BK Polarization Calibration and Frequency Bandpass measurements

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CMB-CAL 2024

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Summary

Polarization Calibration

Paper now on arXiv! [2410.12089]

- Motivation
- Calibration
- Instrumental Error
- CMB Uncertainties
- Impact on *r*

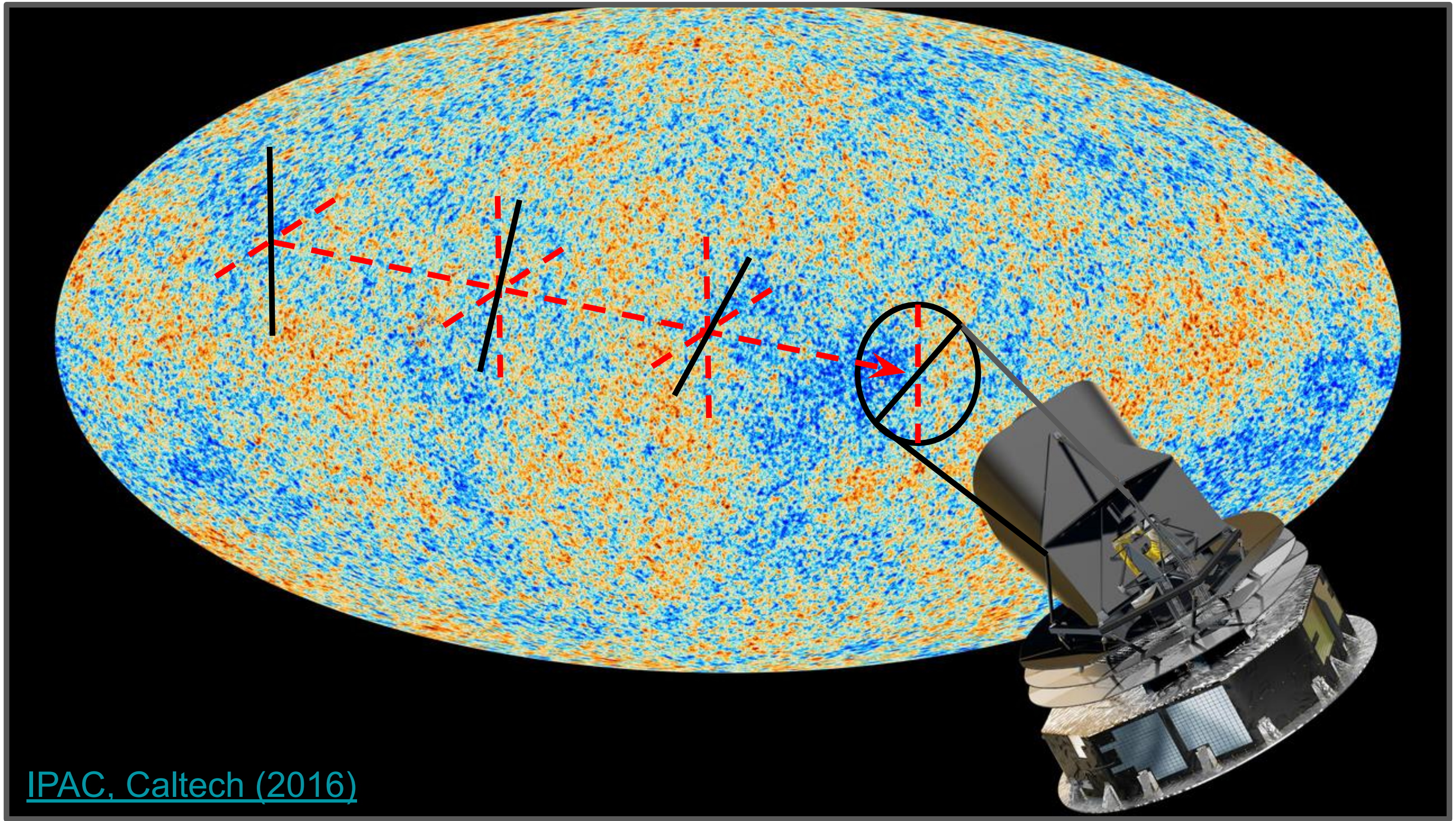
Bandpass Results

Motivation

- Makes us sensitive to potential signals of EM parity violations (aka Isotropic Cosmic Birefringence)
- Understand (or mitigate) systematics on r
- Enables EE abscal
- Understand divergences between T and Q beams

How is the CMB affected by Cosmic Birefringence?

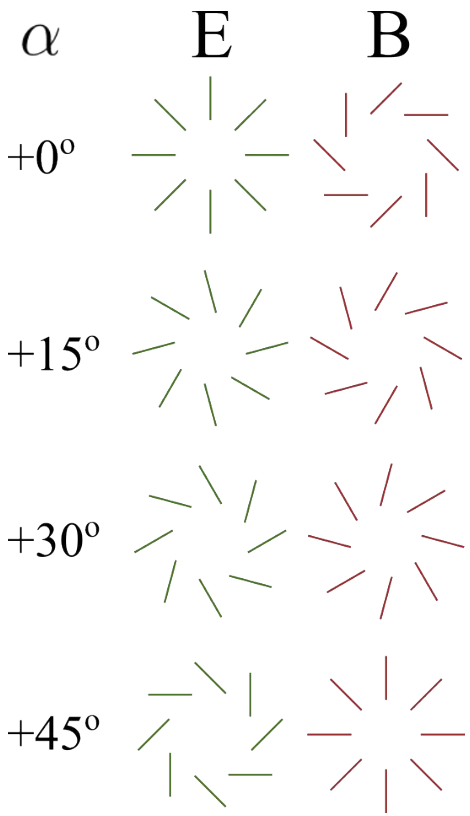
Linear polarization rotates as it travels through spacetime

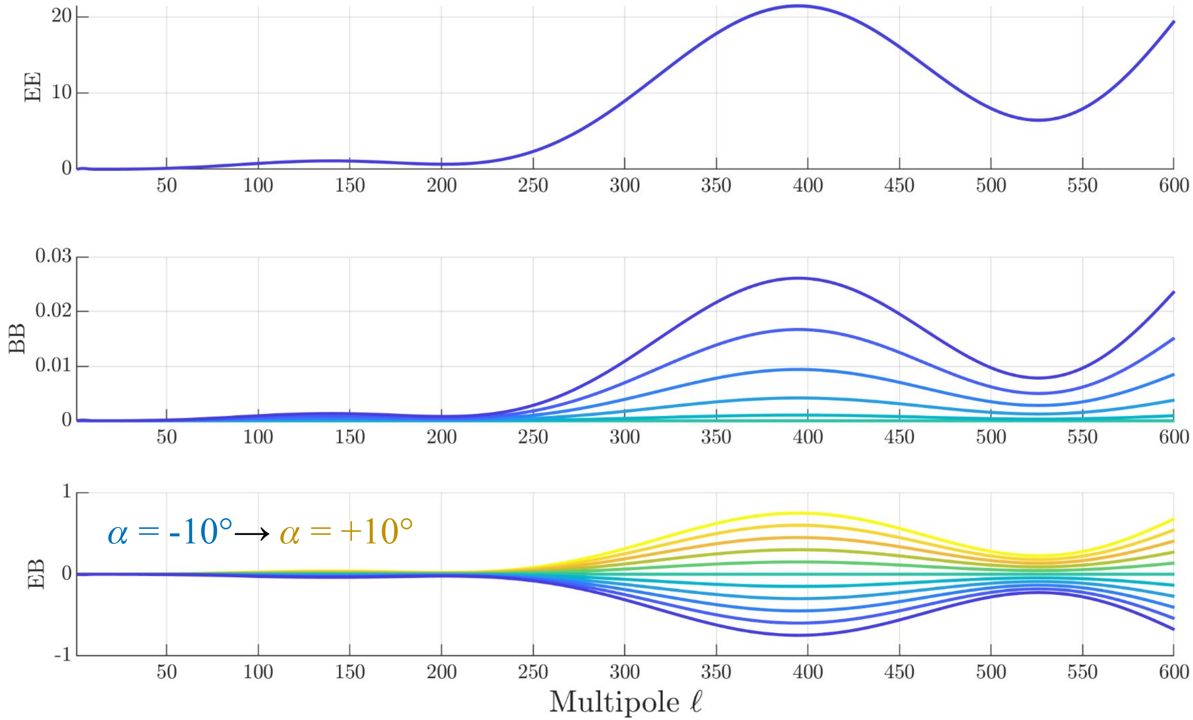


IPAC, Caltech (2016)

How is the CMB affected by Cosmic Birefringence?

E rotates into B and vice versa. E and B correlations become non-zero!

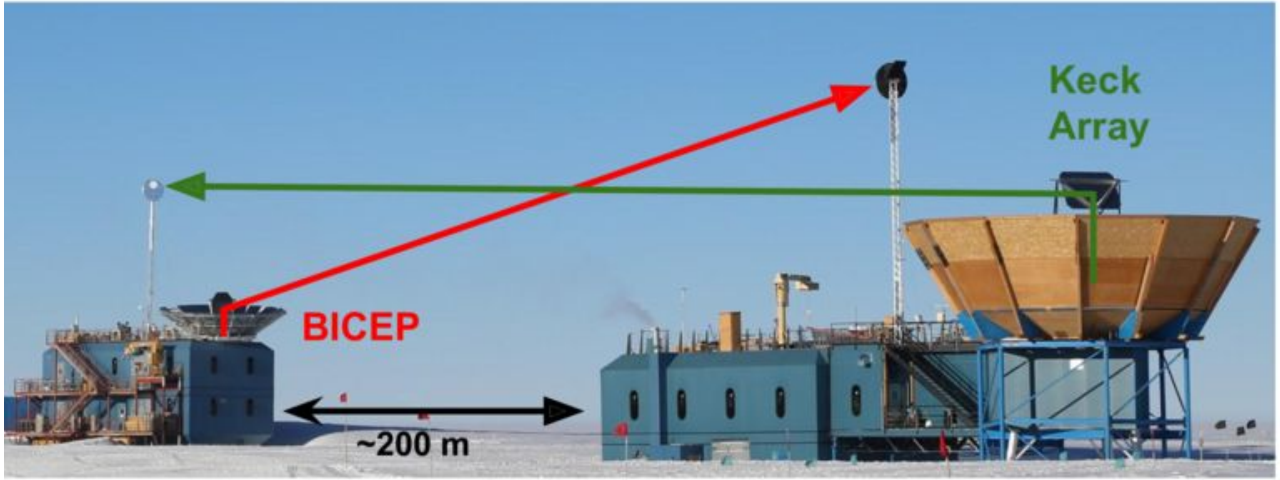




Characterizing *BICEP3* Performance

- Large, flat, aluminum mirror redirects the view onto the horizon (like a periscope!)

- Calibrators are installed on masts



The Rotating Polarized Source (RPS)

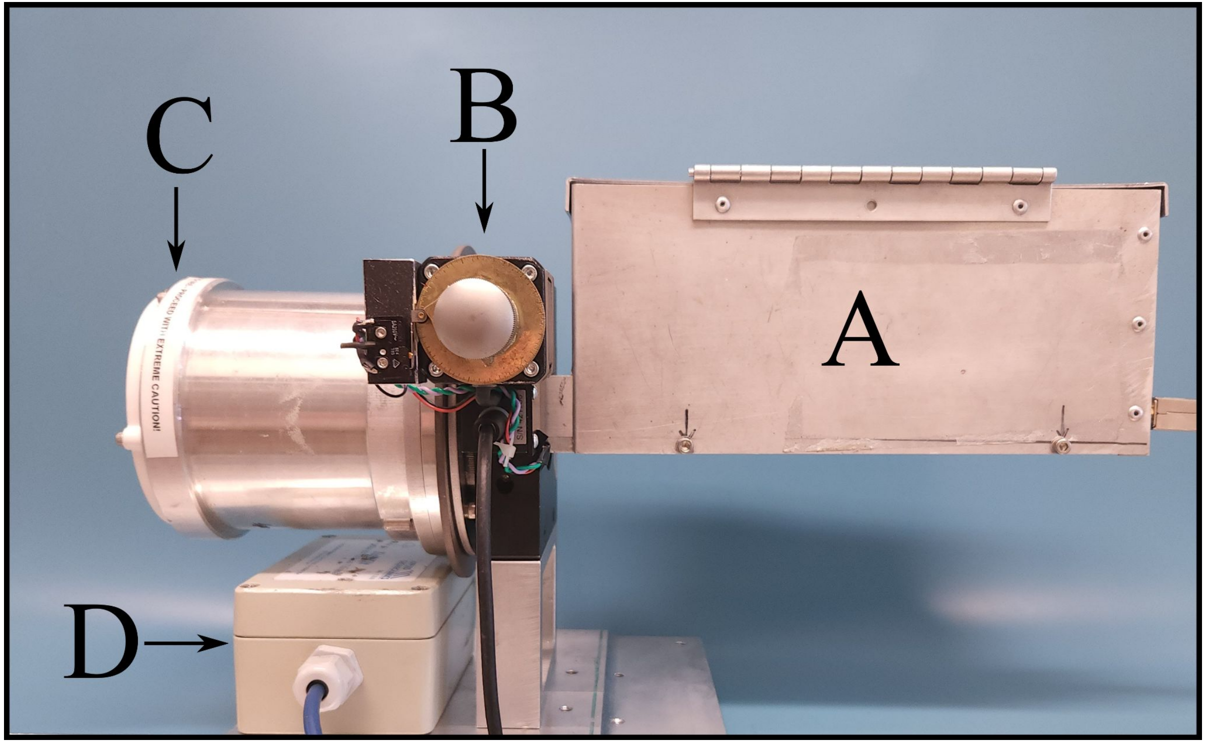
What calibrator are we using to measure angles?

A. Broad Spectrum Noise Source
   a. 95GHz source, instantaneous 10GHz band

B. Rotation Stage
   a. Rotates source to various pol angles
   b. σ as good as O(0.01°)

C. Wire Grid Polarizer
   a. Establishes pol angle of source

D. Tilt Meter
   a. Registers grid angle WRT gravity
   b. σ~0.01°



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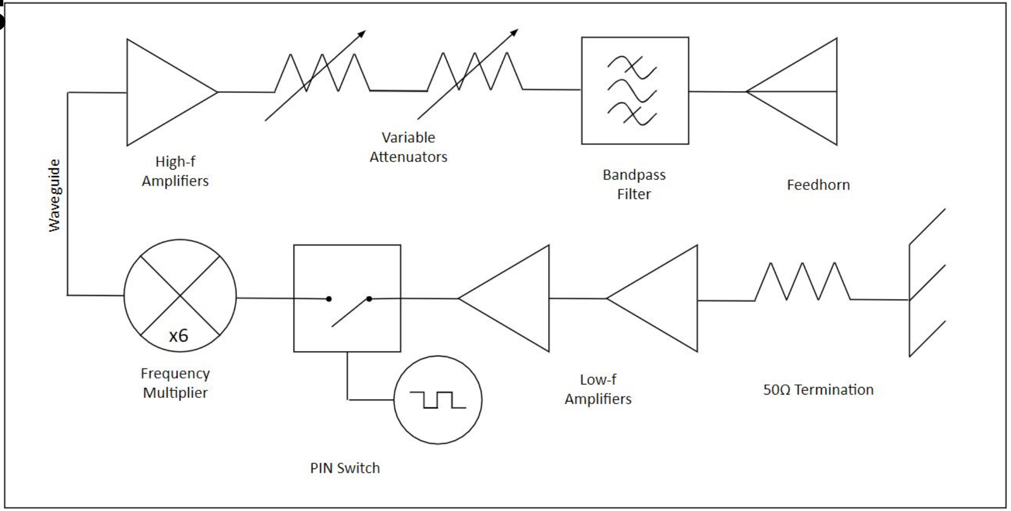
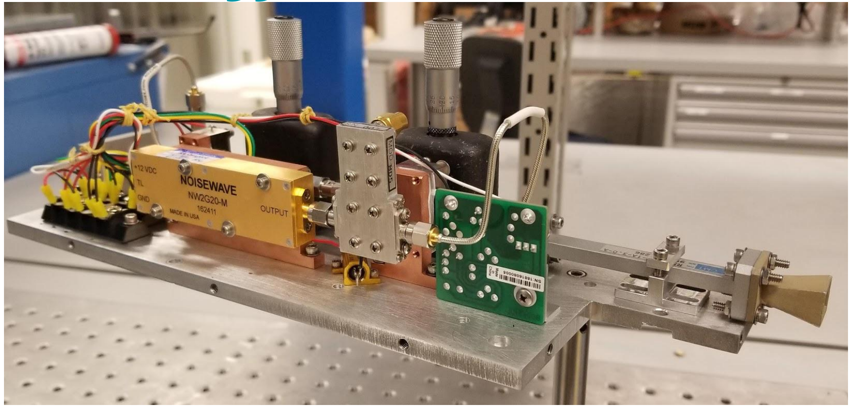
Broad Spectrum Noise Sources

"Quasi-Thermal"

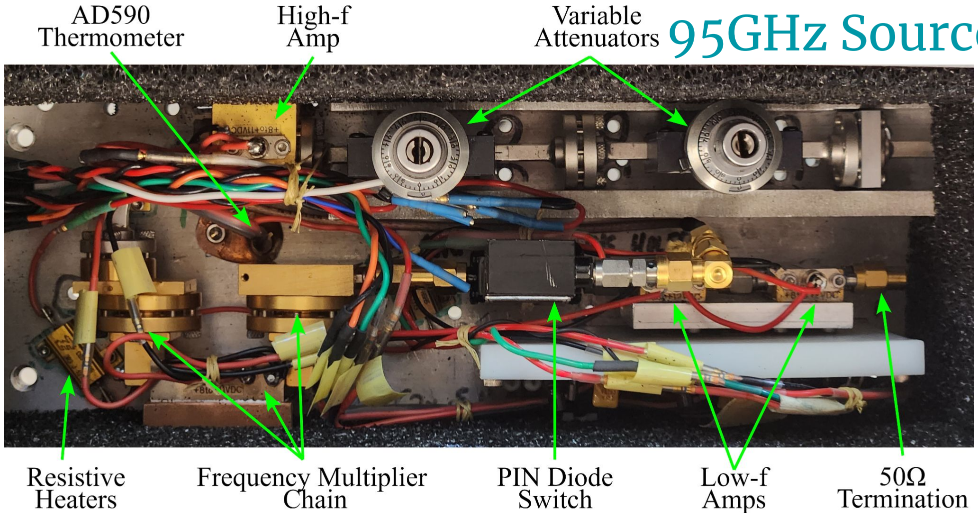
- Instantaneous band
- Flat spectrum (in T_{RJ})
- Linearly polarized
- Electrically chopped
- ~70dB dynamic range



35GHz Source

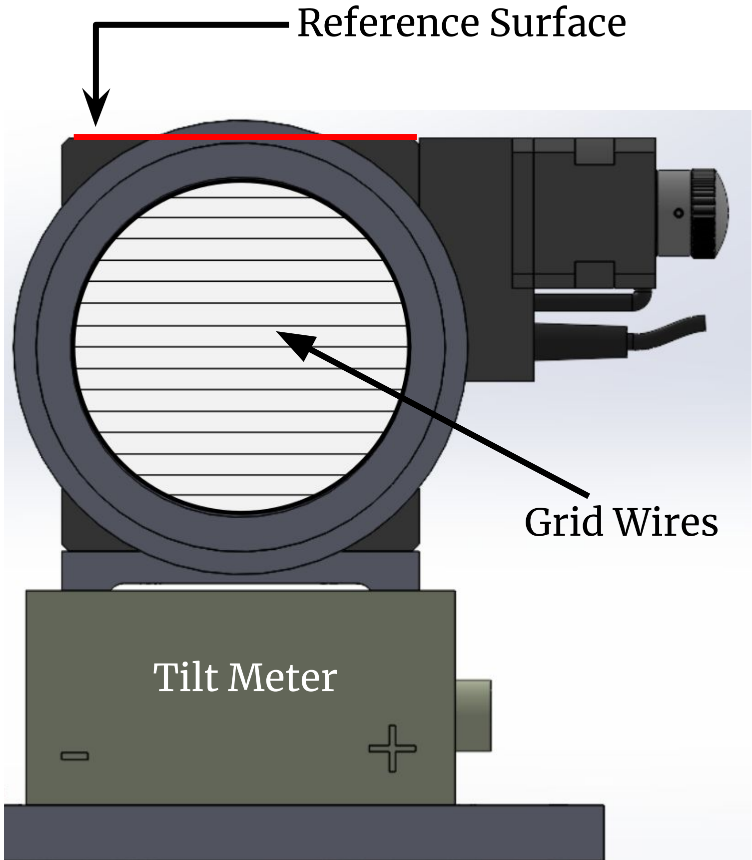


95GHz Source



Calibrating the calibrator

How do we know the polarization orientation of the RPS?



- Register the wire grid orientation to gravity
- Wire grid WRT reference surface by sighting wires on knee mill
- Tilt Meter to reference surface using a precision level

Calibrating the calibrator

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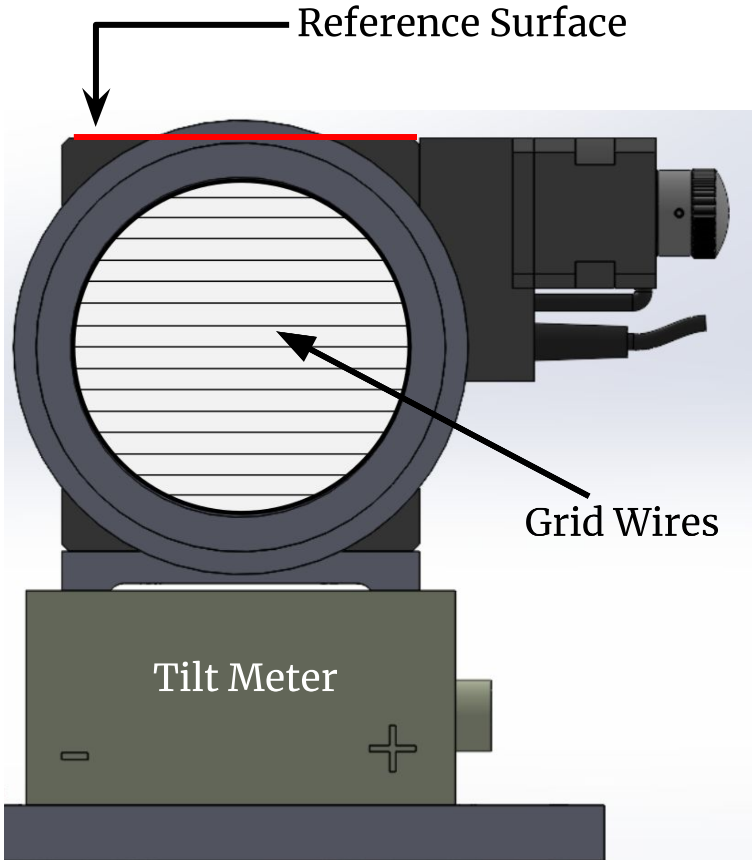

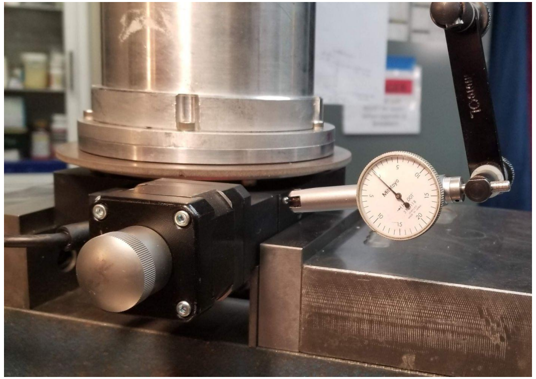

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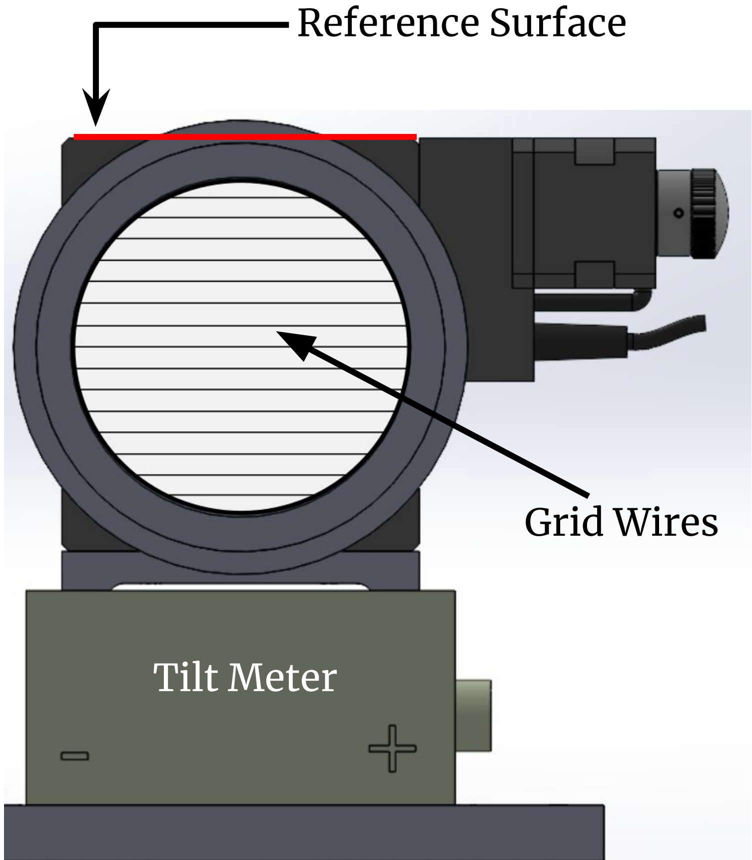

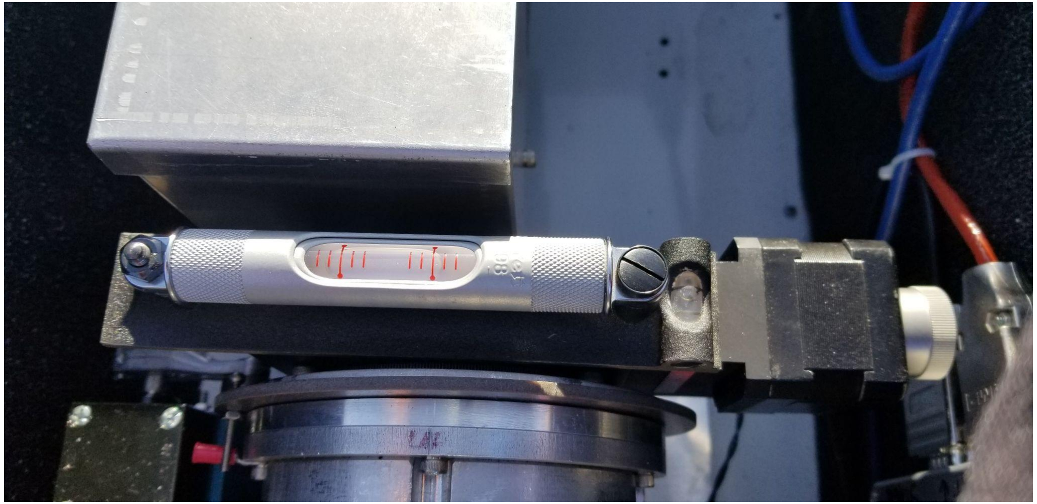

Observations and Analysis

How do we get angles from observing the RPS?

- Observe RPS with telescope by rastering back and forth in azimuth & elevation
- Map detector response at 13 different RPS angles
- Amplitude vs. RPS angle is a **modulation curve**
- Multiple curves for each ~2000 BICEP3 detectors = **~25 days of observing**

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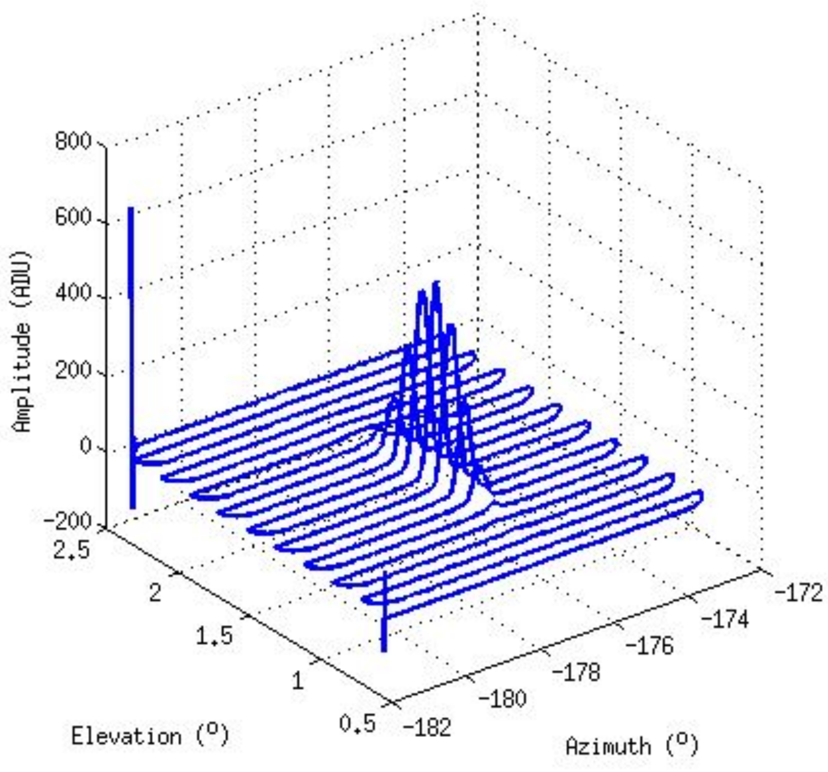

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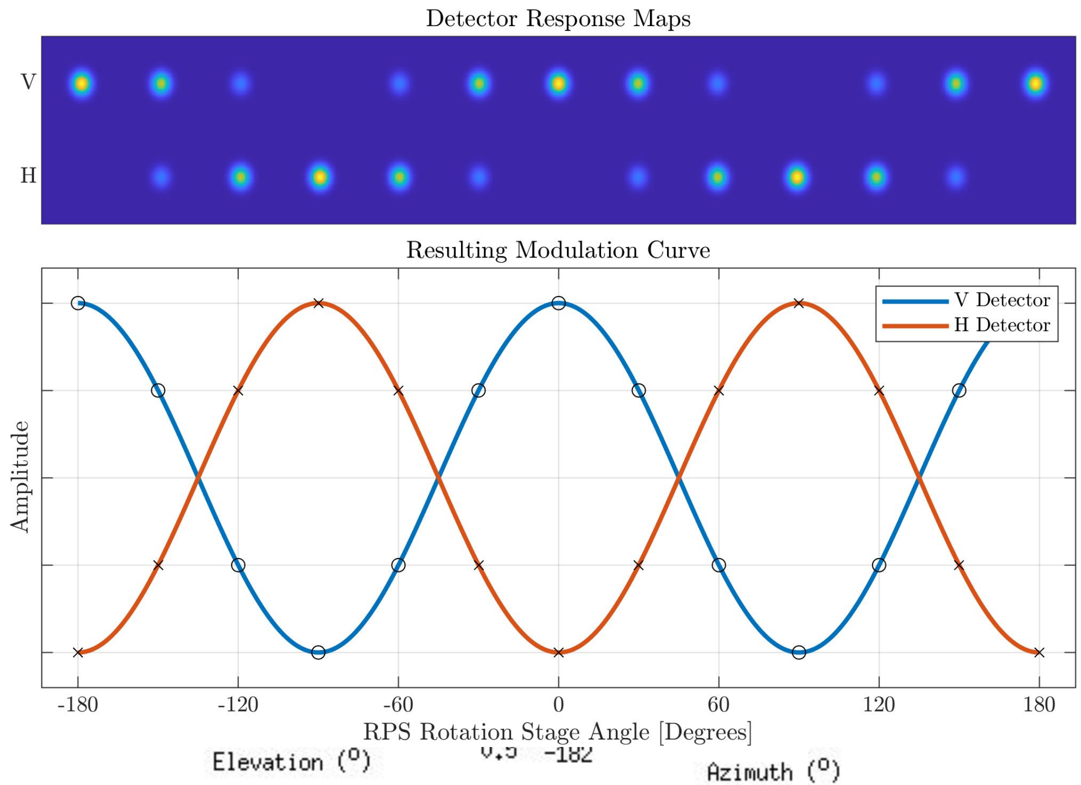
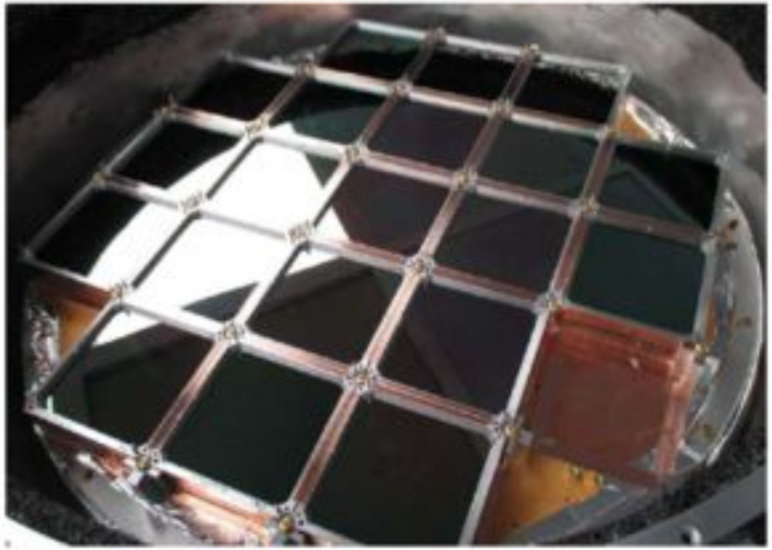


Calibration Validation

How can the data validate our analysis?

- We know the actual pointing of our detectors from the CMB
- Orientation of the tiles by comparing ideal to CMB-derived pointing
- **Overall pol angle tiles matches rotation of tiles from pointing** (with an extra offset)



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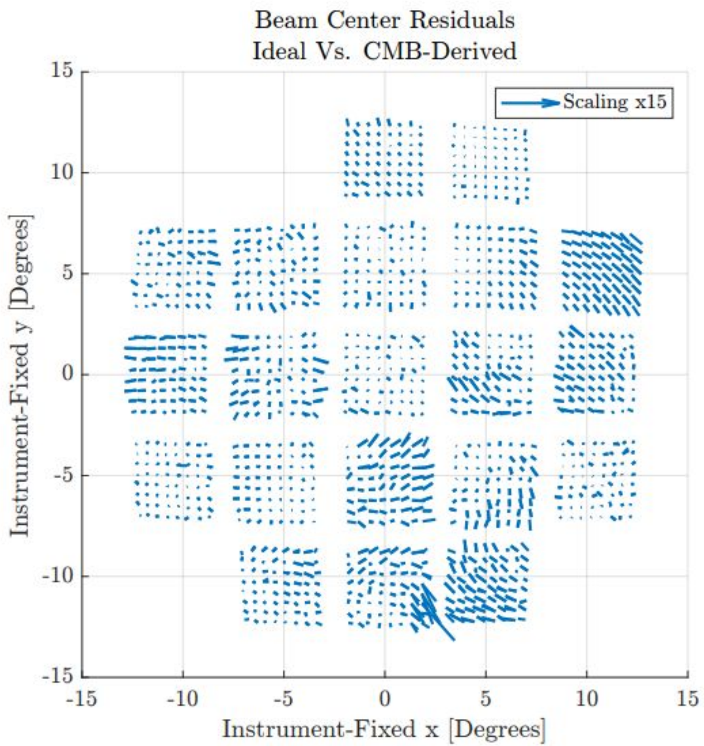

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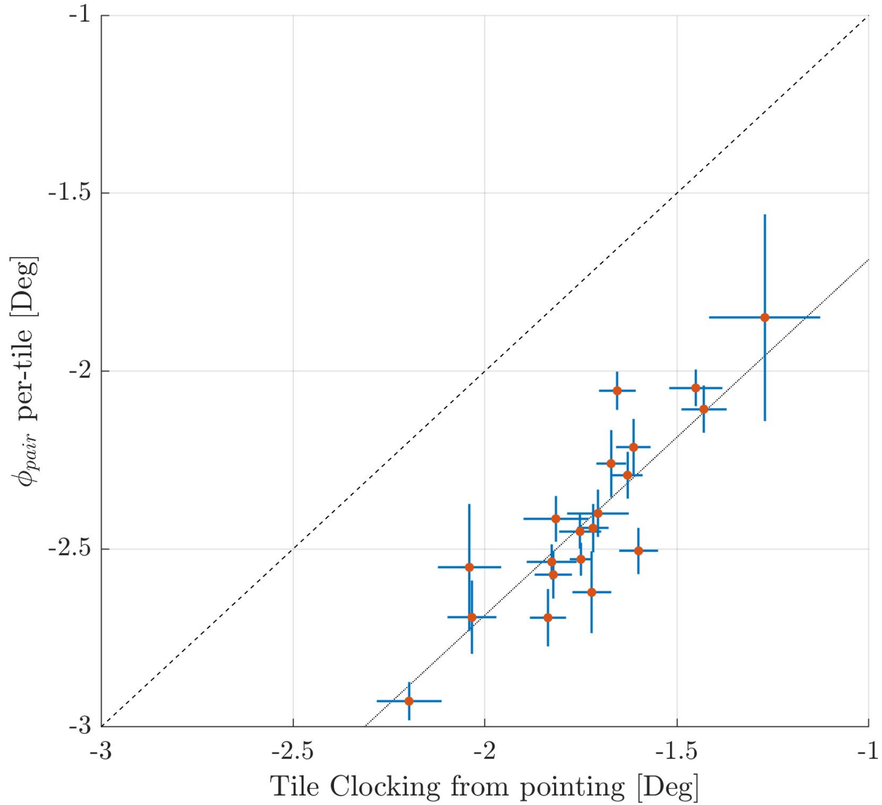
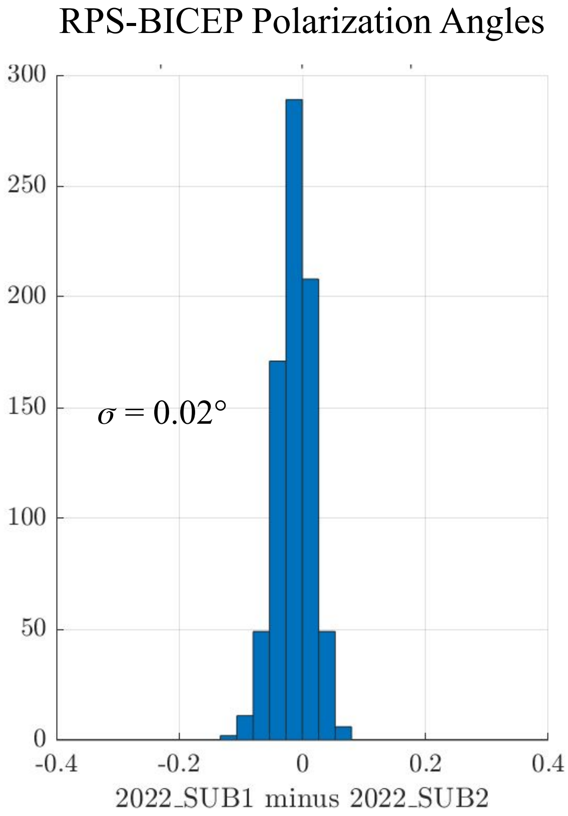
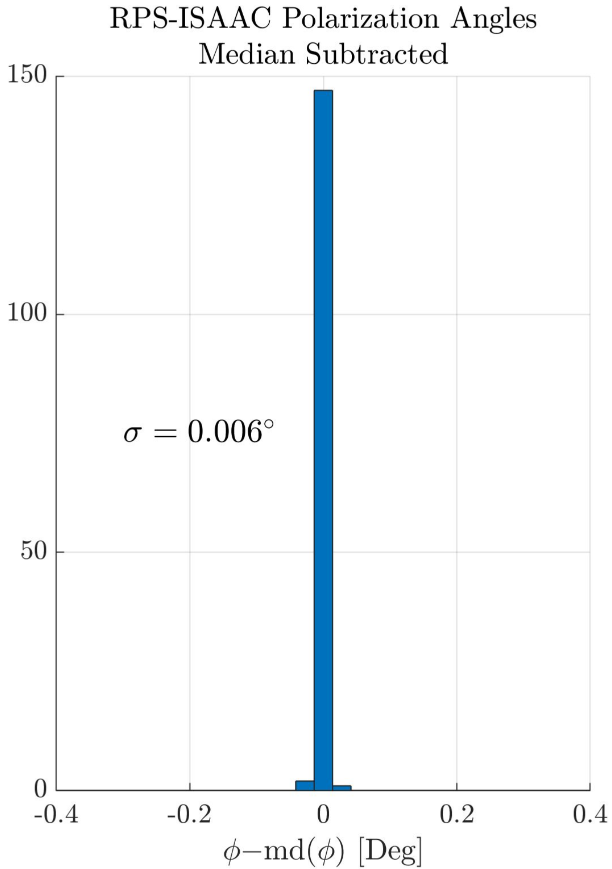


Statistical Uncertainty





Systematic Uncertainty

- Considered many different sources of systematics
- Most systematics are well-understood and within nominal limits
- Ultimately limited by alignment errors discovered on the benchtop

Systematic Uncertainty		
Category	Amplitude	$\sigma(\phi_d)$
RPS Calibration		
Stage Repeatability	0.002°	< 0.001°
Homing Uncertainty	0.005°	0.005°
Tilt Calibration	0.014°	0.014°
Motor Backlash	0.06°	0.060°
Pointing Model		
FPU Angle	0.012°	0.012°
Modulation Curve		
Obs-to-Obs Fluctuations	0.042°	0.042°
Alignment Error (Model)	$1°\,Az/5°\,El$	0.035°
Alignment Error (Measured)		0.300°
Total Uncertainties	**Lower**	**Upper**
Statistical		0.020°
Systematic	0.085°	0.309°
Total Stat.+Sys.	0.086°	0.310°
Precision goal	**<0.100°**	

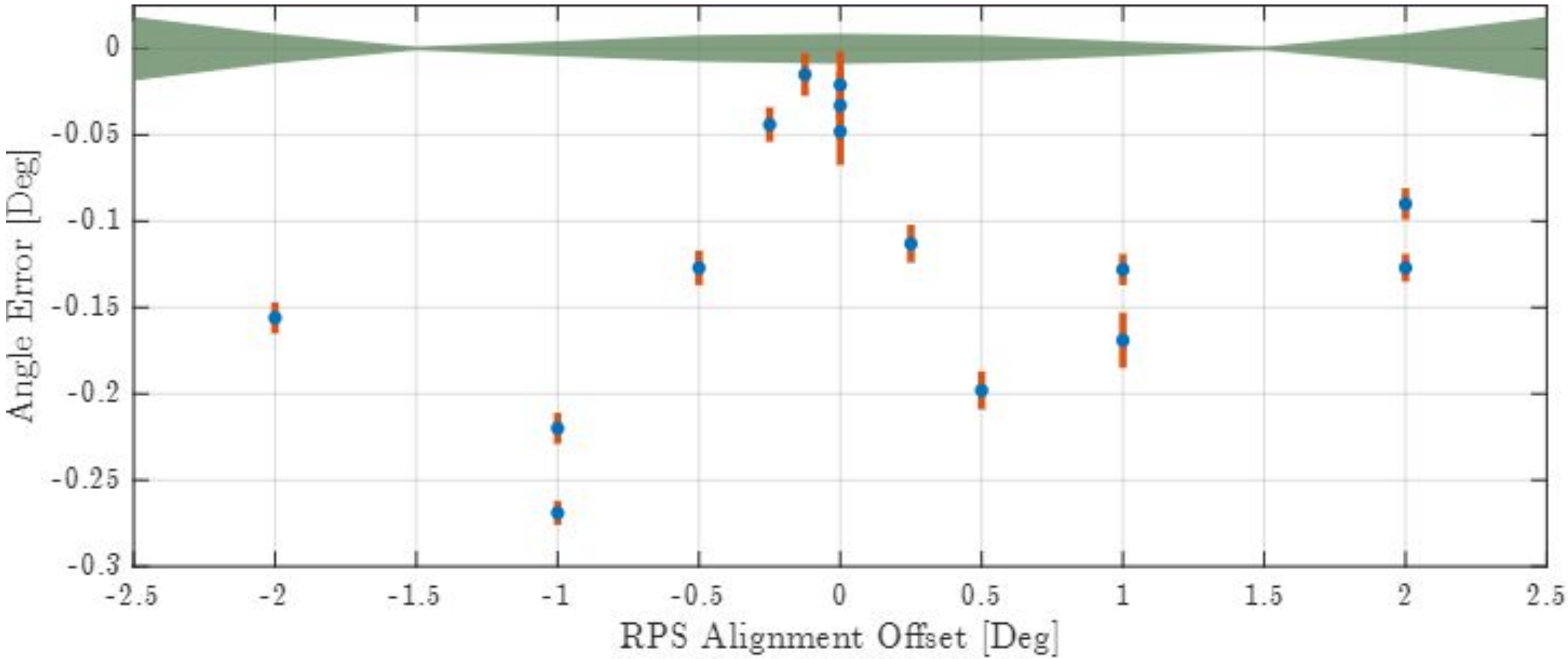
Independent Cross Checks

- Using receiver with wire grid+tiltmeter to measure RPS mod curves
- Angle fit from mod curves should equal measured angle of RX’s wire grid WRT to gravity
- Is intended to provide strong cross check that we understand end-to-end measurement.

Independent Cross Checks

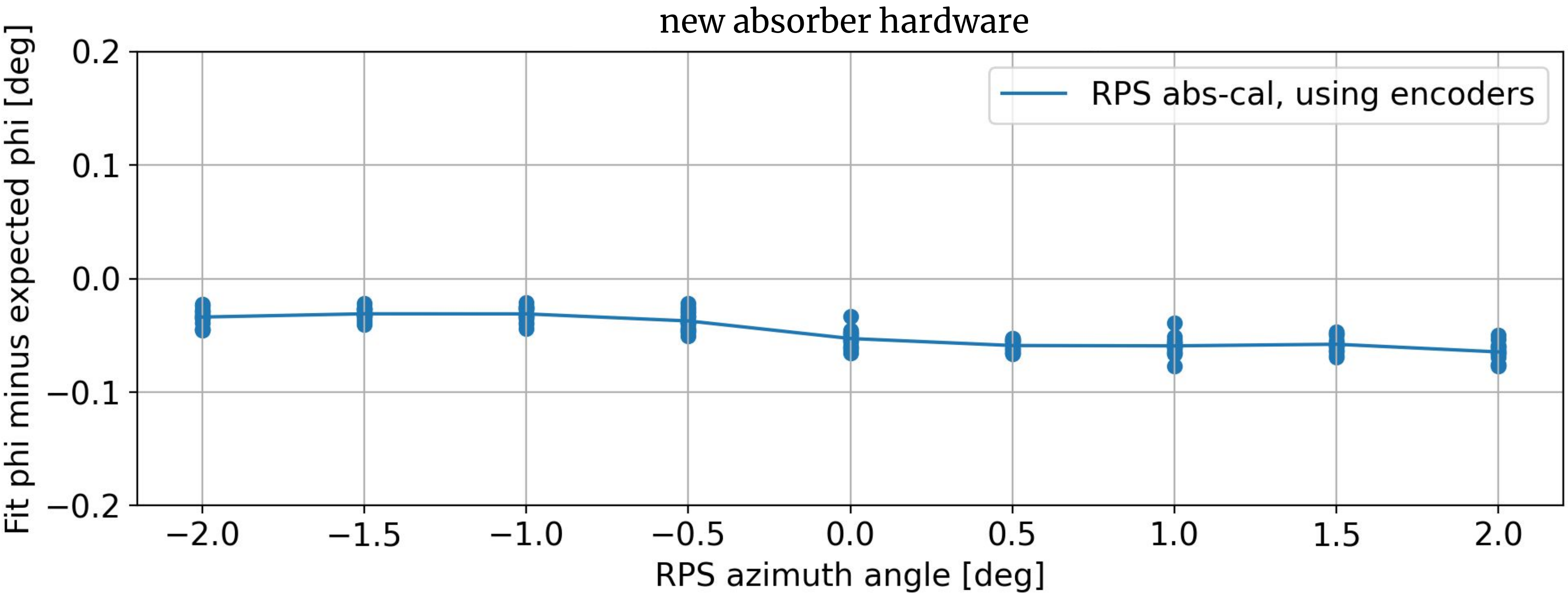
- Empirical measurements of alignment error much larger than current modelling suggests

- Priors on RPS alignment: 1° Az/2.5° El → ~0.3° angle error



Independent Cross Checks

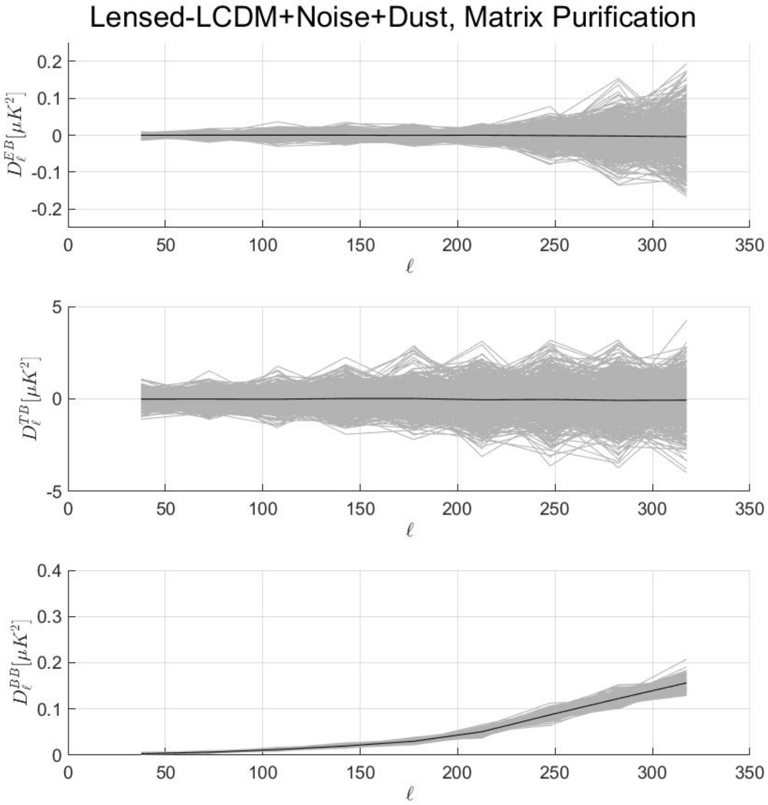
We think we understand things now. Stay tuned!



Actual CMB Stuff:

Uncertainty from CMB comes mostly from sims

- Good ol' CMB (LCDM-only)
- Gravitationally Lensed-CMB
- Galactic Dust
- Instrumental Noise
- Various Combinations



CMB Error Budget

Sim Type	σ [Degrees]
Noise	0.061
CMB-only	0.004
Lensed CMB	0.035
Dust	0.007
L-CMB+Dust+Noise	**0.078**

- Currently dominated by noise
  - Will decrease by integrating more observing years
  - Comparable to lensing when including up to Y2023 BICEP3 data! → 50% overall improvement
- Next limited by gravitational lensing
  - Requires delensing analyses by combining external CMB data

Birefringence Forecasting

- We find that variance on angle is linearly dependent on residual BB (from noise & lensing)
- Allows for rudimentary forecasting

Data years + delensing	**Noise σ [Deg]**	**Delens σ [Deg]**	**Total**
2 yrs (17-18)	0.061	0.035	0.078
7 yrs (17-23)	0.004	0.035	0.055
2 yrs + delens	0.035	0.024	0.073
7 yrs + delens	0.007	0.024	0.048

Impact on *r*

Self-calibration mitigates systematics from unknown overall polarization angle, but not det-to-det and tile-to-tile variations.

TABLE VI: ρ estimates for various configurations, showing impact of residual B-modes power after mitigation by calibration and/or analysis (derotation).

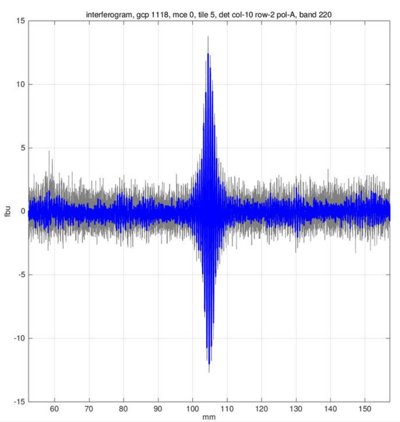
	Case	$\rho\ (10^{-5})$	
	Uncalibrated	510 ± 64	
(Self)	Calibrated, no variation	0 ± 2	
	Uncalibrated derotated — all detectors	4 ± 3	
	Uncalibrated derotated — tile clocking only	4 ± 1	
We're currently here	Calibrated with error	8 ± 3	
	Calibrated with error + derotated	0 ± 2	Best-case scenario

Impact is still subdominant by ~2 orders of magnitude

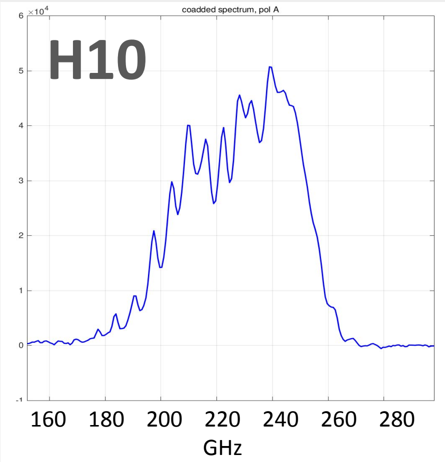
BA 220/270 GHz Receiver: Status and Performance

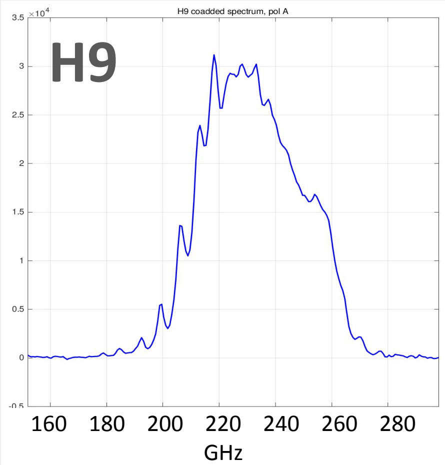
220 GHz detector module optical testing: **FTS**

Interferogram of a typical detector



Co-added spectral response for polarization A





Custom-built Martin-Puplett interferometer mounted to receiver window

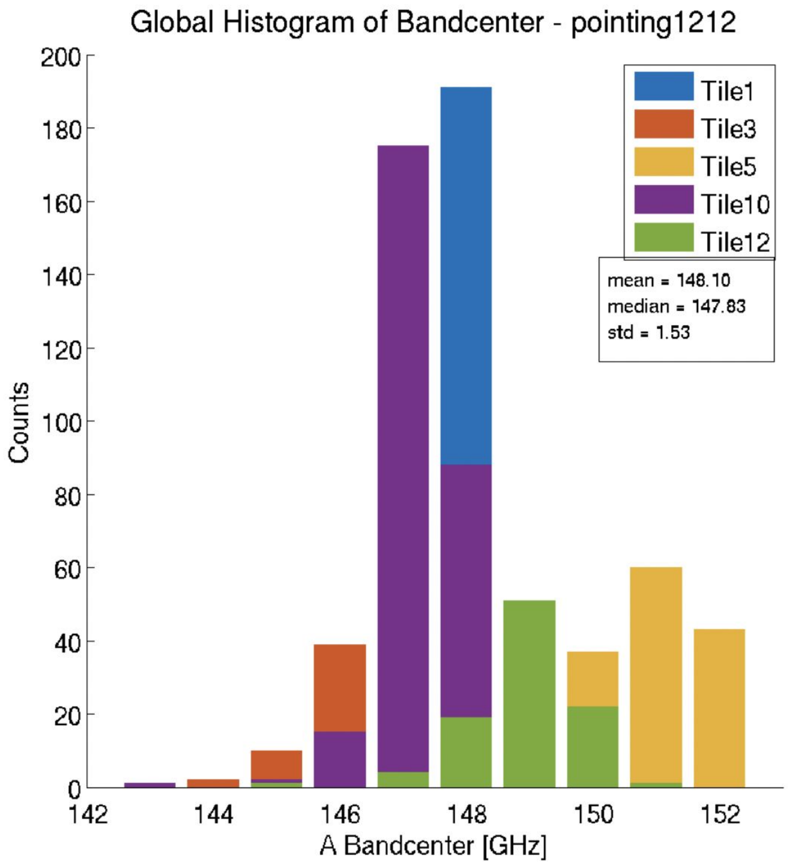
Band center: 228 GHz (H10), 233 GHz (H9), and 231 GHz (H1)

Bandwidth: 28% (H10), 26% (H9), and 25% (H1)

BA 150 GHz

Highlights from tilemaps and statistics compiled by Min for 2023 data

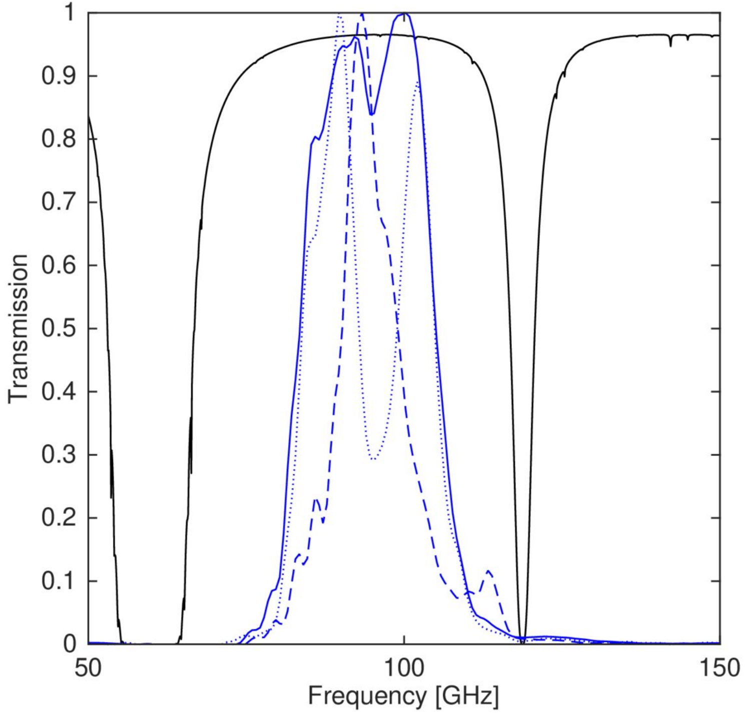
- Overall statistics: bandcenter = 148GHz, bandwidth = 44GHz (30%)
  - Tile-to-tile differences, differential bandpass, sensitivity to FTS pointing not quantified
- Tilemaps look relatively uniform, except for L6 which has a clear radial pattern + dip in the bandpass



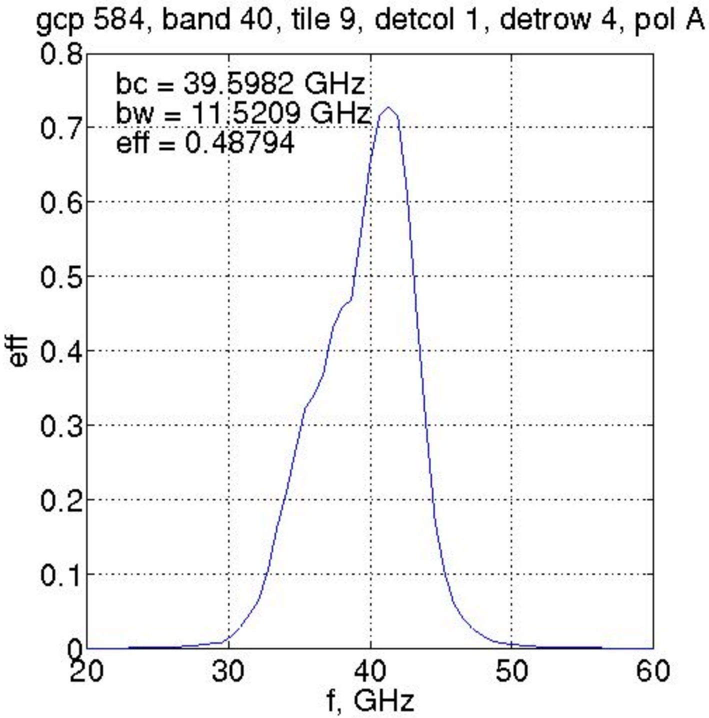
Courtesy of Min Gao, Clara Verges

Current BICEP3 / BICEP Array Bandpasses

BICEP3 95 GHz



BA 40 GHz

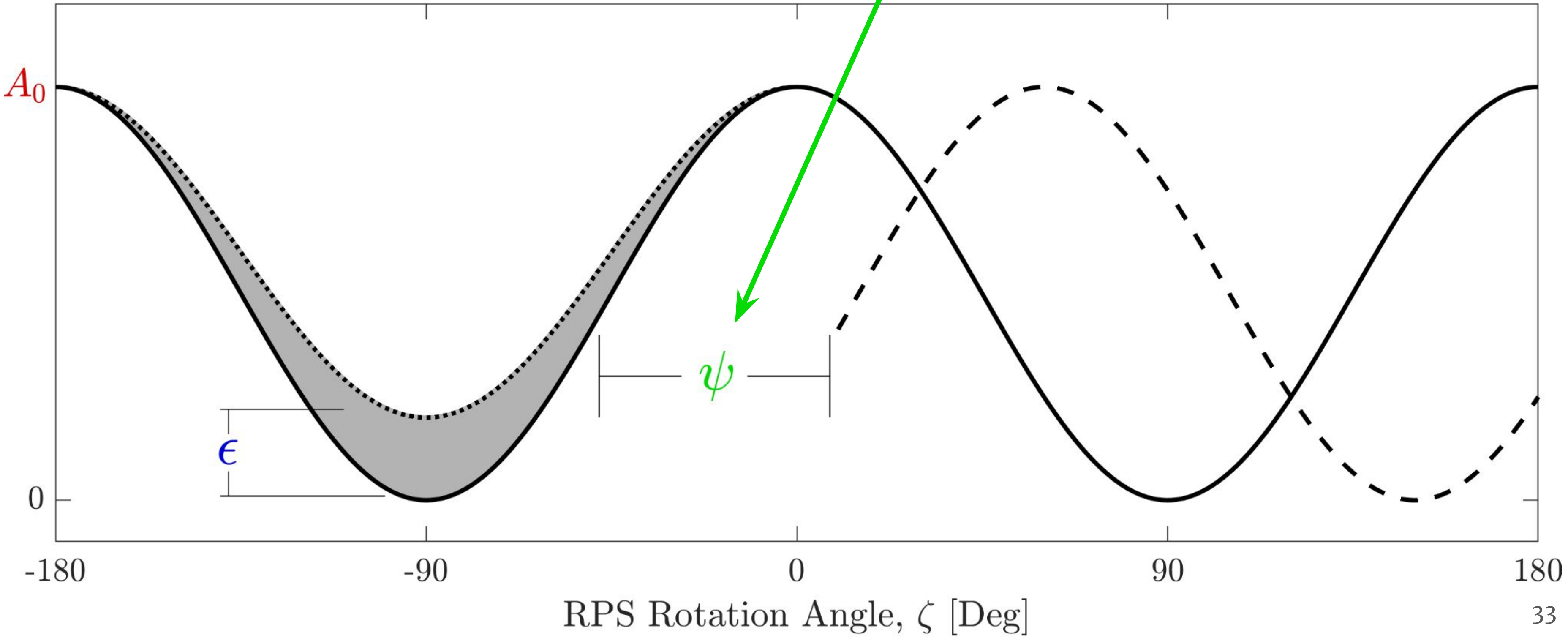


Backup Slides

The Model

$$A = A_0 \left[\cos[2(\zeta + \psi)] - \frac{\epsilon + 1}{\epsilon - 1} \right]$$

Angle between detector polarization axis and RPS (when at zero degrees)



Angle wrt RPS → Angle wrt FPU

- Need a way of converting ψ into an angle that can be transferred to the CMB.
- Pick an arbitrary reference point of the focal plane and use a pointing model
- Very complex geometry problem
- Needed to consider many potential sources of systematics