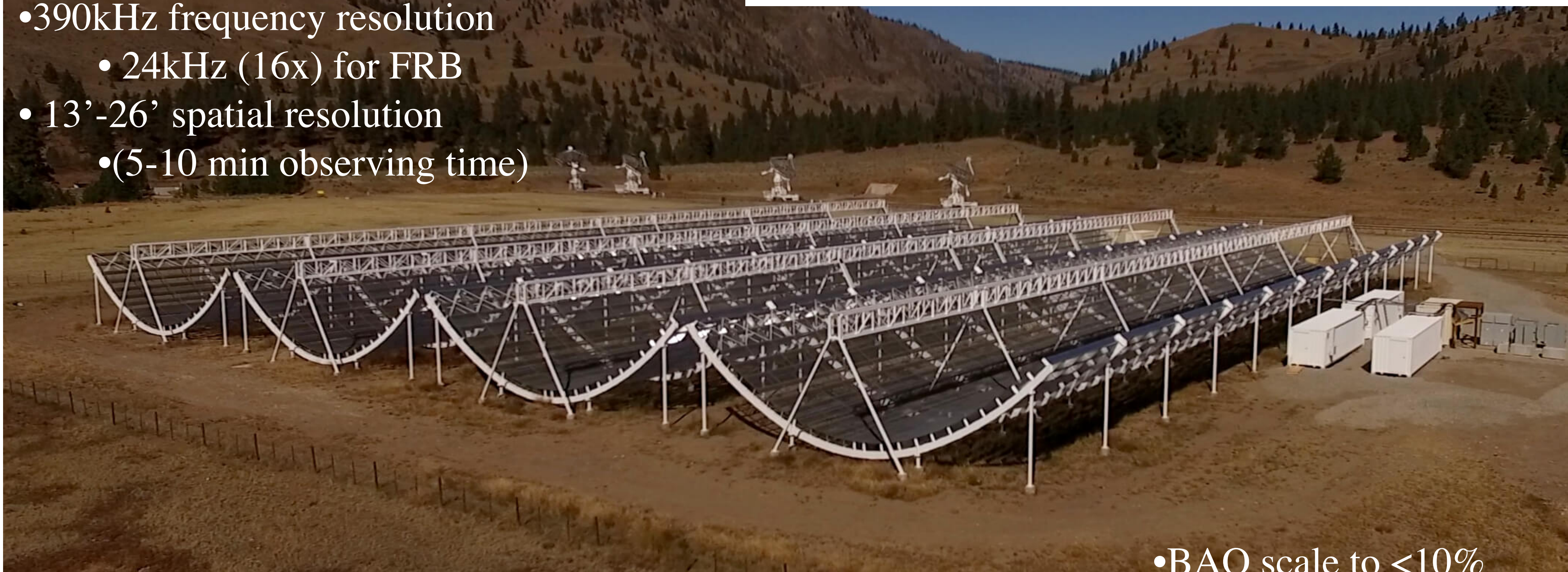
CHIME

The Canadian Hydrogen Intensity Mapping Experiment



- Drift scan = 1/2 sky daily
  - Due to actual N-S beam
- 400-800MHz band
  - 0.8 < z < 2.5 (for 21cm)
- 390kHz frequency resolution
  - 24kHz (16x) for FRB
- 13’-26’ spatial resolution
  - (5-10 min observing time)





- BAO scale to <10%
  - w0 to ±0.05 (w0 ~ 1)

HIRAX

- 1024 6m Dishes
- Karoo Desert
- South Africa

Broadband Signal Injection