Optical Characterization of BICEP3 and the Keck Array CMB Polarimeters from 2016 to 2019

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BICEP3 + Keck Array

BICEP3 and the Keck Array are refracting telescopes at the South Pole observing the polarized Cosmic Microwave Background (CMB) in search for the signature of primordial gravitational waves. Design features:

- Cold optics with an aperture diameter of 26cm (Keck) / 52 cm (BICEP3)
- ~5000 total antenna-coupled transition edge sensor (TES) detectors at frequency bands spanning 95, 150, 220, and 270 GHz.

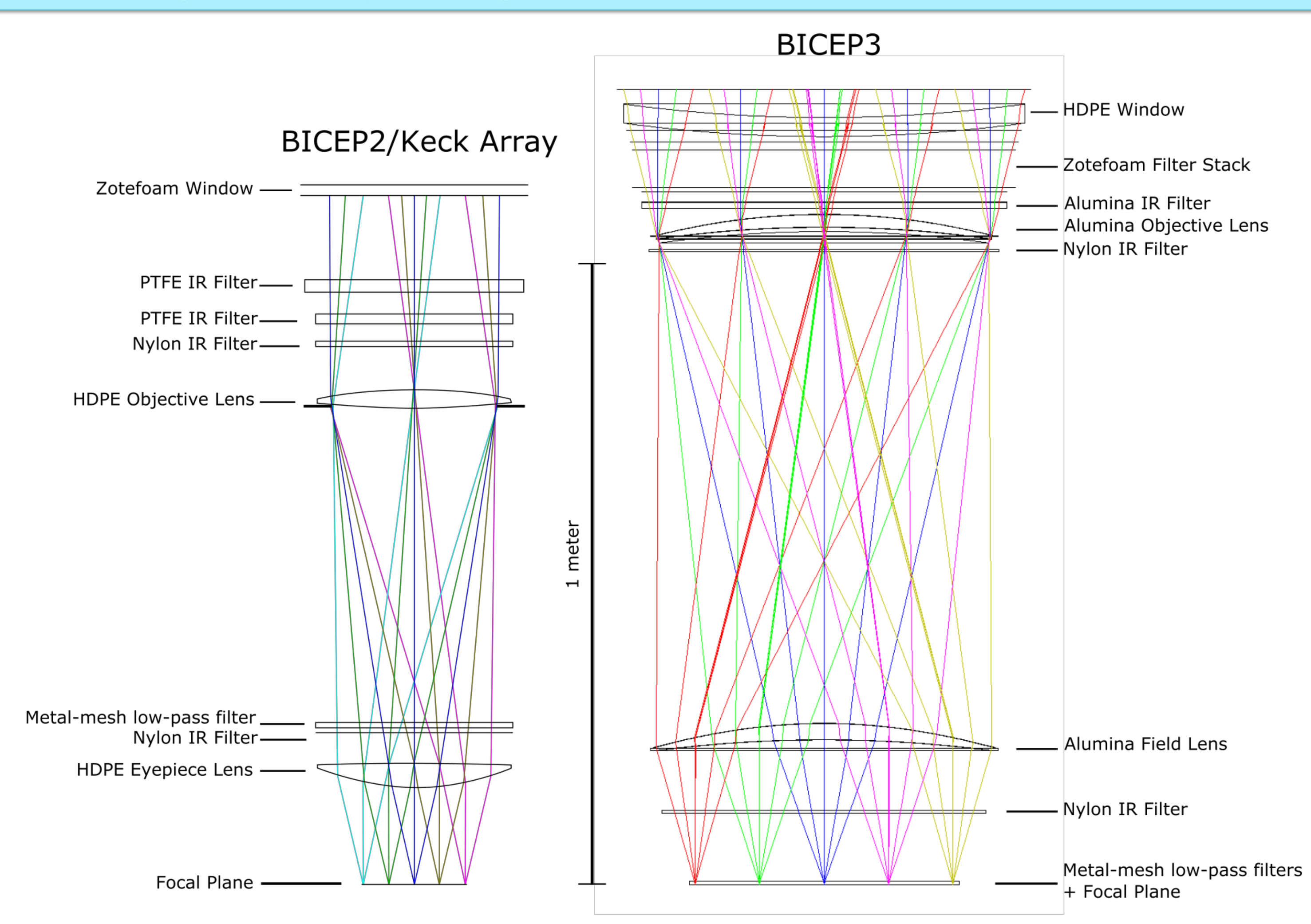

Figure 1: Optical Design of Keck (left) and BICEP3 (right)

Calibration Hardware + Procedures

Far-field Beam Mapping: Every Austral summer, we measure our beams by installing a large honeycomb aluminum mirror to redirect the beams to a chopped thermal source located on a mast on a building ~211 m away from the receiver. Our newest thermal source, installed summer 2016, chops a 24" aperture at 16 Hz between an ambient temperature microwave absorber (~260 K) and zenith (~12 K).

Fourier Transform Spectrometer (FTS): We use a field-deployable Martin-Puplett interferometer to measure the spectral response of all our detectors in-situ. This is done at least once every time a new focal plane array is installed. The spectral resolution is ~ 0.5 GHz.

Spectral Response

High signal/noise spectra are taken for each working detector, with repeated measurements for estimating uncertainty. Reasons why we need to know our spectral response:

- Foreground separation in likelihood analysis
- Temperature to polarization (T → P) leakage from bandpass mismatch
- Feedback on detector fabrication

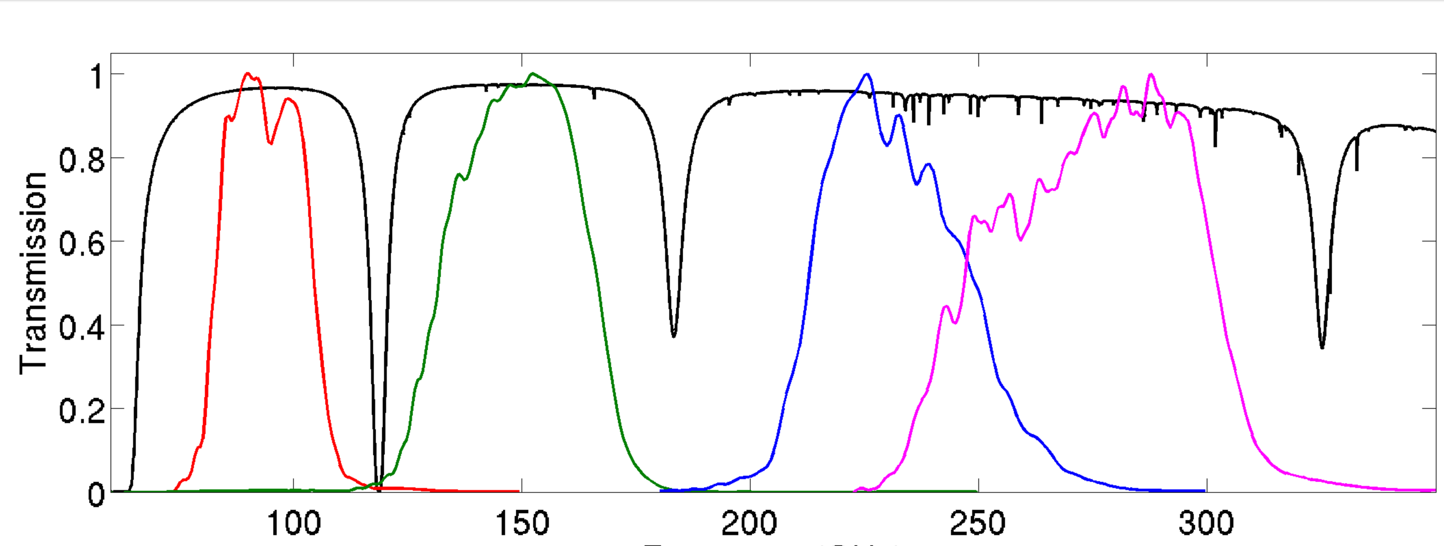

Figure 2: Array-averaged spectral response for each observing frequency from 2016-2019. South Pole atmospheric transmission in black.

BICEP3		K150		K220		K270	
BC	BW	BC	BW	BC	BW	BC	BW
94.2	26.7	149.0	43.4	231.9	51.2	275.4	69.8

Table 1: Band centers (BC) and band widths (BW) of array-averaged spectra in GHz.

Array-Averaged Beam Maps and Profiles

The timestreams are demodulated, then binned into 0.1° pixels. Contaminated signal (the ground and source mount structure) is masked. Maps at different boresight rotation angles are combined to give high-fidelity, full-coverage composite maps for each detector. These composite maps are coadded to create array-averaged maps and window functions per frequency band.

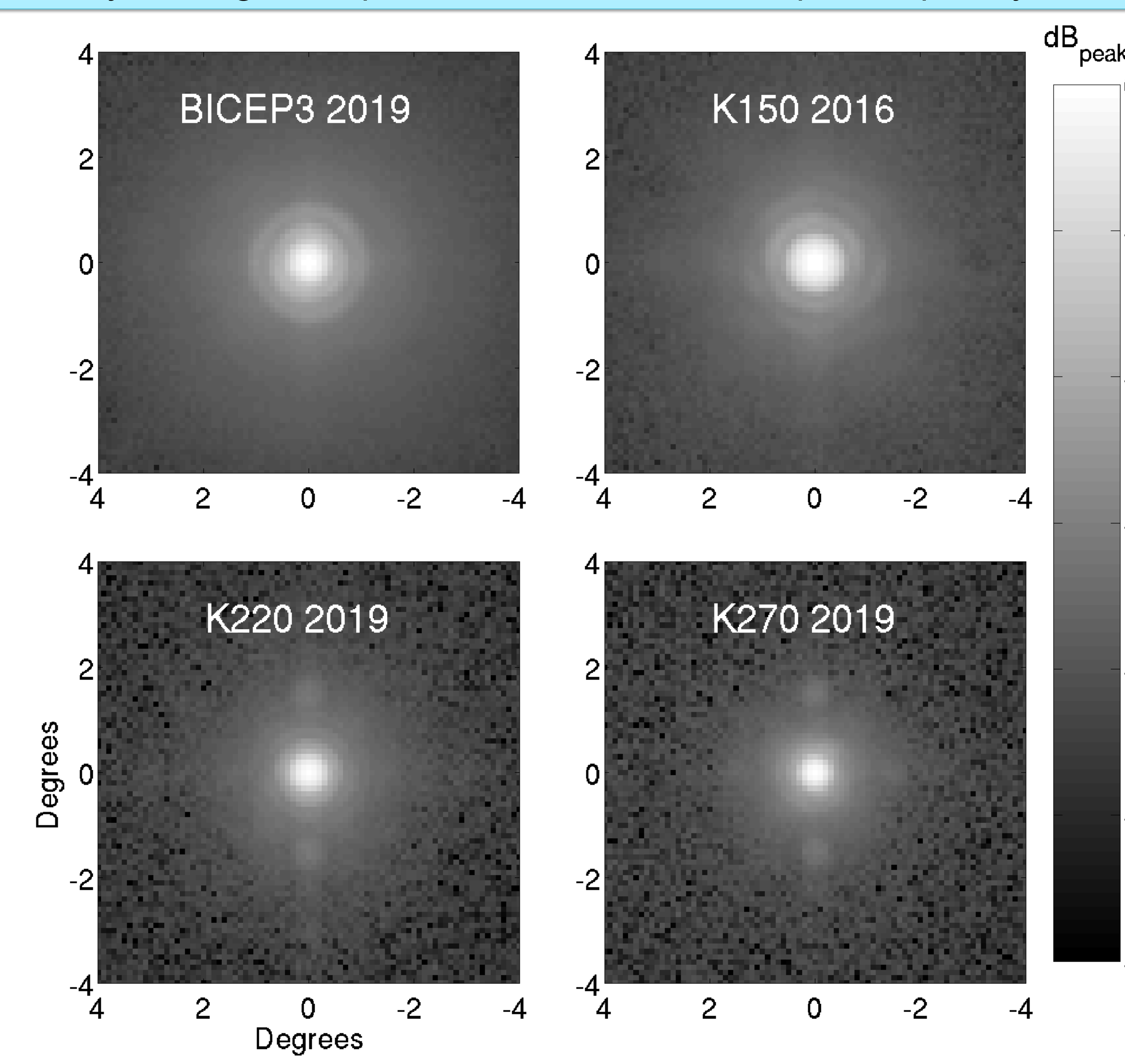

Figure 3: Array averaged beams for each observing frequency. They are averaged from a single year.

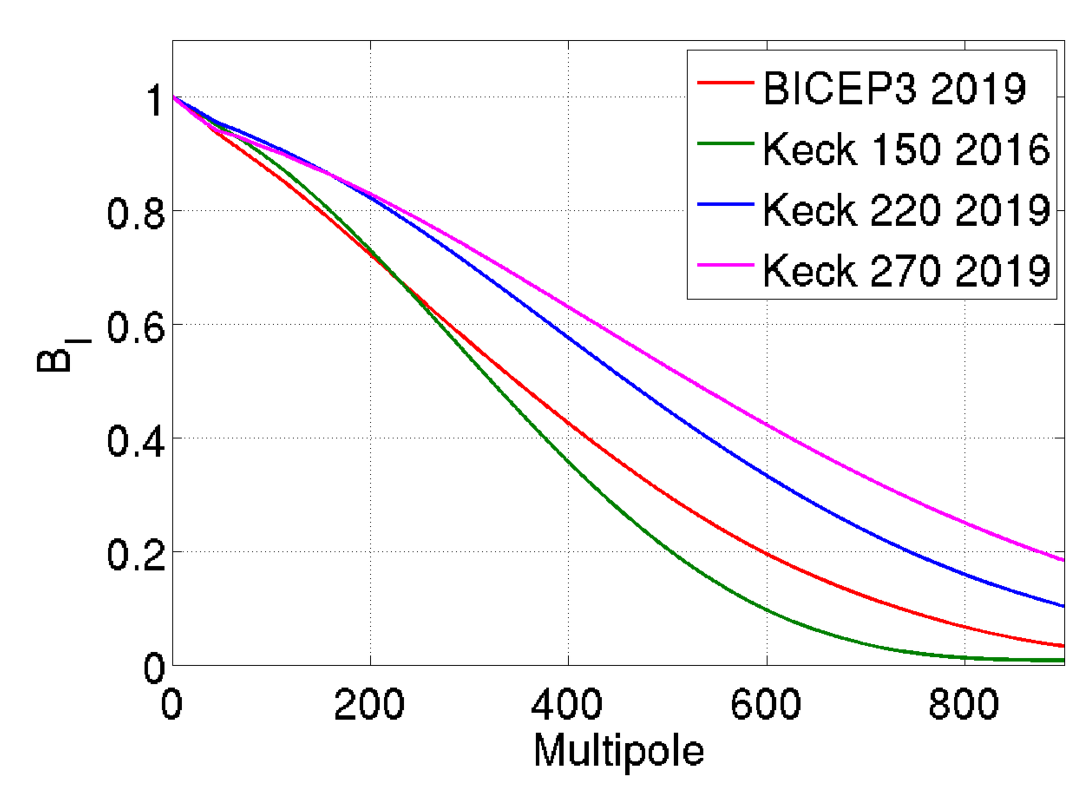

Figure 4: Window functions corresponding to the beams shown in Figure 3.

Beam Parameters

Each beam is fit to a 2D elliptical Gaussian, and statistics on these parameters are calculated for each detector. These can be differenced within each detector pair to create differential beam parameters. These difference modes lead to CMB T → P leakage that can be filtered out (deprojection) or subtracted directly. Improvements in differential beam measurement uncertainty leads to better estimates on the bias (and its uncertainty) on our estimate of the tensor-to-scalar ratio *r* due to T → P leakage.

Parameter	BICEP3 2019	K150 2016	K220 2019	K270 2019
Beamwidth (°)	0.166 ± 0.002	0.201 ± 0.004	0.139 ± 0.003	0.120 ± 0.003
Ellipticity Plus	-0.023 ± 0.018	0.005 ± 0.029	0.000 ± 0.037	0.005 ± 0.033
Ellipticity Cross	-0.026 ± 0.017	0.004 ± 0.031	0.004 ± 0.039	0.006 ± 0.041
Diff Ellip Plus	0.004 ± 0.002	-0.021 ± 0.003	-0.018 ± 0.002	-0.016 ± 0.006
Diff Ellip Cross	-0.001 ± 0.002	-0.002 ± 0.003	-0.003 ± 0.003	-0.006 ± 0.006
Diff Pointing X (′)	-0.05 ± 0.05	0.18 ± 0.12	-0.53 ± 0.04	-0.77 ± 0.04
Diff Pointing Y (′)	0.02 ± 0.06	-0.11 ± 0.11	0.42 ± 0.04	0.18 ± 0.04

Table 2: Beam parameters (median ± measurement uncertainty) for each frequency.