

UC San Diego

UC San Diego Electronic Theses and Dissertations

Title

Precise Astronomical Polarization Angle Calibration and its Impact on Studying Lorentz and Parity Violation in the Cosmic Microwave Background

Permalink

<https://escholarship.org/uc/item/1380c9mn>

Author

Navaroli, Martin Frank

Publication Date

2020

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA SAN DIEGO

**Precise Astronomical Polarization Angle Calibration and its Impact on Studying Lorentz
and Parity Violation in the Cosmic Microwave Background**

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Physics

by

Martin Frank Navaroli II

Committee in charge:

Professor Brian Keating, Chair
Professor Kam Arnold
Professor Craig Callender
Professor Tom Murphy
Professor Gabriel Rebeiz

2020

Copyright
Martin Frank Navaroli II, 2020
All rights reserved.

The dissertation of Martin Frank Navaroli II is approved,
and it is acceptable in quality and form for publication on
microfilm and electronically:

Chair

University of California San Diego

2020

DEDICATION

To Ryanna.

EPIGRAPH

Remember to look up at the stars and not down at your feet. Try to make sense of what you see and wonder about what makes the universe exist. Be curious. And however difficult life may seem, there is always something you can do and succeed at. It matters that you don't just give up.

—Stephen Hawking

TABLE OF CONTENTS

Signature Page	iii
Dedication	iv
Epigraph	v
Table of Contents	vi
List of Figures	ix
List of Tables	xv
Acknowledgements	xvi
Vita	xxii
Abstract of the Dissertation	xxx
Chapter 1	
Introduction	1
1.1 Our Expanding Universe	1
1.2 The Cosmic Microwave Background	4
1.2.1 Blackbody Spectrum	4
1.2.2 Temperature Anisotropies and Power Spectrum	6
1.2.3 Polarization of the CMB	7
1.2.4 E- and B-modes	10
1.2.5 Polarized Foreground Contamination	12
1.3 Inflation	15
1.4 Cosmic Polarization Rotation	16
1.4.1 Cosmic Birefringence from Modifications to Electrodynamics	17
1.4.2 Faraday Rotation from Primordial Magnetic Fields	19
1.4.3 Astrophysical Constraints on CPR	21
1.5 Outline of Thesis	25
1.6 Acknowledgements	26
Chapter 2	
POLARBEAR-1 and the Simons Array	28
2.1 Chilean Observing Site at the James Ax Observatory	28
2.2 The POLARBEAR-1 Experiment	30
2.2.1 Science Goals and Scan Strategy	30
2.2.2 Huan Tran Telescope	32
2.2.3 Cryogenic Receiver and Optics	32
2.3 Significant POLARBEAR-1 Science Results	36
2.3.1 Degree and Sub-degree Angular Scale B-modes	36

	2.3.2 Constraints on Cosmic Birefringence and Equivalent Primordial Magnetic Field Strength	42
2.4	POLARBEAR-2 and the Simons Array	44
2.4.1	POLARBEAR-2a, -2b, and -2c Cryogenic Receivers	47
2.5	Summary	50
2.6	Acknowledgements	51
Chapter 3	Calibration of the POLARBEAR-1 and POLARBEAR-2a CMB Experiments	55
3.1	Taurus A	56
3.2	Map Making Procedure	60
3.2.1	I, Q, U, and Polarization Maps from Pixel-pair Differencing	61
3.2.2	Detector Angles from Tau A Observations	68
3.3	POLARBEAR-1 Observations of Tau A	70
3.4	POLARBEAR-2a Observations	74
3.4.1	Tau A I, Q, U, and P Maps	74
3.4.2	Jupiter Pointing Offsets, Beam Shapes, and Intensity Maps	76
3.4.3	Focusing the Receiver	80
3.5	Summary	81
Chapter 4	Design and Characterization of a Ground-Based Absolute Polarization Calibrator	83
4.1	POLCAL Phase One	84
4.1.1	Design and Hardware	84
4.1.2	Calibration to the Local Gravity Vector	88
4.1.3	Laboratory Characterization	89
4.1.4	Systematic Error Estimation	92
4.2	POLCAL Phase Two	98
4.2.1	Modifications to the Polarized RF Source Circuit	98
4.2.2	Modifications to the POLCAL Enclosure and Pointing	101
4.2.3	Laboratory Characterization	103
4.3	Summary	106
4.4	Acknowledgements	106
Chapter 5	Results From POLCAL Polarization Calibration on the POLARBEAR-1 Experiment and POLARBEAR-2b Receiver	111
5.1	POLCAL Deployment on the POLARBEAR-1 Telescope	112
5.1.1	POLCAL Observation Strategy	112
5.1.2	Chopped Polarized Optical Signal and Demodulation Verification	115
5.1.3	POLCAL Derived Detector Angles and Comparisons to Tau A Calibration	116
5.2	POLCAL Demonstration on the POLARBEAR-2b Cryogenic Receiver	117
5.2.1	Bolometer Time Constants	118

5.2.2	Bolometer Polarization Angles	125
5.2.3	Sinuous Antenna Polarization Wobble	131
5.3	Summary	141
Chapter 6	Conclusions	142
Bibliography		144

LIST OF FIGURES

Figure 1.1:	The CMB intensity spectrum as measured by the FIRAS instrument on the COBE satellite, compared to a 2.725 K blackbody spectrum. Plotted error bars have been magnified by a factor of 400 on each side so as to become visible. Data from [66].	5
Figure 1.2:	Full sky map of the CMB temperature anisotropies as measured by the Planck satellite in 2018.	6
Figure 1.3:	The CMB temperature anisotropy spectrum plus best-fit cosmological model (top) and residuals (bottom) as measured by the Planck satellite in 2015, with $\mathcal{D}_\ell = \ell(\ell + 1)C_\ell/2\pi$. Image from [5].	8
Figure 1.4:	Cartoon diagram of CMB photons Thomson scattering off of a free electron (located at the origin) at the time of recombination in the presence of a quadrupolar anisotropy.	9
Figure 1.5:	<i>Top:</i> Compilation of the most recent CMB E-mode measurements. <i>Bottom:</i> Compilation of all CMB B-mode measurements to date.	13
Figure 1.6:	C_ℓ^{TB} (left) and C_ℓ^{EB} (right) power spectra after applying a -2.5° (darkest red) to $+2.5^\circ$ (darkest blue) polarization rotation to the primordial C_ℓ^{TB} and C_ℓ^{EB} power spectra in 0.5° steps.	23
Figure 1.7:	<i>Left:</i> Induced C_ℓ^{BB} power spectrum from E-B mixing due to detector angle miscalibration or CPR angle α , shown for rotation angles of 0.1° to 1.0° (red to blue). <i>Right:</i> E-B mixing from left panel normalized against C_ℓ^{BB} tensor-to-scalar ratio of $r = 10^{-3}$	24
Figure 1.8:	Compendium of constraints on CPR angle α from both radio and UV observations (red), as well as from CMB observations (blue).	26
Figure 2.1:	Atmospheric transmission at varying precipitable water vapor values as seen looking at zenith on Cerro Toco in the Chilean Atacama Desert, as generated by the <i>am</i> atmospheric model package [76].	30
Figure 2.2:	The POLARBEAR-1 observation patches overlaid on the full-sky 857 GHz intensity map generated by Planck [7]. Patches were chosen for low dust emission, overlap with other observations, and to allow nearly continuous CMB observations from the James Ax Observatory in Chile. Image from [10].	31
Figure 2.3:	<i>Left:</i> The Huan Tran Telescope housing the POLARBEAR-1 receiver on the Cerro Toco plateau in the Chilean Atacama Desert. <i>Right:</i> Ray-tracing of the path light takes through the telescope optics.	33
Figure 2.4:	A cross-section CAD drawing of the POLARBEAR-1 receiver. Light enters from the right and passes through a series of IR blocking filters, a cold stepped rotating half-wave plate, a cold aperture stop, and several re-imaging lenses until it finally arrives at the focal plane. Image from [54].	34

Figure 2.5:	<i>Left:</i> A POLARBEAR-1 wafer module, a zoom in of one of the pixels, and an SEM close up of a single bolometer island. <i>Right:</i> The fully assembled POLARBEAR-1 focal plane, consisting of seven wafers as depicted in the left image.	34
Figure 2.6:	The measured POLARBEAR-1 B-mode power spectrum at sub-degree scales from the first two seasons of observations. The results from two parallel analysis pipelines A (red) and B (blue) are plotting along with the standard model C_ℓ^{BB} theory. Image from [11].	37
Figure 2.7:	Estimated levels or upper bounds on instrumental systematic uncertainties in the four bins of the C_ℓ^{BB} power spectrum measurement from Figure 2.6. . .	38
Figure 2.8:	The B-mode power spectrum measured at degree scales with the POLARBEAR-1 experiment from the third to fifth seasons of observation. The solid (dashed) black line represents the best-fit cosmological (foreground) model. Image from [3].	40
Figure 2.9:	Systematic contributions to the B-mode power spectra as reported in 2.8. .	40
Figure 2.10:	The EB power spectrum as measured by the POLARBEAR-1 experiment after applying an angle rotation from calibration to Tau A (green) and then from self-calibration [53] (blue).	41
Figure 2.11:	The anisotropic cosmic rotation power spectra as measured from the first season of POLARBEAR-1 observations. First season data observed three sky patches: RA23 (green), RA12 (blue), and RA4.5 (yellow) as defined in Figure 2.2.	44
Figure 2.12:	<i>Top:</i> The B-mode polarization power spectrum sourced by a scale-invariant PMF. <i>Bottom:</i> The posterior distribution function of amplitude B_{1Mpc} for PMFs using the POLARBEAR first season C_ℓ^{BB} measurement.	45
Figure 2.13:	Photo of the three telescopes that comprise the Simons Array.	46
Figure 2.14:	<i>Top:</i> CAD cross-section depiction of the POLARBEAR-2a receiver with ray tracings through the receiver optics. <i>Right:</i> CAD cross-section of the POLARBEAR-2b and POLARBEAR-2c receiver design.	48
Figure 2.15:	Image of a sinuous antenna pixel on a POLARBEAR-2a wafer. Four bolometers are connected to the antenna with on-chip band-defining filters to measure two frequency bands at two linear polarizations. Image from [18].	50
Figure 3.1:	Composite visible light image of the Crab Nebula (Tau A) taken by NASA's Hubble Space Telescope. Image courtesy of NASA.	57
Figure 3.2:	Measurements of the Tau A intensity by the IRAM (blue) [16], Planck (green) [92], WMAP (red) [94], and various other experiments (black) [64].	57
Figure 3.3:	Measurements of the Tau A polarization angle by the IRAM (blue) [16], ACTPol (black) [71], ABS (purple) [58], WMAP (red) [94], Planck (green) [92], and POLARBEAR-1 (cyan) [10] experiments.	60
Figure 3.4:	A sample PSB pair d_{sum} timestream from a POLARBEAR-2a Tau A observation before (blue) and after (green) applying a fifth-order polynomial filter.	67

Figure 3.5:	<i>Top:</i> A zoom in of a fifth-order polynomial-filtered L/R subscan from Figure 3.4 (left). <i>Bottom:</i> The same plots as above but with source-masked polynomial filtering applied.	68
Figure 3.6:	I (left), Q (middle), and U (right) maps made from a single observation of Tau A by the POLARBEAR-1 telescope. The color scale is in temperature units of μK	70
Figure 3.7:	<i>Left:</i> Histogram of Tau A polarization angles as measured from 190 POLARBEAR-1 observations across three seasons, with an overall measured angle of $150.86^\circ \pm 1.06^\circ$. <i>Right:</i> The same Tau A polarization angles plotted as a function of time.	71
Figure 3.8:	Polarization map of Tau A from three seasons of POLARBEAR-1 observations.	72
Figure 3.9:	PSB pixel-pair polarization angle differences $\Delta_{tb, TauA}$ in POLARBEAR-1 as derived from three seasons of Tau A observations.	73
Figure 3.10:	The PSD f_{knee} (left column) and β (right column) parameters for six POLARBEAR-2a observations of Tau A for both 90 GHz (top row) and 150 GHz (bottom row) bolometers.	75
Figure 3.11:	I (first row), Q (second row), and U (third row) coadded maps of two POLARBEAR-2a observations of Tau A, for both 90 GHz (left column) and 150 GHz (right column) detectors. After data cuts, a total of 427 90 GHz bolometers and 529 150 GHz bolometers are present in the coadded maps.	77
Figure 3.12:	Polarization intensity (in arbitrary power units) coadded map from two POLARBEAR-2a observations of Tau A, for both 90 GHz (left) and 150 GHz (right) detectors.	78
Figure 3.13:	The PSD f_{knee} (left column) and β (right column) parameters for four POLARBEAR-2a observations of Jupiter for both 90 GHz (top row) and 150 GHz (bottom row) bolometers.	79
Figure 3.14:	Coadded intensity maps of five observations of Jupiter with POLARBEAR-2a for 90 GHz (left) and 150 GHz (right) bolometers.	79
Figure 3.15:	Detector pointing offsets (left) and beam shapes (right) for one POLARBEAR-2a observation of Jupiter. After data cuts, 1306 90 GHz bolometers and 1127 150 GHz bolometers remain.	80
Figure 3.16:	Overall beam shape for five POLARBEAR-2a observations of Tau A (left) and Jupiter (right) for both 90 GHz (solid lines) and 150 GHz (dotted lines) detectors.	81
Figure 4.1:	<i>Left:</i> The Gunn oscillator + doubler + pyramidal horn circuit mounted on the rotation stage. <i>Right:</i> The co-rotating blackened aluminum cylinder with adjustable co-rotating polarizing wire grid mounted around the Gunn oscillator circuit.	86
Figure 4.2:	<i>Left:</i> The microscope and dual-axis translation stage used to measure the angles of the wire grid wires and frame. <i>Right:</i> View through the microscope showing some of the wire grid's tungsten wires.	87

Figure 4.3:	The four precision-ground aluminum planes used for calibrating to the local gravity vector.	89
Figure 4.4:	<i>Top:</i> Normalized, demodulated laboratory detector response (blue) for one example calibrator scan fitted to the model in Equation 4.2 (orange). Normalized error bars represent statistical error only. <i>Bottom:</i> Weighted residual between the data and the model with $\chi = (S_{data} - S_{fit})/\sigma_{data}$	91
Figure 4.5:	Histogram of POLCAL repeatability between 1012 scans, with an error of $\sigma_{\phi} = 0.049^{\circ}$	92
Figure 4.6:	<i>Left:</i> Beam map of the source and room-temperature detector diode. <i>Right:</i> Measured E- and H-plane beam profiles with errors given by the respective shaded regions.	93
Figure 4.7:	<i>Top:</i> The 75-115 GHz tunable Gunn oscillator RF source in POLCAL. <i>Bottom:</i> The source with the doubler attached after the PIN switch diode to allow source frequencies of 150-230 GHz.	99
Figure 4.8:	<i>Left:</i> A beam map measured with phase one POLCAL's smaller exit aperture. <i>Right:</i> Beam map measured with phase two POLCAL's larger exit aperture.	102
Figure 4.9:	The enlarged polarizing wire grid designed to fill the entire expanded aperture for POLCAL.	103
Figure 4.10:	Images of the testing setup used to characterize POLCAL phase two in this section.	104
Figure 4.11:	Stacked histogram of repeatability between calibration scans using POLCAL phase two at various frequencies.	105
Figure 4.12:	Beam maps and E- and H-plane beam profiles measured in the 95 GHz band. Measurements were made at source frequencies of 76, 80, 85, and 90 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.	107
Figure 4.13:	Beam maps and E- and H-plane beam profiles measured in the 95 GHz band. Measurements were made at source frequencies of 95, 100, 105, and 110 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.	108
Figure 4.14:	Beam maps and E- and H-plane beam profiles measured in the 150 GHz band. Measurements were made at source frequencies of 150, 160, and 170 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.	109
Figure 4.15:	E- and H-plane FWHM fitted values (blue and orange, respectively) plotted against POLCAL source frequency (offset by ± 0.5 GHz for visual purposes).	110
Figure 5.1:	Images of the POLCAL calibrator on the Cerro Toco saddle during the POLARBEAR-1 engineering test run deployment.	113
Figure 5.2:	Photo of the POLARBEAR-1 focal plane with the center wafer's central pixel highlighted in blue and surrounding 18 pixels marked in red.	114

Figure 5.3:	<i>Top:</i> Screen shot of the live focal plane viewer that shows chopped polarized POLCAL response in POLARBEAR-1 detector timestreams. <i>Bottom Left:</i> An example detector timestream. <i>Bottom Right:</i> The demodulated timestream for three successive calibration scans.	115
Figure 5.4:	<i>Left:</i> The orthogonality $\Delta_{tb, meas}$ for 45 pixels across three wafers as measured with POLCAL on the POLARBEAR-1 telescope. <i>Right:</i> The difference between the POLCAL derived orthogonality and the Tau A derived values.	117
Figure 5.5:	<i>Top:</i> Image of POLCAL pointed towards the POLARBEAR-2b receiver in the laboratory. <i>Bottom:</i> Another image of the same setup but from the opposite perspective.	119
Figure 5.6:	An example of a few seconds of the modulated POLCAL signal as seen by a single POLARBEAR-2b bolometer. POLCAL emits polarized radiation when the PIN switch is open (blue) and is blocked when the PIN switch is closed (orange). The modulation frequency depicted here is 1 Hz.	121
Figure 5.7:	Two sample modulation transitions from Figure 5.6.	122
Figure 5.8:	Estimated time constants for bolometers in the POLARBEAR-2b receiver as measured with POLCAL.	123
Figure 5.9:	<i>Top row:</i> Bolometer time constants for the PIN switch switching open (green) and closed (red) in the overbias state at 90 GHz (left) and 150 GHz (right). <i>Bottom row:</i> Same as the above row but in the bolometer tuned state.	124
Figure 5.10:	A sample POLARBEAR-2b detector timestream for one POLCAL PIN switch cycle with the CRHWP spinning and respective demodulation coefficients.	127
Figure 5.11:	<i>Top:</i> The calculated $4f$ phase δ_{4f} plotted against POLCAL calibration angle (blue) and best fit model to Equation 5.7 (dashed orange line) for a sample detector in the POLARBEAR-2b receiver. <i>Bottom:</i> Weighted residual between the data and the model with $\chi = (S_{data} - S_{fit})/\sigma_{data}$ for both.	129
Figure 5.12:	<i>Top:</i> Measured angles for 1265 overbiased bolometers across three wafers in the POLARBEAR-2b receiver. <i>Bottom:</i> Statistical and systematic errors associated with bolometer angle values from above plot.	132
Figure 5.13:	<i>Top:</i> Measured angles for 1174 tuned bolometers across three wafers in the POLARBEAR-2b receiver. <i>Bottom:</i> Statistical and systematic errors associated with bolometer angle values from above plot.	133
Figure 5.14:	The orthogonality between top and bottom bolometer angles as defined by the POLARBEAR-2b hardware map (as of Run18b).	134
Figure 5.15:	Simulated polarization wobble in a sinuous antenna between 70 GHz and 170 GHz. Image from [88].	135
Figure 5.16:	<i>Top:</i> An example A- (left) and B-sense (right) mirror-imaged sinuous antenna pixel pair. <i>Bottom:</i> A schematic showing the location of four types of pixels on a single wafer.	136
Figure 5.17:	Histograms of the measured polarization angle difference between A- and B-sense bolometer pairs across three wafers in the POLARBEAR-2b receiver in the overbiased state.	138

Figure 5.18: Histograms of the measured polarization angle difference between A- and B-sense bolometer pairs across three wafers in the POLARBEAR-2b receiver in the tuned state.	139
Figure 5.19: Measurements of the polarization wobble using the POLARBEAR-2b receiver as a function of POLCAL frequency.	140

LIST OF TABLES

Table 1.1:	Several radio and ultraviolet rotation angle measurements of polarized extra-Galactic sources, as shown in [29].	22
Table 1.2:	Compendium of constraints on CPR angle α from several CMB experiments. Statistical uncertainties are listed after the measurement followed by systematic uncertainty in parenthesis (where available).	25
Table 3.1:	Compendium of Tau A polarization angle measurements from various CMB experiments. Statistical uncertainties are listed after the measurement followed by systematic uncertainties in parenthesis (where available). All measurements are reported in equatorial coordinates.	59
Table 4.1:	Calculated and estimated statistical and systematic errors.	94

ACKNOWLEDGEMENTS

I would first like to thank my amazing wife Ryanna. Thank you for sticking by my side through all the ups and downs of this journey. Without your love and support, none of this would have been possible.

I would like to thank my advisor Brian Keating for your support and guidance over the years, which helped shape me into the scientist I am today. Without your passion and insistence to break the standard model of cosmology, this work would not have been possible. I would also like to thank Kam Arnold whose advice over the years provided an invaluable resource for me. And a special thanks to Grant Teply who provided unending guidance, support, and discussion over the last several years. The three of you proved to be wonderful mentors during my time here at UCSD.

I would also like to thank the entire POLARBEAR collaboration for your hard work and dedication toward our experiment to make it stand out in such a competitive field. It has been incredible to work alongside you and I thank you for all of your input, advice, and suggestions over the years that helped shape the outcome of this work.

I'd like to express my sincerest thanks to my amazing fellow graduate students and group members over the years: Chris Aleman, Darcy Barron, Dave Boettger, Kevin Crowley, Tucker Elleflot, Chang Feng, Nick Galitzki, Logan Howe, Jen Ito, Del Johnson, Kavon Kazemzadeh, David Leon, Lindsay Lowry, Frederick Matsuda, Steph Moyerman, Megan Russel, Max Silva-Feaver, Joe Seibert, Praween Siritanasak, Jake Spisak, Nate Stebor, Calvin Tsai, Tran Tsan, Taige Wang, and Alex Zahn. I couldn't have done any of this without your insightful discussions, friendship, and, of course, baked goods over the years. And a special thanks to Jon Kaufman for laying the ground work for the project that would become the focus of this work.

I'd like to express my profound gratitude to all of my family for their unfailing support throughout my journey. Thank you Mom and Dad for raising me to always be curious. Thank you Nick for being the big brother whose steps I have inevitably followed in my entire life. Thank

you grandma Mary and grandpa Al for your love and wisdom whenever I visited home. Thanks to Cassey, AJ, Lauren, Keith, Victoria, Scott, Kristoffer, Jesse, and Jo for your love and support over the years. And thank you to the rest of my family who has shown me immense support along the way.

Thank you to Alan, Nicole, Wendell, Hao, Mitch, and Jaime for your friendship and keeping me mentally grounded with the many nights of board games and MTG to help me relax and escape academia, if only for a few hours at a time.

A final thanks to my community at Kairos Christian Church, especially Pastor Peter, for your fellowship, wisdom, and prayers over the years. I love and appreciate each and every one of you.

Figure 1.5 (top) has been submitted for publication of the material as it may appear in: S. Adachi, M.A.O.A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, M. Hasegawa, M. Hazumi, H. Hirose, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, S. Kikuchi, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, C. L. Reichardt, Y. Segawa, P. Siritanasak, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. “A measurement of the CMB E-mode angular power spectrum at subdegree scales from 670 square degrees of POLARBEAR data.” Submitted to The Astrophysical Journal. May 2020. The dissertation author made essential contributions to this work.

Figure 2.1 is a reprint of the material as it appears in: J. Errard, P. A. Ade, Y. Akiba, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, J. Delabrouille, M. Dobbs, A. Ducout, T. Elleflot, G. Fabbian, C. Feng, S. Feeney, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W.

L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, O. Jeong, N. Katayama, J. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, F. Matsuda, T. Matsumura, N. J. Miller, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, G. Puglisi, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, D. E. Schenck, B. D. Sherwin, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, A. Tikhomirov, T. Tomaru, N. Whitehorn, B. Wilson, A. Yadav, and O. Zahn. “Modeling Atmospheric Emission for CMB Ground-Based Observations.” *The Astrophysical Journal*, 809(1):63, Aug 2015. The dissertation author made essential contributions to this work.

Figure 2.2 is a reprint of the material as it appears in: P. A. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, D. Flanagan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, A. Orlando, H. Paar, J. Peloton, D. Poletti, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, D. E. Schenck, B. D. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. “A measurement of the cosmic microwave background B-mode polarization power spectrum at sub-degree scales with POLARBEAR.” *The Astrophysical Journal*, 794(2):171, May 2014. The dissertation author made essential contributions to this work.

Figures 2.6 and 2.7 are reprints of the materials as they appear in: P. A. R. Ade, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, K. Crowley, A. Cukierman, R. Dunner, M. Dobbs, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald,

J. C. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, M. L. Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, Y. Minami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, P. L. Richards, C. Ross, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, T. Tomaru, C. Tucker, N. Whitehorn, and A. Zahn. "A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Subdegree Scales from Two Years of POLARBEAR Data." *The Astrophysical Journal*, 848(2):121, 2017. The dissertation author made essential contributions to this work.

Figures 2.8, 2.9, and 2.10 have been submitted for publication of the materials as they may appear in: S. Adachi, M. A. O. Aguilar Faundex, K. Arnold, C. Baccigalupi, B. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, A. Cukierman, M. Dobbs, H. El Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, Y. Inoue, G. Jaehnig, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Lindner, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, Y. Zhou. "A Measurement of the Degree Scale CMB B-mode Angular Power Spectrum with POLARBEAR." Submitted to *The Astrophysical Journal*. Oct 2019. The dissertation author made essential contributions to this work.

Figures 2.11, 2.12 (top), and 2.12 (bottom) are reprints of the materials as they appear in: P. A. R. Ade, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S.

Feeney, C. Feng, A. Gilbert, N. Goeckner-Wald, J. Groh, W. L. Holzapfel, Y. Hori, L. Howe, A. H. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, Y. Li, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. J. Myers, M. Navaroli, D. Poletti, G. Puglisi, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, D. E. Schenck, B. D. Sherwin, M. Shimon, I. Shirley, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, A. Suzuki, J.-I. Suzuki, B. Wilson, A. Yadav, A. Zahn, and O. Zahn. “POLARBEAR constraints on cosmic birefringence and primordial magnetic fields.” *Physical Review D*, 92(12):1550–7998, 2015. The dissertation author made essential contributions to this work.

Figure 2.14 (top) is a reprint of the material as it appears in Y. Inoue, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. A. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, F. Irie, G. Jaehnig, A. Jaffe, O. Jeongh, N. Katayama, J. P. Kaufman, K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskital, T. Kisner, A. Kusaka, M. L. Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, K. Mizukami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, Y. Segaw, B. D. Sherwin, I. Shirley, P. Siritanasak, N. Stebor, R. S. A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirol, T. Tomaru, N. Whitehorn, A. Zahn, and O. Zahn. POLARBEAR-2: an instrument for CMB polarization measurements. *SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 991411:1–8, 2016. The dissertation author made essential contributions to this work.

Section 4.1 is an updated reprint of material as it appears in: M. F. Navaroli, K. D. Crowley, G. P. Teply, N. Galitzki, J. P. Kaufman, B. Keating, and K. S. Arnold. “Design and characterization

of a ground-based absolute polarization calibrator for use with polarization sensitive CMB experiments.” Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, page 80. SPIE, Jul 2018. The dissertation author was the primary author of this work.

VITA

2012	B. S. in Physics, University of California Santa Barbara
2013	M. S. in Physics, University of California San Diego
2020	Ph. D. in Physics, University of California San Diego

PUBLICATIONS

M. Navaroli, K. Crowley, G. Teply, N. Galitzki, J. Kaufman, B. Keating, and K. Arnold. Design and characterization of a ground-based absolute polarization calibrator for use with polarization sensitive CMB experiments. Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, page 80. SPIE, jul 2018.

M. A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, J. Carron, K. Cheung, Y. Chinone, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Goeckner-Wald, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, H. Hirose, O. Jeong, N. Katayama, B. Keating, S. Kikuchi, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, R. Stompor, A. Suzuki, O. Tajima, S. Takatori, D. Tanabe, G. P. Teply, and C. Tsai. Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum from Two Years of POLARBEAR Data. *The Astrophysical Journal*, 893(1):85, 2020.

D. Kaneko, S. Adachi, P. A. Ade, M. Aguilar Faundez, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, A. Cukierman, M. Dobbs, R. Dunner, H. El Bouhargani, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. W. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, O. Jeong, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, J. Peloton, A. T. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, C. Ross, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, T. Tomaru, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. Deployment of POLARBEAR-2A. *Journal of Low Temperature Physics*, 199(3):1137–1147, may 2020.

S. Adachi, M. A. Aguilar Faundez, Y. Akiba, A. Ali, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, J. Borrill, J. Carron, K. Cheung, Y. Chinone, K. Crowley, H. El Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Goeckner-Wald, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, N. Katayama, B. Keating, S. Kikuchi, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, T. Namikawa, M. Navaroli, H.

Nishino, J. Peloton, A. T. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, R. Stompor, O. Tajima, S. Takatori, D. Tanabe, G. P. Teply, and C. Verges. Internal Delensing of Cosmic Microwave Background Polarization B-Modes with the POLARBEAR Experiment. *Physical review letters*, 124(13):131301, 2020.

S. Adachi, M. A. O. A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, M. Hasegawa, M. Hazumi, H. Hirose, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, S. Kikuchi, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, C. L. Reichardt, Y. Segawa, P. Siritanasak, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. A measurement of the CMB E-mode angular power spectrum at subdegree scales from 670 square degrees of POLARBEAR data. *arXiv e-prints*; arXiv:2005.061, may 2020.

M. A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, J. Carron, K. Cheung, Y. Chinone, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, N. Galitzki, N. Goeckner-Wald, M. Hasegawa, M. Hazumi, L. Howe, D. Kaneko, N. Katayama, B. Keating, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, B. D. Sherwin, M. Silva-Feaver, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, G. P. Teply, C. Tsai, and C. Verges. Cross-correlation of CMB Polarization Lensing with High- z Submillimeter Herschel-ATLAS Galaxies. *The Astrophysical Journal*, 886(1):38, 2019.

F. Matsuda, L. Lowry, A. Suzuki, M. Aguilar Faundez, K. Arnold, D. Barron, F. Bianchini, K. Cheung, Y. Chinone, T. Elleflot, G. Fabbian, N. Goeckner-Wald, M. Hasegawa, D. Kaneko, N. Katayama, B. Keating, A. T. Lee, M. Navaroli, H. Nishino, H. Paar, G. Puglisi, P. L. Richards, J. Seibert, P. Siritanasak, O. Tajima, S. Takatori, C. Tsai, and B. Westbrook. The POLARBEAR Fourier transform spectrometer calibrator and spectroscopic characterization of the POLARBEAR instrument. *Review of Scientific Instruments*, 90(11), 2019.

S. Takakura, M. A. O. Aguilar-Faundez, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, K. Cheung, Y. Chinone, T. Elleflot, J. Errard, G. Fabbian, C. Feng, N. Goeckner-Wald, T. Hamada, M. Hasegawa, M. Hazumi, L. Howe, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, L. N. Lowry, F. T. Matsuda, A. J. May, Y. Minami, M. Navaroli, H. Nishino, L. Piccirillo, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, M. Silva-Feaver, P. Siritanasak, A. Suzuki, O. Tajima, S. Takatori, D. Tanabe, G. P. Teply, and C. Tsai. Measurements of Tropospheric Ice Clouds with a Ground-based CMB Polarization Experiment, POLARBEAR. *The Astrophysical Journal*, 870(2):102, 2019.

S. Adachi, M. A. O. A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, A.

Cukierman, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. A Measurement of the Degree Scale CMB B-mode Angular Power Spectrum with POLARBEAR. *arXiv e-prints*, 10:38, 2019.

T. Namikawa, Y. Chinone, H. Miyatake, M. Oguri, R. Takahashi, A. Kusaka, N. Katayama, S. Adachi, M. Aguilar, H. Aihara, A. Ali, R. Armstrong, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, K. Cheung, L. Corbett, K. T. Crowley, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, N. Galitzki, N. Goeckner-Wald, J. Groh, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, O. Jeong, D. Kaneko, B. Keating, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, S. Miyazaki, H. Murayama, M. Navaroli, H. Nishino, A. J. Nishizawa, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, J. S. Speagle, R. Stompor, A. Suzuki, P. J. Tait, O. Tajima, M. Takada, S. Takakura, S. Takatori, D. Tanabe, M. Tanaka, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. Evidence for the Cross-correlation between Cosmic Microwave Background Polarization Lensing from POLARBEAR and Cosmic Shear from Subaru Hyper Suprime-Cam. *The Astrophysical Journal*, 882(1):62, 2019.

B. Westbrook, P. A. Ade, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, A. N. Bender, F. Bianchini, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, G. Coppi, K. Crowley, A. Cukierman, T. de Haan, R. Dunner, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, G. Fuller, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. Groh, N. W. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, W. Holzapfel, L. Howe, Y. Inoue, G. Jaehnig, A. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, M. Le Jeune, A. T. Lee, D. Leon, E. Linder, L. Lowry, A. Madurowicz, D. Mak, F. Matsuda, A. May, N. J. Miller, Y. Minami, J. Montgomery, M. Navaroli, H. Nishino, J. Peloton, A. Pham, L. Piccirillo, D. Plambeck, D. Poletti, G. Puglisi, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, H. Roberts, C. Ross, K. M. Rotermund, Y. Segawa, B. Sherwin, M. Silva-Feaver, P. Siritanasak, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, R. Tat, G. P. Teply, A. Tikhomirov, T. Tomaru, C. Tsai, N. Whitehorn, and A. Zahn. The POLARBEAR-2 and Simons Array Focal Plane Fabrication Status. *Journal of Low Temperature Physics*, 193(5-6):758–770, 2018.

S. Takakura, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, S. Beckman, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, T. Fujino, N. Galitzki, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, L. Howe, Y. Inoue, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, L. Lowry, F. Matsuda, T. Matsumura, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. L.

Reichardt, C. Ross, P. Siritanasak, A. Suzuki, O. Tajima, S. Takatori, and G. Teply. Performance of a continuously rotating half-wave plate on the POLARBEAR telescope. *Journal of Cosmology and Astroparticle Physics*, 2017(5):21, 2017.

D. Poletti, G. Fabbian, M. Le Jeune, J. Peloton, K. Arnold, C. Baccigalupi, D. Barron, S. Beckman, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, A. Ducout, T. Elleflot, J. Errard, S. Feeney, N. Goeckner-Wald, J. Groh, G. Hall, M. Hasegawa, M. Hazumi, C. Hill, L. Howe, Y. Inoue, A. H. Jaffe, O. Jeong, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. Lowry, F. Matsuda, M. Navaroli, H. Paar, G. Puglisi, C. L. Reichardt, C. Ross, P. Siritanasak, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, G. Teply, and N. Whitehorn. Making maps of cosmic microwave background polarization for B-mode studies: The POLARBEAR example. *Astronomy and Astrophysics*, 600:1–26, 2017.

P. A. R. Ade, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, K. Crowley, A. Cukierman, R. Dunner, M. Dobbs, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. C. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, M. L. Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, Y. Minami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, P. L. Richards, C. Ross, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, T. Tomaru, C. Tucker, N. Whitehorn, and A. Zahn. A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Subdegree Scales from Two Years of POLARBEAR Data. *The Astrophysical Journal*, 848(2):121, 2017.

N. Stebor, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, S. Beckman, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, T. Fujino, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, Y. Inoue, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. Le Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, Y. Segawa, B. D. Sherwin, I. Shirley, P. Siritanasak, L. Steinmetz, R. Stompor, A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirov, T. Tomaru, B. Westbrook, N. Whitehorn, A. Zahn, and O. Zahn. The Simons Array CMB polarization experiment. *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, volume 9914, page 99141H. SPIE, jul 2016.

Y. Inoue, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. A. Dobbs,

A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskital, T. Kisner, A. Kusaka, M. L. Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, K. Mizukami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, Y. Segaw, B. D. Sherwin, I. Shirley, P. Siritanasak, N. Stebor, R. S. A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirol, T. Tomaru, N. Whitehorn, A. Zahn, and O. Zahn. POLARBEAR-2: an instrument for CMB polarization measurements. *SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 991411:1–8, 2016.

A. Suzuki, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, T. Fujino, G. Fuller, A. Gilbert, N. Goeckner-Wald, J. Groh, T. D. Haan, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. Holzapfel, Y. Hori, L. Howe, Y. Inoue, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. Kaufman, K. Kazemzadeh, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. L. Jeune, A. Lee, D. Leon, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, K. Mizukami, J. Montgomery, M. Navaroli, H. Nishino, J. Peloton, D. Poletti, G. Puglisi, G. Rebeiz, C. Raum, C. Reichardt, P. Richards, C. Ross, K. Rotermund, Y. Segawa, B. Sherwin, I. Shirley, P. Siritanasak, N. Stebor, R. Stompor, J. Suzuki, O. Tajima, S. Takada, S. Takakura, S. Takatori, A. Tikhomirov, T. Tomaru, B. Westbrook, N. Whitehorn, T. Yamashita, A. Zahn, O. Zahn. The POLARBEAR-2 and the Simons Array Experiments. *Journal of Low Temperature Physics*, 184(3-4):805–810, aug 2015.

J. Errard, P. A. Ade, Y. Akiba, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, J. Delabrouille, M. Dobbs, A. Ducout, T. Elleflot, G. Fabbian, C. Feng, S. Feeney, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, O. Jeong, N. Katayama, J. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, F. Matsuda, T. Matsumura, N. J. Miller, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, G. Puglisi, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, D. E. Schenck, B. D. Sherwin, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, A. Tikhomirov, T. Tomaru, N. Whitehorn, B. Wilson, A. Yadav, and O. Zahn. MODELING ATMOSPHERIC EMISSION FOR CMB GROUND-BASED OBSERVATIONS. *Astrophysical Journal*, 809(1):63, 2015.

P. A. R. Ade, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, A. Gilbert, N. Goeckner-Wald, J. Groh, W. L. Holzapfel, Y. Hori, L. Howe, A. H. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner,

A. Kusaka, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, Y. Li, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. J. Myers, M. Navaroli, D. Poletti, G. Puglisi, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, D. E. Schenck, B. D. Sherwin, M. Shimon, I. Shirley, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, A. Suzuki, J.-I. Suzuki, B. Wilson, A. Yadav, A. Zahn, and O. Zahn. POLARBEAR constraints on cosmic birefringence and primordial magnetic fields. *Physical Review D*, 92(12):1550–7998, 2015.

D. Barron, P. A. R. Ade, Y. Akiba, C. Aleman, K. Arnold, M. Atlas, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, N. Katayama, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. L. Jeune, A. T. Lee, E. M. Leitch, E. Linder, F. Matsuda, T. Matsumura, X. Meng, H. Morii, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. Rotermond, D. E. Schenck, B. D. Sherwin, I. Shirley, M. Sholl, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, J. Suzuki, S. Takada, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, H. Yamaguchi, and O. Zahn. Development and characterization of the readout system for POLARBEAR-2. *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, 9153:915335, oct 2014.

P. A. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, D. Flanigan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. Linder, E. M. Leitch, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, H. Paar, J. Peloton, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, D. E. Schenck, B. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. Measurement of the cosmic microwave background polarization lensing power spectrum with the POLARBEAR experiment. *Physical Review Letters*, 113(2), 2014.

A. Suzuki, P. Ade, Y. Akiba, C. Aleman, K. Arnold, M. Atlas, D. Barron, J. Borrill, S. Chapman, Y. Chinone, a. Cukierman, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, G. Feng, a. Gilbert, W. Grainger, N. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. Holzapfel, Y. Hori, Y. Inoue, G. Jaehnig, N. Katayama, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, a. Lee, F. Matsuda, T. Matsumura, H. Morii, S. Moyerman, M. Myers, M. Navaroli, H. Nishino, T. Okamura, C. Reichart, P. Richards, C. Ross, K. Rotermond, M. Sholl, P. Siritanasak, G. Smecher, N. Stebor, R. Stompor, J. Suzuki, S. Takada, S. Takakura, T. Tomaru, B. Wilson, H. Yamaguchi, and O. Zahn. The POLARBEAR-2 Experiment. *Journal of Low Temperature Physics*, 176(5-6):719–725, feb 2014.

P. A. R. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, C. Borys, S. Chapman, Others, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng,

D. Flanigan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. Rotermond, I. Schanning, D. E. Schenck, B. D. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, S. Takakura, A. Tikhomirov, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. Evidence for gravitational lensing of the cosmic microwave background polarization from cross-correlation with the cosmic infrared background. *Physical Review Letters*, 112(13):131302, 2014.

K. Arnold, N. Stebor, P. a. R. Ade, Y. Akiba, a. E. Anthony, M. Atlas, D. Barron, a. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, a. Cukierman, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, a. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, a. H. Jaffe, N. Katayama, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, a. T. Lee, E. M. Leitch, E. Linder, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, D. E. Schenck, B. D. Sherwin, I. Shirley, M. Sholl, P. Siritanasak, G. Smecher, B. Steinbach, R. Stompor, a. Suzuki, J. Suzuki, S. Takada, S. Takakura, T. Tomaru, B. Wilson, a. Yadav, and O. Zahn. The Simons Array: expanding POLARBEAR to three multi-chroic telescopes. *SPIE Astronomical Telescopes+ Instrumentation*, 9153:91531F, aug 2014.

Y. Inoue, N. Stebor, P. a. R. Ade, Y. Akiba, K. Arnold, a. E. Anthony, M. Atlas, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, A. Gilbert, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, G. C. Jaehnig, a. H. Jaffe, N. Katayama, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, a. T. Lee, E. M. Leitch, E. Linder, F. Matsuda, T. Matsumura, X. Meng, H. Morii, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, D. E. Schenck, B. D. Sherwin, P. Siritanasak, G. Smecher, M. Sholl, B. Steinbach, R. Stompor, A. Suzuki, J. Suzuki, S. Takada, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, H. Yamaguchi, and O. Zahn. Thermal and optical characterization for POLARBEAR-2 optical system. *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, 9153:91533A, aug 2014.

P. A. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, D. Flanigan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, A. Orlando, H. Paar, J. Peloton, D. Poletti, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, D. E. Schenck, B. D. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A.

Suzuki, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. A measurement of the cosmic microwave background B-mode polarization power spectrum at sub-degree scales with POLARBEAR. *The Astrophysical Journal*, 794(2):171, may 2014.

P. A. R. Ade, Y. Akiba, A. E. Anthony, K. Arnold, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, Others, Polarbear Collaboration, P. A. R. Ade, Y. Akiba, A. E. Anthony, K. Arnold, D. Barron, D. Boettger, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, R. Keskitalo, T. Kisner, M. L. Jeune, A. T. Lee, E. Linder, M. Lungu, F. Matsuda, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, H. Paar, J. Peloton, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, and D. E. Schenck. Gravitational Lensing of Cosmic Microwave Background Polarization. astro-ph preprint, arXiv:1312:1–8, 2013.

ABSTRACT OF THE DISSERTATION

Precise Astronomical Polarization Angle Calibration and its Impact on Studying Lorentz and Parity Violation in the Cosmic Microwave Background

by

Martin Frank Navaroli II

Doctor of Philosophy in Physics

University of California San Diego, 2020

Professor Brian Keating, Chair

Precise measurements of the polarization of the Cosmic Microwave Background (CMB) provide a wealth of knowledge regarding fundamental physics and the origins of our universe. We are currently in an era where the CMB polarization B-mode power spectrum is being measured at both small and large angular scales, providing increasingly tighter constraints on both the effects of gravitational lensing and the amount of primordial gravitational waves generated during the epoch of inflation. As we look toward the next generation of ground-based CMB experiments such as the Simons Observatory and CMB-S4, we must further our understanding of the systematic uncertainties that currently limit constraining power on both the tensor-to-scalar ratio and searches

for exotic new physics.

Lorentz and parity violating physics such as cosmic birefringence have the effect of rotating the polarization of CMB photons as they traverse cosmological distances, generating B-mode polarization signal and non-zero correlations between the CMB temperature and B-mode power spectra as well as the CMB E-mode and B-mode power spectra, both of which are disallowed by the current standard model of cosmology. This cosmic polarization rotation (CPR) is degenerate with an overall detector misalignment of similar angle magnitude. The precision with which current state-of-the-art polarization calibrators are characterized is presently inadequate to allow for meaningful detections of non-zero CPR from physics that diverge from the standard model to be claimed.

This dissertation provides an overview of the current CMB polarization calibration standards and methodology in the context of the POLARBEAR-1 and Simons Array experiments, as well as the design and characterization of a novel ground-based absolute polarization calibrator that will enable new searches for Lorentz and parity violating physics. The calibrator's repeatability between calibrations scans was proven to better than 0.1 degrees, and results from calibration performed on the POLARBEAR-1 telescope and the POLARBEAR-2b receiver are presented in this work.

Chapter 1

Introduction

1.1 Our Expanding Universe

Modern cosmology is fundamentally rooted in what is known as the Cosmological Principle, which states that our universe is both homogeneous and isotropic. On large scales, the universe looks the same at any particular location and in any given direction. The implication that follows from this notion is that we do not exist in any particularly special location in our universe and that there is therefore no preferred location or direction in our universe, an idea suggested as early as the 1500s by Nicolaus Copernicus.

A breakthrough in our understanding of cosmology came in the mid-1920s when an American astronomer named Edwin Hubble noticed a peculiar trend in the relative velocity of distant galaxies. Not only did he observe that these other galaxies were moving away from us, but also that their recession velocities increased the further away from us they were. This proportionality between a distant galaxy's recession velocity and its distance from us became known as "Hubble's Law" and is considered the first observational evidence that our universe is currently expanding. Based on this astounding finding, astronomer Georges Lemaître posited in 1927 that, if the universe is in fact expanding, then all matter we observe must have been closer

together at some point in the past. By rewinding the metaphorical universal clock even more, he suggested that all matter must have originated from a single point some finite amount of time ago - at the “beginning” of time. The so-called “Big Bang model of cosmology” was born.

In any model of cosmology it is useful to define a metric which dictates the relation between coordinate distance and physical distance. The metric that governs an expanding, homogeneous, isotropic universe such as ours is the Friedmann-Lemaître-Robertson-Walker (FLRW) metric given by [30]

$$ds^2 = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right) \quad (1.1)$$

where r, θ, ϕ are spherical spatial coordinates and c is the speed of light, and k represents the curvature of space (and can only have value 0, -1, or +1 corresponding to flat, closed, and open spatial curvature, respectively). The scale factor $a(t)$ describes the contraction or expansion of the universe and relates the co-moving distance between two points, which remains constant with time, to the physical distance that evolves with time. The value of the scale factor is normalized to 1 at the current epoch and was smaller at earlier times.

Using the FLRW metric to solve the Einstein field equation in general relativity yields a unique solution that governs the evolution of the scale factor known as the Friedmann equation, given by [30]

$$H(t)^2 = \frac{8\pi G}{3} \rho(t) - \frac{kc^2}{R_0^2 a(t)^2} \quad (1.2)$$

where $\rho(t)$ is the energy density in the universe at time t , R_0 is the radius of curvature, and G is the gravitational constant. $H(t)$ is known as the Hubble parameter and is defined by

$$H(t) = \frac{\dot{a}(t)}{a(t)}. \quad (1.3)$$

In general, the energy density $\rho(t)$ is made up of three components that all scale differently with

time: non-relativistic matter (scales as $a(t)^{-3}$), radiation (scales as $a(t)^{-4}$), and dark energy (constant in time). In the case of a flat universe with curvature $k = 0$, the second term in Equation 1.2 drops out and solving for the energy density yields what is known as the critical density, given by

$$\rho_{cr}(t) = \frac{3H(t)^2}{8\pi G}. \quad (1.4)$$

It is useful to compare the three constituent energy densities to this critical value to form the dimensionless quantity $\Omega_a(t)$ given by

$$\begin{aligned} \Omega_a(t) &= \frac{\rho_a(t)}{\rho_{cr}(t)} \\ \Omega(t) &= \sum \Omega_a, \end{aligned} \quad (1.5)$$

where the subscript a refers to the energy densities corresponding to non-relativistic matter, radiation, and dark energy, and $\Omega(t)$ is the sum of all three. If $\Omega(t)$ is equal to 1, less than 1, or greater than 1 then space is considered to be flat, closed, or open respectively.

As the universe expands, light emitted from matter moving away from us is Doppler shifted to lower energy with a longer wavelength. This stretching is known as “redshift” and is defined by [30]

$$1 + z = \frac{\lambda_{obs}}{\lambda_{emit}} = \frac{1}{a_{emit}} \quad (1.6)$$

where z is the redshift, λ_{obs} and λ_{emit} are the wavelengths of the light when it was observed and emitted, and a_{emit} is the scale factor when the light was emitted. As the scale factor increases monotonically with time in a flat, expanding universe the redshift is a measure of both the age of the light being observed and how far away the source of the light is. A redshift equal to zero represents the current epoch while a redshift greater than zero refers to distant objects emitting light some amount of time in the past.

1.2 The Cosmic Microwave Background

In the Big Bang model of cosmology the very early universe was a hot dense plasma consisting of electrons, protons, photons, and other fundamental particles. Photons in this epoch remained in thermal equilibrium with the hot dense matter via Thomson scattering off of free electrons, preventing the formation of any atoms by immediately breaking their bonds. When the universe was approximately 380,000 years old ($z \sim 1100$), the temperature of this plasma cooled to approximately ~ 1 eV ($T \sim 12,000$ K) as it expanded, allowing free protons and electrons to form neutral hydrogen unimpeded. This epoch of hydrogen formation is referred to as “recombination.” At the end of this recombination period, photons decoupled from matter at what is known as “the surface of last scattering” and began free streaming through the universe. As the universe continued to expand these photons were redshifted to an effective temperature of ~ 3 K today. This uniform radiation across our sky is known as the Cosmic Microwave Background (CMB) and was first detected by Arno Penzias and Robert Woodrow Wilson at Bell Labs in 1965 [77].

Because the universe only became transparent at the end of the epoch of recombination, the CMB is the “oldest” observable electromagnetic radiation in our universe and offers a detailed snapshot of the universe 380,000 years after the big bang. Although we cannot directly observe the universe prior to this epoch, the CMB provides an invaluable test bed for the fundamental physics and composition of the very early universe in the form of the CMB’s temperature and polarization anisotropies.

1.2.1 Blackbody Spectrum

In 1994, thirty years after Penzias and Wilson’s discovery of the CMB, the FIRAS instrument on the COBE satellite measured the intensity spectrum of the CMB and found that the CMB adheres to that of a 2.725 ± 0.010 K blackbody with extreme precision [66], as shown in Figure 1.1. Perhaps more remarkably, COBE-FIRAS found that the CMB looks like this

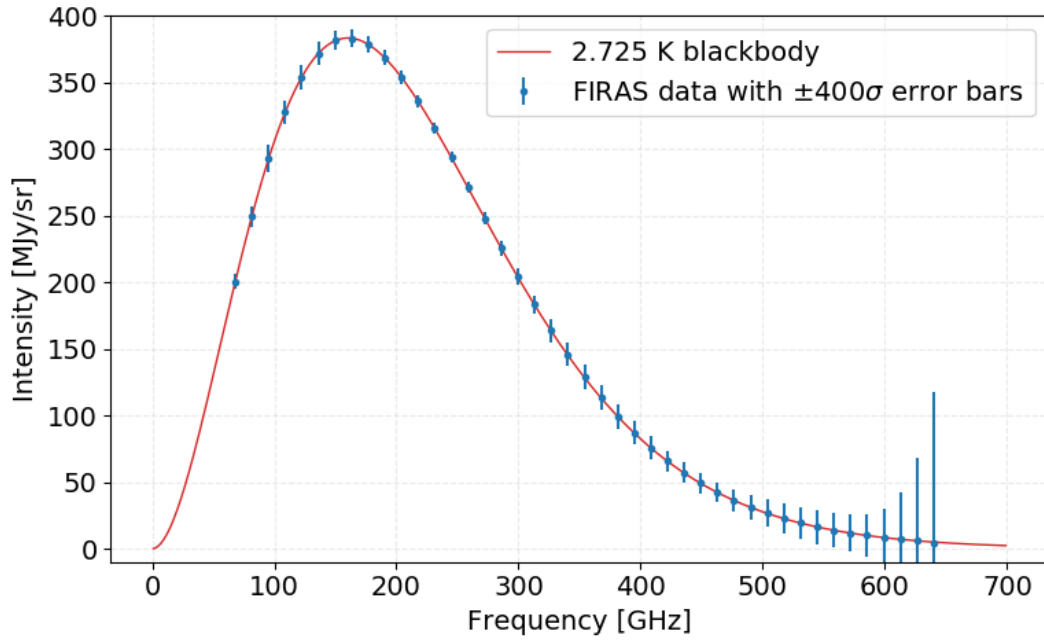


Figure 1.1: The CMB intensity spectrum as measured by the FIRAS instrument on the COBE satellite, compared to a 2.725 K blackbody spectrum. Plotted error bars have been magnified by a factor of 400 on each side so as to become visible. Data from [66].

2.725 K blackbody regardless of which direction they looked in the sky, suggesting that all CMB photons were once in good thermal equilibrium and further evidence that we do indeed live in a homogeneous, isotropic universe following an initial big bang [66, 86].

However, the discovery of this isotropic CMB signal seems extremely improbable as points separated on the sky by greater than ~ 2 degrees couldn't have been in causal contact even allowing free-streaming photons to travel unimpeded for the duration of currently known age of the universe. That these points on the sky were both in thermal contact at some point but also couldn't have ever been in causal contact is a paradox that motivates a more sophisticated model of the very early universe which allows for a period of rapid expansion of space called “inflation”, which is discussed in more detail in Section 1.3.

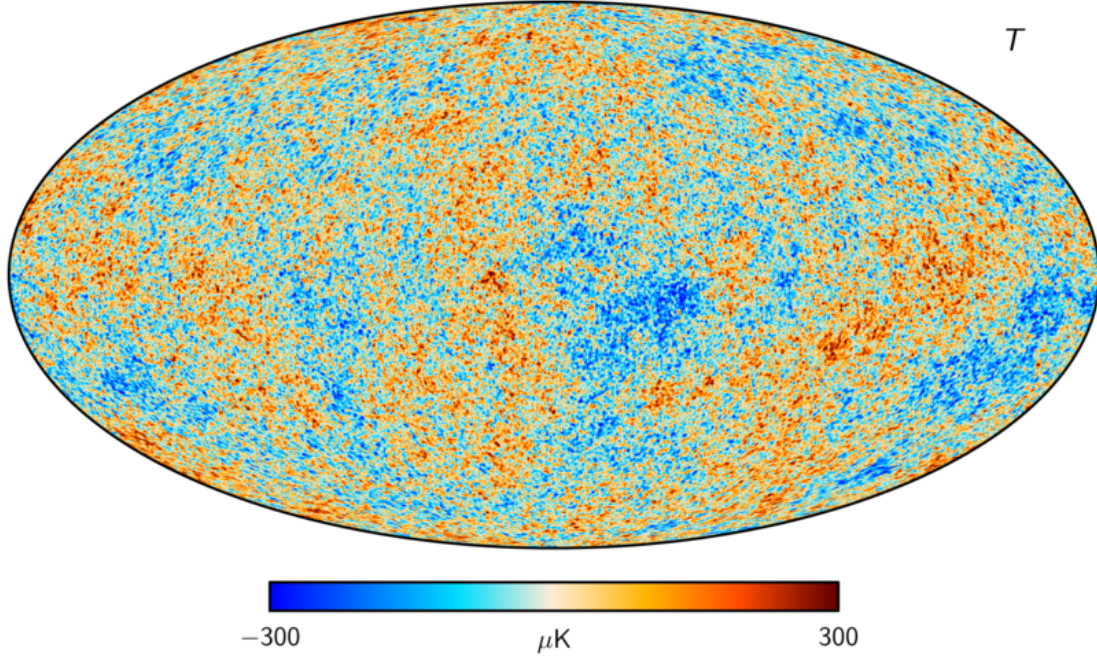


Figure 1.2: Full sky map of the CMB temperature anisotropies as measured by the Planck satellite in 2018. Both the signal from the plane of the Milky Way and the dipole from our Galactic velocity relative to the CMB have been subtracted in this map and anisotropies are shown on the scale of $\pm 300 \mu\text{K}_{\text{CMB}}$. Image from [13].

1.2.2 Temperature Anisotropies and Power Spectrum

If we subtract the uniform 2.725 K CMB signal across the entire sky, we are left with residual temperature anisotropies of order $\sim \pm 100 \mu\text{K}$. These anisotropies were first mapped across the sky in 1992 by the WMAP experiment [86] and recent measurements have culminated in the most detailed all-sky CMB temperature anisotropy map made by the Planck satellite in 2018 [13], shown in Figure 1.2.

The motivation for the “cold” (blue) and “hot” (red) spots in Figure 1.2 is as follows. At the time of recombination there were baryonic acoustic oscillations permeating the plasma of the universe. These oscillations created both over-dense and under-dense regions of matter that correspond to higher and lower gravitational potential wells respectively. Photons at the surface of last scattering in over-dense regions had to climb out of a deeper gravitational well than those scattering in under-dense regions, and as a result were redshifted to lower energy.

Therefore, these lower energy CMB photons represented by the blue cold spots in the Planck map are correlated with areas of over-density in the universe caused by baryonic acoustic oscillations at the end of recombination, and gives us great insight into the composition of the universe when it was 380,000 years old and how it might have evolved into what we observe today.

These temperature anisotropies Δ_T can be quantified by decomposing the temperature map into spherical harmonics $Y_{\ell m}$ with coefficients $a_{\ell m}^T$ as

$$\Delta_T(\theta, \phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m}(\theta, \phi). \quad (1.7)$$

For Gaussian fluctuations, all of the statistical behavior of the spherical harmonic coefficients $a_{\ell m}^T$ is captured by their power spectrum C_{ℓ}^{TT} , defined as

$$\langle a_{\ell m}^{T*} a_{\ell' m'}^T \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}^{TT}. \quad (1.8)$$

The CMB temperature anisotropy power spectrum C_{ℓ}^{TT} as measured by the Planck satellite in 2015 [5] is shown in Figure 1.3. An interesting characteristic of this measurement is the larger intrinsic error bars at large angular scale (or lower ℓ). The power spectrum in Equation 1.8 is essentially an average over all $2\ell + 1$ values of m , so increasing the angular scale (and thus lowering ℓ) represents fewer modes to be averaged over, representing a fundamental lower limit on error bars at low ℓ known as the “cosmic variance.”

1.2.3 Polarization of the CMB

Acoustic oscillations not only generate small temperature anisotropies in the CMB at the surface of last scattering but also impart a small amount of net polarization in the CMB due to Thomson scattering in regions of quadrupolar temperature anisotropy [30]. Note that net polarization from Thomson scattering only arises due to quadrupolar anisotropies as you need

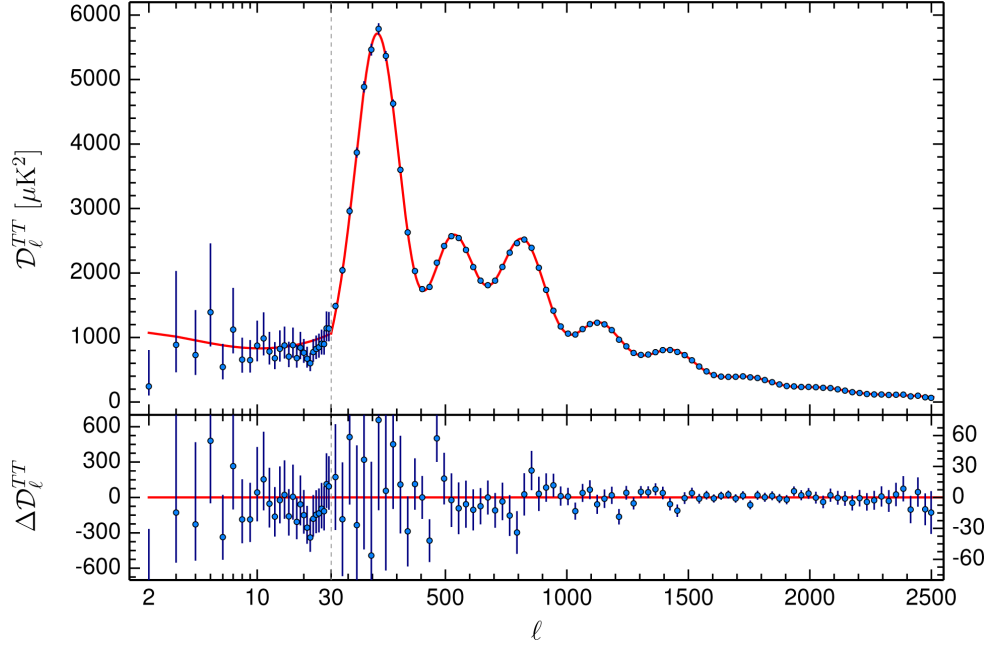


Figure 1.3: The CMB temperature anisotropy spectrum plus best-fit cosmological model (top) and residuals (bottom) as measured by the Planck satellite in 2015, with $\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$. Image from [5].

two photons of differing energies to scatter off a free electron at the same time coming from perpendicular directions (i.e. a quadrupolar temperature anisotropy). A cartoon diagram of this situation is shown in Figure 1.4.

The resulting polarization vectors in the CMB can be described by Stokes parameters

$$\begin{aligned}
 I &= |E_x|^2 + |E_y|^2 \\
 Q &= |E_x|^2 - |E_y|^2 \\
 U &= 2\text{Re}\langle E_x E_y^* \rangle \\
 V &= -2\text{Im}\langle E_x E_y^* \rangle,
 \end{aligned} \tag{1.9}$$

where, for a wave traveling in the $\hat{z}$ direction, E_x and E_y are the electric field amplitudes in the $\hat{x}$ and $\hat{y}$ directions respectively. I is the total intensity of the radiation, Q represents polarization in the 0° and 90° directions (relative to us), U represents polarization in the $\pm 45^\circ$ directions

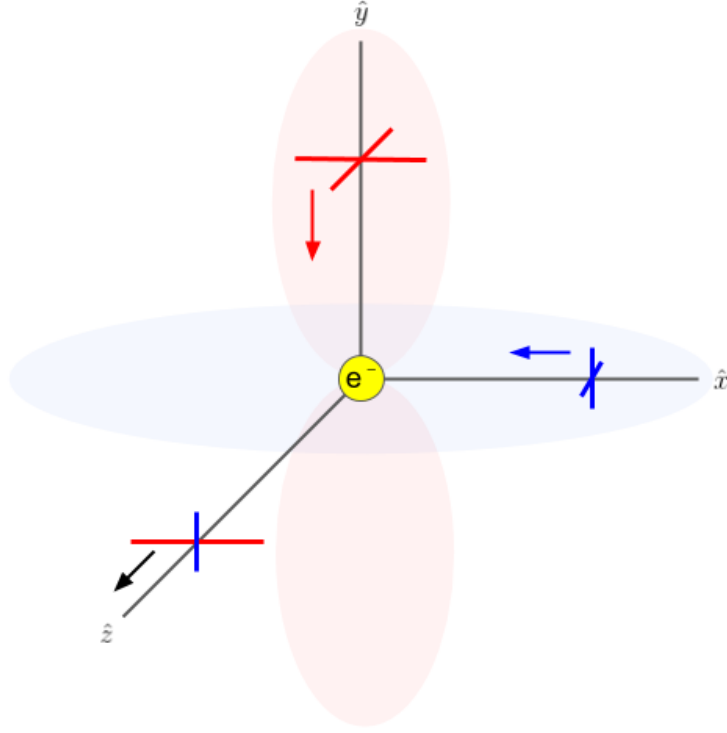


Figure 1.4: Cartoon diagram of CMB photons Thomson scattering off of a free electron (located at the origin) at the time of recombination in the presence of a quadrupolar anisotropy. The red regions represent an over-density in the plasma corresponding to a hot photon while the blue regions indicate an under-density corresponding to a cold photon. Unpolarized warm radiation (red, traveling down on the $\hat{y}$ -axis) and cold radiation (blue, traveling left on the $\hat{x}$ -axis) scatter off of the free electron which results in outgoing radiation along the positive $\hat{z}$ -axis with a net polarization along the $\hat{x}$ -axis (net polarization will always be aligned with the under-dense regions of the quadrupolar anisotropies).

(relative to us), and V is circular polarization. Note that V is expected to be zero for the CMB as the mechanism behind polarization only generates linear polarization. A few useful quantities to define for polarized radiation with $V = 0$ are

$$\begin{aligned} I_p &= \sqrt{Q^2 + U^2} \\ \theta &= \frac{1}{2} \tan^{-1} \frac{U}{Q} \\ P &= \frac{I}{I_p}, \end{aligned} \tag{1.10}$$

where I_p is the polarized intensity, θ is the polarization angle, and P is the polarization fraction of the radiation.

1.2.4 E- and B-modes

While the Stokes parameters are useful to define the polarization of incoming radiation, they are subject to the orientation angle of the observer. In other words, if the coordinate angle between the observer and the incoming polarization radiation is rotated by an angle α then Q and U can be rotated into each other as

$$\begin{aligned} Q' &= Q \cos(2\alpha) + U \sin(2\alpha) \\ U' &= -Q \sin(2\alpha) + U \cos(2\alpha), \end{aligned} \tag{1.11}$$

with spin-2 behavior (i.e. rotations by 180° leave the polarization state unaltered). It is therefore useful to decompose the CMB Stokes parameters into coordinate independent quantities known as E-modes and B-modes. E-modes represent parity-symmetric (divergence free) polarization while B-modes represent parity-antisymmetric (curl free) polarization. Scalar perturbations such as acoustic oscillations in the early universe source E-modes while tensor perturbations such as primordial gravitational waves source B-modes (and, to a lesser extent, E-modes).

To perform this decomposition, we follow the logic in [49, 55] and decompose the Stokes

parameters into spin-2 spherical harmonics, analogous to Equation 1.8, as

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\pm 2, \ell m \pm 2} Y_{\ell m}(\hat{n}). \quad (1.12)$$

We can then relate the coefficients $a_{\pm 2, \ell m}$ to E and B coefficients defined as

$$\begin{aligned} a_{\ell m}^E &\equiv -\frac{(a_{2, \ell m} + a_{-2, \ell m})}{2} \\ a_{\ell m}^B &\equiv -\frac{(a_{2, \ell m} - a_{-2, \ell m})}{2i} \end{aligned} \quad (1.13)$$

to generate the spherical harmonic decomposition of E- and B-mode that relates to Stokes Q and U parameters as

$$\begin{aligned} E(\hat{n}) &= \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^E Y_{\ell m}(\hat{n}) \\ B(\hat{n}) &= \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^B Y_{\ell m}(\hat{n}). \end{aligned} \quad (1.14)$$

We now have the tools to generalize Equation 1.8 to obtain power spectra for T, E, and B as

$$\langle a_{\ell m}^X a_{\ell' m'}^{*X'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}^{XX'}, \quad (1.15)$$

where X and X' are combinations of T, E, and B (i.e. TT, EE, BB, TE, TB, EB).

$C_{\ell}^{TT}, C_{\ell}^{EE}, C_{\ell}^{BB}$ are the autocorrelation power spectra for T, E, and B, but we can also correlate each with one another as well. Cross-correlations between T and E (C_{ℓ}^{TE}) are expected to be non-zero as both T and E are sourced from the same physical mechanisms and are both parity-even. On the other hand, the even-parity and odd-parity correlations C_{ℓ}^{TB} and C_{ℓ}^{EB} are expected to vanish according the standard model but can appear to be non-zero if CMB detectors are misaligned or if the CMB polarization is rotated by Lorentz or parity violating physics such as cosmic birefringence, which will be discussed in more detail in Section 1.4.

While B-modes sourced by primordial gravitational waves only show up at large angular scales, B-modes can be observed at small angular scales due to gravitational lensing. While the CMB free streamed through the universe, some photons were gravitationally lensed by the intervening matter between the surface of last scattering and today. This has the effect of mixing E- and B-modes and only occurs at small angular scales (i.e. roughly the scale on which large galaxy clusters are observed). Measurements of the gravitationally lensed B-modes not only provide a mechanism to help untangle lensing B-modes from primordial B-modes [37], but also provide a constraint on the sum of the neutrino masses as structure formation (and thus lensing) depends heavily on this quantity [2].

Many experiments have been designed in the last few decades targeting measurements of the E-mode and B-mode power spectra at both large and small angular scales. A compendium of the most recent measurements made by modern CMB experiments of the E-mode power spectrum C_ℓ^{EE} and the B-mode power spectrum C_ℓ^{BB} is depicted in Figure 1.5.

1.2.5 Polarized Foreground Contamination

Any polarized source emitting at CMB frequencies between the surface of last scattering and our telescope is referred to as a polarized foreground and can dominate the B-mode power spectrum at various angular scales and frequencies depending on what sources them. The contaminating signal from these foregrounds make detection of both primordial and lensing B-modes extremely difficult and must be well characterized to untangle their effects from the true B-mode spectrum.

The dominant sources of polarized foregrounds that originate within our galaxy include Galactic synchrotron emission and thermal dust emission, both of which depend on the strength of the magnetic fields that permeate our galaxy. Synchrotron emission occurs when charged particles are accelerated in the Milky Way in the presence of these magnetic fields. The strength of this emission depends on the inverse of emission frequency and can dominate B-mode signals

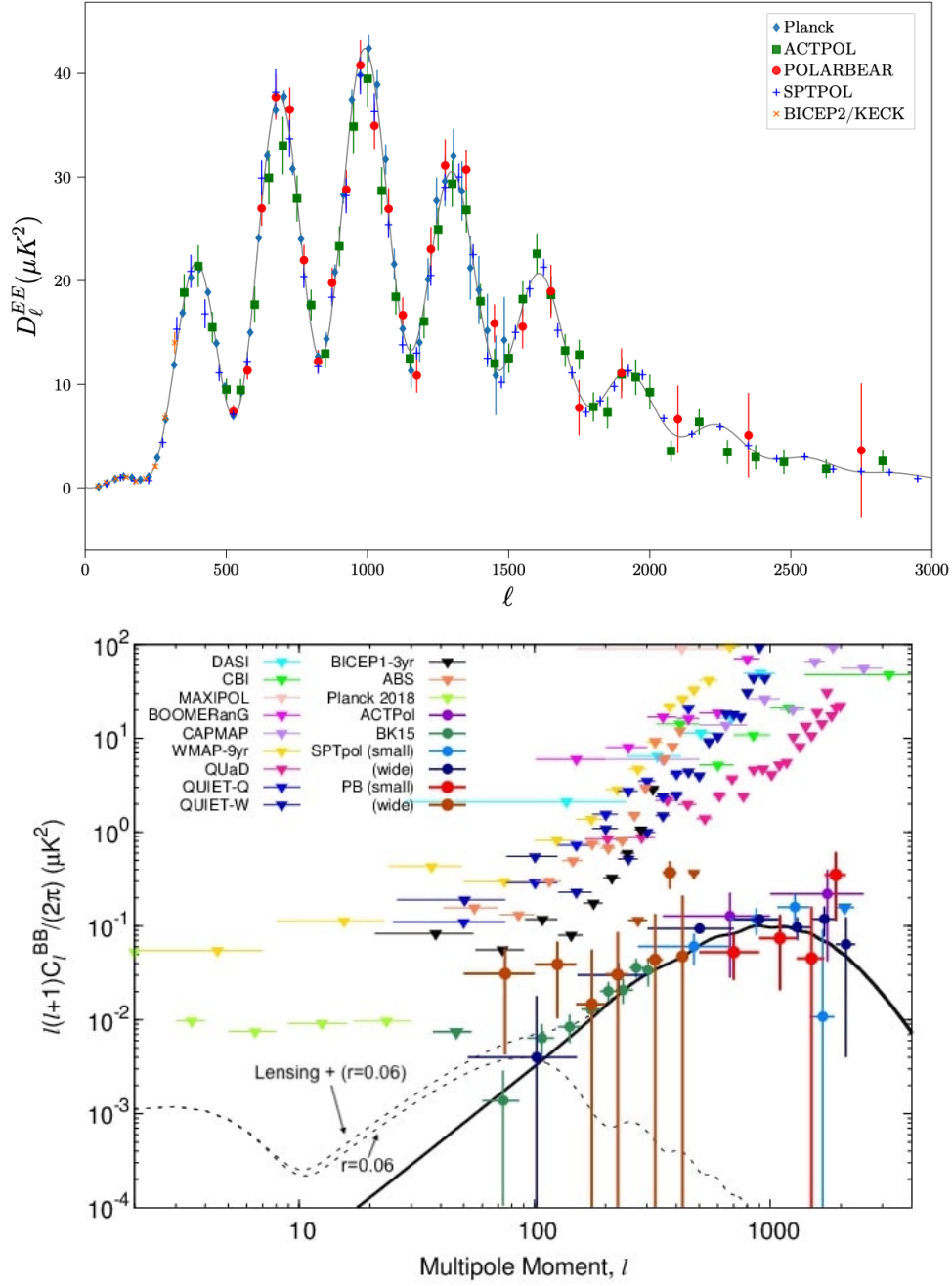


Figure 1.5: *Top:* Compilation of the most recent CMB E-mode measurements, with the standard model theory plotted as the solid black line. Image courtesy of Thi Phuong Anh Pham, from [4]. *Bottom:* Compilation of all CMB B-mode measurements to date. The primordial B-mode power spectrum for a tensor-to-scalar ratio of $r = 0.06$, the current best upper bound from [8], is depicted by the lower black dashed line while the gravitational lensing B-mode power spectrum is represented by the solid black line. The top black dashed line is the sum of the primordial and lensing B-mode spectra. Note that the “PB-wide” data are foreground subtracted as per [3] and only shown here for display. Image courtesy of Yuji Chinone.

at low observing frequencies. Thermal dust emission occurs when clouds of asymmetric dust particles align themselves with the permeating magnetic fields. If the emission axis points towards the telescope, this emission can register as a B-mode signal that depends proportionally on the emission frequency and thus can dominate signal at higher frequencies. To remove the effects of these two Galactic foreground contaminants, observations can be cross-correlated with either an experiment's own differing observation frequencies, or with existing all sky measurements at multiple frequencies from experiments such as WMAP and Planck [82].

The primary extra-Galactic source of polarized foreground contamination originates from polarized point sources. If not removed from an observation, these point sources can contribute significant power to the B-mode spectrum, especially at low frequencies. Luckily these point sources can be removed or masked from an observation by making use of all-sky surveys such as those generated by the WMAP experiment [82].

Another potentially crippling polarizing contaminant comes from our own Earth's atmosphere in the form of water vapor emission from water molecules in the air. As this is only a contaminating effect for CMB experiments on the ground (as opposed to satellite missions), this effect will be discussed in more detail in Section 2.1 in the context of CMB observations from the Atacama Desert in Chile.

While most of these polarized foregrounds are unavoidable when attempting B-mode power spectrum, modern CMB experiments can mitigate their effects with a combination of observing at many frequencies, cross-correlating with the multitude of existing all-sky measurements, and developing appropriate scan strategies with respect to the intended angular scales and frequencies at which the experiment observes.

1.3 Inflation

While the Big Bang model does a decent job of explaining the universe we observe around us, it is not without its faults. There are a number of issues that cannot be explained without enforcing very specific conditions, which is referred to as the “fine-tuning” problem. In this section we address these issues and their resolution in the context of the theory of inflation.

The first issue we run into is that, as we saw in Section 1.2.1, the CMB has a remarkably uniform temperature across the entire sky. However, points separated by more than a couple of degrees could not have been in causal contact at time zero. Therefore, there is no way these non-causal points could have equilibrated to the same temperature. This is referred to as the “horizon problem.”

From measurements of the CMB we have determined that the universe is nearly flat. That is, the energy density we measure is within about one percent [5] of the critical density described in Section 1.1. Using Equations 1.2, 1.4, and 1.5 we can relate the dimensionless energy density parameter $\Omega(t)$ to the scale factor as

$$1 - \Omega(t) = -\frac{kc^2}{R_0^2 a(t)^2 H(t)^2}. \quad (1.16)$$

The right hand side of Equation 1.16 does not change sign with time, so neither does $1 - \Omega(t)$. This means that any deviations from $\Omega(t) = 1$ are amplified in time as the scale factor increases with time. As measurements of $\Omega(t)$ today are consistent with $\Omega_0 = 1$, this would imply a special value of $\Omega(t = 0) = 1$ to extreme precision. This “fine-tuning” of the parameter $\Omega(t)$ is referred to as “the flatness problem”.

Both the horizon and flatness problems can be explained by a rapid expansion of the universe very shortly after the big bang known as inflation [40]. If such a period of inflation did occur, then all matter that was previously in good thermal equilibrium would be pushed out of causal contact after inflation finishes. In addition, any curvature the universe had prior to inflation

would be, in a sense, “washed out” after undergoing such an exponential expansion. These two results from such an inflationary period are consistent with what we observe today.

Another consequence of inflation is that any quantum fluctuations in the inflationary scalar field would be magnified. These magnified fluctuations provide the seeds for over- and under-densities in the early universe, guiding the formation of all structure in the universe, and are observable as the anisotropies we see in the CMB itself. Inflation also predicts the generation of tensor fluctuations in the metric known as inflationary (or primordial) gravitational waves. These gravitational waves provide a quadrupolar stretching and squeezing of space and are exponentially magnified relative to scalar fluctuations through inflation, imprinting their signature in the CMB polarization at the surface of last scattering and uniquely sourcing B-modes at large angular scales. Therefore, a detection of non-zero primordial B-modes would be a “smoking-gun” observation of inflationary gravitational waves, providing direct evidence for inflation!

A useful quantity to define is the ratio of the amplitude of tensor perturbations to scalar perturbations, referred to as the tensor-to-scalar-ratio r . A measurement of r is analogous to a measurement of the energy scale of inflation. Current best estimates place an upper limit of $r < 0.06$ [8].

1.4 Cosmic Polarization Rotation

As we saw in Section 1.2.4 cross-correlations between even- and odd-parity modes, C_ℓ^{TB} and C_ℓ^{EB} , are expected to be zero in the standard model. From Equation 1.11 and Equation 1.14 we see that any rotation of the Stokes Q and U parameters by angle α has the effect of “mixing” E-modes into B-modes (and vice versa). As any B-modes generated by this rotation are sourced directly from existing E-modes (which happen to be correlated with the CMB temperature modes), this rotation therefore has the potential to generate non-zero C_ℓ^{TB} and C_ℓ^{EB} correlations. Stated in other words, linearly polarized electromagnetic radiation is said to undergo Cosmic

Polarization Rotation (CPR) by angle α if the radiation’s polarization plane experiences a rotation as it traverses cosmological distances and has the effect of generating non-zero correlations between parity even and odd modes [63, 24]. A detection of non-zero CPR in our universe is synonymous with a detection of charge, parity, and time-reversal (CPT) violating physics that break away from our Lorentz-invariant standard model and would be a significant advancement in our understanding of fundamental physics.

The idea of CPR was first proposed in 1973 by Wei-Tou Ni in response to Leonard Schiff’s conjecture in 1960 that any theory of gravity that follows the weak equivalence principle (WEP) must also obey the Einstein equivalence principle (EEP) [83]. Ni found that coupling a pseudo-scalar field to electromagnetism and gravity generates a rotation of the polarization plane of electromagnetic radiation, resulting in a modified electromagnetic theory that obeys the WEP but manifestly violates parity and time-reversal invariance and also therefore the EEP [73].

While modern experiments have not yielded evidence for the existence of CPR in our universe (the results of which will be discussed in Section 1.4.3), this Lorentz-invariance violating “new” physics is poorly constrained due to large systematic uncertainties in the polarization angle calibration of each experiment. In the context of the search for CPR, a global misalignment of detectors by an angle α is exactly degenerate with a CPR angle of identical value [53]. While the current degree of uncertainty in polarization angle is not currently a limiting factor in searching for B-modes (discussed in more detail in Section 2.3.1), improving the polarization angle calibration methodology in modern CMB experiments is crucial for detection of CPR from Lorentz and parity violating physics that depart from the cosmological standard model.

1.4.1 Cosmic Birefringence from Modifications to Electrodynamics

In this section we follow the logic of Ni [73] and Carroll and Field [25] to modify the electromagnetic Maxwell Lagrangian by adding a Lorentz-invariance and CPT-symmetry violating Chern-Simons term and show how the polarization plane of electromagnetic radiation is

consequently rotated via CPR.

We begin with the standard electromagnetic Maxwell Lagrangian given by

$$\mathcal{L}_{EM} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta}, \quad (1.17)$$

where $F_{\alpha\beta}$ is the electromagnetic tensor $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$, with A_α being the electromagnetic four-vector potential. To this Lagrangian we add a Chern-Simons term given by

$$\mathcal{L}_{CS} = -\frac{1}{2}p_\alpha A_\beta \tilde{F}^{\alpha\beta}, \quad (1.18)$$

where $\tilde{F}^{\alpha\beta}$ is the dual electromagnetic tensor, $\tilde{\mathbf{F}}^{\alpha\beta} = \frac{1}{2}\epsilon^{\alpha\beta\mu\nu}\mathbf{F}_{\mu\nu}$, and p_α is a four-vector coupling to the electromagnetic field. It is the non-vanishing spatial components of p_α which violate rotational invariance, while the non-vanishing time component violates invariance under Lorentz boosts [25]. In other words, p_α creates a preferred directionality in the universe that violates both Lorentz-invariance and isotropy.

Adding the Chern-Simons term to the standard electromagnetic Lagrangian yields a modified version:

$$\mathcal{L} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} - \frac{1}{2}p_\alpha A_\beta \tilde{F}^{\alpha\beta}. \quad (1.19)$$

This modification has the effect of changing the usual four-current to $J^\beta \rightarrow J^\beta + p_\alpha \tilde{F}^{\alpha\beta}/4\pi$, resulting in a modified version of Maxwell's equations for electromagnetism given by

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho - \mathbf{p} \cdot \mathbf{B} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{J} - p_0\mathbf{B} + \mathbf{p} \times \mathbf{E}, \end{aligned} \quad (1.20)$$

which yields the original Maxwell's equations when $p_\alpha = 0$. Solving the resulting wave equations modifies the dispersion relation

$$\omega^2 - k^2 = \pm (p_0 k - \omega p \cos \theta) \left(1 - \frac{p^2 \sin^2 \theta}{\omega^2 - k^2} \right)^{-1/2}, \quad (1.21)$$

where $p_\alpha = (p_0, \vec{p})$, $p = |\vec{p}|$, and θ is the angle between $\vec{p}$ and the wave vector $\vec{k}$. Here, $+$ and $-$ represent right- and left-handed circular polarization respectively.

As $|p_\alpha|$ is expected to be small, we can Taylor expand this dispersion relation to get

$$k = \omega \mp \frac{1}{2} (p_0 - p \cos \theta). \quad (1.22)$$

The difference in propagation speeds of left- and right-handed circularly polarized light suggested by Equation 1.22 is equivalent to light traveling in a birefringent medium having differing indices of refraction in perpendicular directions. As such, CPR generated by the addition of a Chern-Simons term to the electromagnetic Lagrangian is often referred to as “cosmic birefringence”.

Assuming a dispersion relation given by Equation 1.22, optical electromagnetic radiation traveling a distance L generates a phase change ϕ in each circularly polarized mode given by $\phi = kL$. If we consider the difference in phase changes between the left- and right-handed circularly polarized modes $\Delta\phi$, we find that the polarization vector of the radiation is rotated by an angle α given by

$$\alpha \equiv \Delta\phi = \frac{1}{2} (\phi_L - \phi_R) = -\frac{1}{2} (p_0 - p \cos \theta) L, \quad (1.23)$$

where α is the CPR angle.

1.4.2 Faraday Rotation from Primordial Magnetic Fields

Another phenomenon that could generate non-zero cross-correlations in the CMB between even- and odd-parity modes, C_ℓ^{TB} and C_ℓ^{EB} , are magnetic fields embedded in the photon-baryon

plasma at the surface of last scattering. These magnetic fields, referred to as primordial magnetic fields (PMFs), are theorized to have been generated by inflation or by phase transitions in the early universe and could be the magnetic seed fields that source the currently unexplained microgauss level magnetic fields that have been observed in galaxies [95, 33].

Any photon that is scattered at the surface of last scattering in the presence of a magnetic field will have their polarization plane Faraday rotated by an angle $\alpha(\mathbf{n})$ given by [12]

$$\alpha(\mathbf{n}) = \frac{3c^2}{16\pi^2 e} \nu^{-2} \int \hat{\mathbf{t}} \cdot \mathbf{B} \cdot d\mathbf{l}, \quad (1.24)$$

where e is the electron charge, ν is the frequency of the photon, $\hat{\mathbf{t}}$ is the differential optical depth, $\mathbf{B}$ is the co-moving magnetic field, and $d\mathbf{l}$ is the co-moving length element along the photon trajectory. The consequence of this rotation is to mix E-modes into B-modes at the surface of last scattering, generating non-zero cross-correlations C_ℓ^{TB} and C_ℓ^{EB} .

While the CPR angle is additive if both PMFs and cosmic birefringence influence the CMB polarization, these two effects can be untangled from one another due to the strong frequency dependence of Faraday rotation in Equation 1.24. Therefore it is critical for modern CMB experiments to observe in multiple frequency bands in order to separate these two effects to be able to place reasonable constraints on the existence of PMFs or parity violating physics. Luckily, as was shown in Section 1.2.5, the next generation of CMB experiments such as the Simons Array (described later in Chapter 2) are already planning to observe in multiple bands in order to better untangle CMB B-mode signal from astrophysical foregrounds. As such, all that is needed then to place more stringent limits on CPR is improved accuracy on the calibration of detector polarization angles.

1.4.3 Astrophysical Constraints on CPR

From Equation 1.23 we see that the farther a photon travels before being observed, the larger any induced CPR angle α is. Thus, in order to place accurate limits on the amount of CPR that may exist in our universe from parity violating physics, we want to observe photons that were emitted with a known polarization angle at a great cosmological distance from us. Logically, then, ideal candidates to observe would be polarized radiation emitted from distant galaxies and, of course, the polarized CMB. Note that all observational constraints on α presented in this section follow the CMB sign convention discussed in [38].

Constraints From Distant Galaxies

Distant radio galaxies and quasars can emit polarized radiation due to synchrotron emission as charged particles orbit in the presence of magnetic fields [27]. If the alignment of these magnetic fields can be determined for these sources (expected to be either aligned with the elongated axis of the galaxy or perpendicular to it), the initial polarization plane of synchrotron emission can be inferred after correcting for Faraday rotation. Additionally, high redshift galaxies can emit polarized UV radiation perpendicular to their elongated axes as radiation from a quasar is scattered [15], giving another source of distant polarized radiation with a known emitted polarization angle. Any discrepancy between these initial polarization angles and what is observed could be evidence of an induced phase lag via CPR as radiation traverses the cosmological distance to us. Table 1.1 shows limits placed on the CPR angle α from measurements of such extra-Galactic polarized emission. While these measurements show rotation angles that are weakly consistent with a small positive value for α , systematic errors are still about an order of magnitude higher than desired for a more significant detection.

Table 1.1: Several radio and ultraviolet rotation angle measurements of polarized extra-Galactic sources, as shown in [29].

Frequency band	α [deg]	Redshift	Citation
Radio	0.6 ± 1.5	$\langle z \rangle = 0.78$	[24]
UV	1.4 ± 1.1	$z = 0.811$	[93]
UV	0.8 ± 2.2	$\langle z \rangle = 2.80$	[14]

Constraints From Measurements of the CMB

The polarized CMB is perhaps the most promising candidate to measure non-zero CPR from Lorentz and parity violating effects such as cosmic birefringence. As CMB photons have traveled the largest cosmological distance of any observable radiation in the universe they would have undergone the largest possible polarization angle rotation α if our universe were in fact birefringent. Between this realization and the potential existence of PMFs at the surface of last scattering, the CMB is an extremely sensitive probe of both parity violating physics and potential PMFs.

The spurious B-modes generated by the mixing of E-modes into B-modes by rotating the CMB by an angle α has the effect of leaking C_ℓ^{TE} to C_ℓ^{TB} and C_ℓ^{EE} to C_ℓ^{BB} as [63, 53]

$$\begin{aligned}
C_\ell'^{TT} &= C_\ell^{TT} \\
C_\ell'^{TE} &= C_\ell^{TE} \cos(2\alpha) \\
C_\ell'^{EE} &= C_\ell^{EE} \cos^2(2\alpha) + C_\ell^{BB} \sin^2(2\alpha) \\
C_\ell'^{BB} &= C_\ell^{EE} \sin^2(2\alpha) + C_\ell^{BB} \cos^2(2\alpha) \\
C_\ell'^{TB} &= C_\ell^{TE} \sin(2\alpha) \\
C_\ell'^{EB} &= \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB}) \sin(4\alpha),
\end{aligned} \tag{1.25}$$

where $C_\ell'^{XY}$ is the observed angular power spectra (with X and Y being combinations of T, E, and B), C_ℓ^{XY} is the theoretical non-rotated angular power spectra, and α is the applied rotation

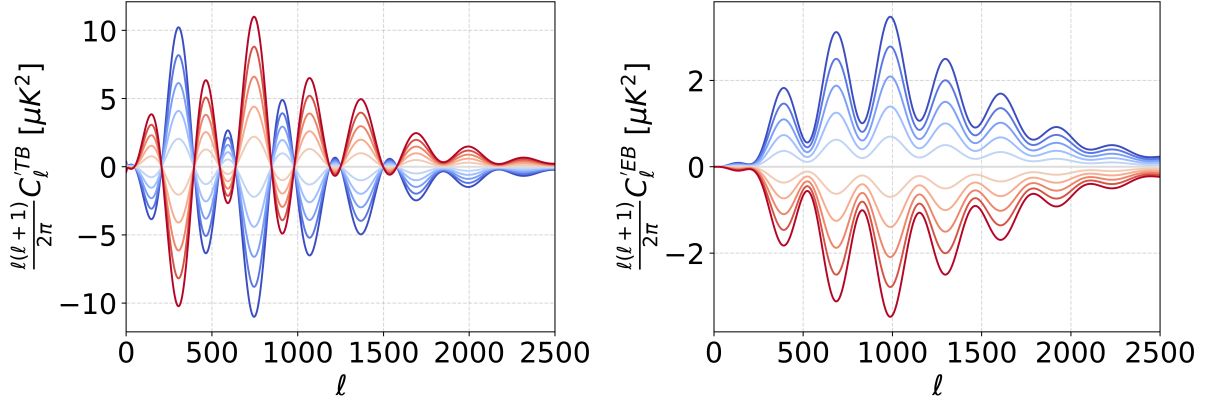


Figure 1.6: $C_\ell'^{TB}$ (left) and $C_\ell'^{EB}$ (right) power spectra after applying a -2.5° (darkest red) to $+2.5^\circ$ (darkest blue) polarization rotation to the primordial C_ℓ^{TB} and C_ℓ^{EB} power spectra in 0.5° steps. Note that C_ℓ^{TB} and C_ℓ^{EB} are both zero for $\alpha = 0$ as per the standard model. Power spectra are calculated using the CAMB package [60].

angle. An example of the rotated $C_\ell'^{TB}$ and $C_\ell'^{TE}$ power spectra for several values of α are shown in Fig. 1.6. It is important to note that these non-zero, rotated power spectra that are of cosmological origin are degenerate with a systematic misalignment of instrument detector orientation [28, 53, 72], which is the only instrumental systematic error that is capable of producing non-zero C_ℓ^{TB} and C_ℓ^{EB} with a common rotation angle [51, 70].

The spurious B-modes generated by this E-mode and B-mode mixing can also be quantified in terms of an equivalent tensor-to-scalar ratio r by comparing the magnitude of the rotated $C_\ell'^{BB}$ from Equation 1.25 to the theoretical standard model generated C_ℓ^{BB} at various r values. This comparison is shown in Figure 1.7 and shows that a CPR angle value of $\alpha = 0.5^\circ$ is equivalent to a value of C_ℓ^{BB} associated with an r value of $r = 0.001$ at large angular scales.

Many CMB experiments have used their measured C_ℓ^{TB} and C_ℓ^{EB} spectra to constrain a potential CPR angle α , with results and respective references shown in Table 1.2. A corresponding graphic depicting both the constraints from CMB measurements and distant galaxies is shown in Figure 1.8. Studies suggest that a joint analysis of the data sets yield no detection of a non-zero value for α as the large systematic uncertainties (of order 0.5° to 1.5°) dominate over statistical uncertainties [38, 61, 98]. In fact, so long as the systematic errors in these measurements remain

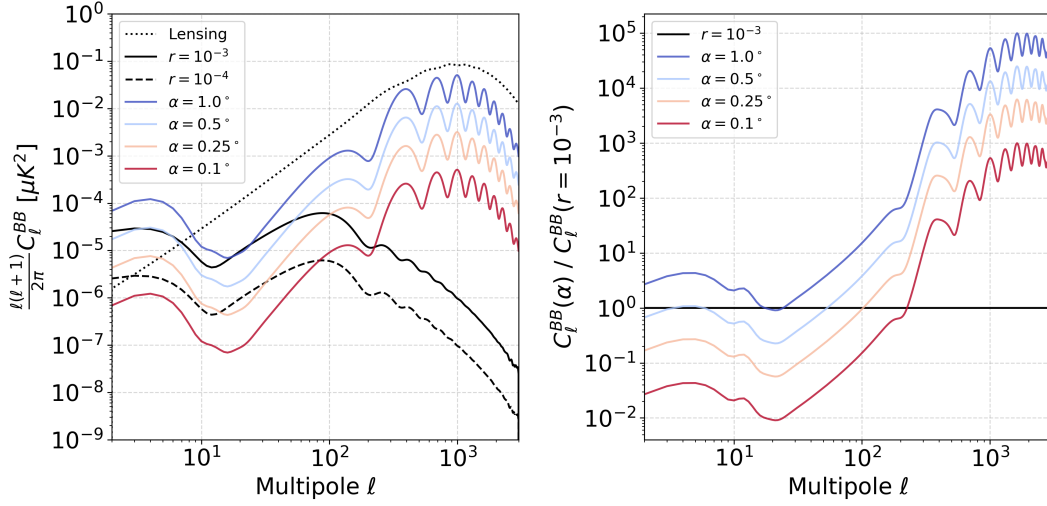


Figure 1.7: *Left:* Induced $C_\ell'^{BB}$ power spectrum from E-B mixing due to detector angle miscalibration or CPR angle α , shown for rotation angles of 0.1° to 1.0° (red to blue). Standard model primordial C_ℓ^{BB} is plotted at tensor-to-scalar ratios of $r = 10^{-3}$ (solid black) and $r = 10^{-4}$ (dashed black) along with the lensing C_ℓ^{BB} (dotted black). *Right:* E-B mixing from left panel normalized against C_ℓ^{BB} tensor-to-scalar ratio of $r = 10^{-3}$. Power spectra for lensing and primordial B-modes are calculated using the CAMB package [60].

larger than the statistical errors, it is fundamentally not possible to simply co-add these constraints to result in any meaningful detection of CPR [51].

It is clear that the level of systematic uncertainties involved with placing constraints on CPR from CMB measurements is too large for any meaningful search of Lorentz or parity violating physics in our universe. As these uncertainties are primarily dominated by detector polarization angle miscalibration, what is needed is an order of magnitude increase in the precision of existing polarization calibration methods. In addition to enabling searches of standard model breaking physics, driving down the systematic uncertainties associated with calibration errors in modern CMB experiments also enables us to place tighter upper limits on the tensor-to-scalar ratio r , increasing our sensitivity to the existence of primordial gravitational waves.

Table 1.2: Compendium of constraints on CPR angle α from several CMB experiments. Statistical uncertainties are listed after the measurement followed by systematic uncertainty in parenthesis (where available).

Experiment	ν [GHz]	α [deg]	Year	Citation
WMAP3	41 + 61+ 94	-2.5 ± 3	2007	[22]
WMAP5	41 + 61+ 94	-1.7 ± 2.1	2008	[56]
BOOMERanG	143	-4.3 ± 4.1	2009	[75]
QUaD	100 + 150	$0.64 \pm 0.5 (\pm 0.5)$	2009	[21]
WMAP7	41 + 61+ 94	$-1.1 \pm 1.4 (\pm 1.5)$	2010	[57]
QUIET	150	1.88 ± 1.15	2012	[61]
WMAP9	150	$-0.36 \pm 1.24 (\pm 1.5)$	2013	[44]
BICEP1 (<i>DSC</i>)	100 + 150	$-2.77 \pm 0.86 (\pm 1.3)$	2013	[52]
(<i>Wire grid far field</i>)	100 + 150	$-1.71 \pm 0.86 (\pm 1.3)$	2013	[52]
(<i>Wire grid near field</i>)	100 + 150	$-1.91 \pm 0.86 (\pm 1.3)$	2013	[52]
(<i>As designed</i>)	100 + 150	$-1.27 \pm 0.86 (\pm 1.3)$	2013	[52]
POLARBEAR	150	$-1.08 \pm 0.20 (\pm 0.5)$	2014	[10]
	150	-0.79 ± 0.16	2017	[11]
	150	-0.61 ± 0.22	2019	[3]
BICEP2	150	-1 ± 0.2	2014	[51]
ACTPol	146 GHz	0.2 ± 0.5	2014	[71]
Planck	30-857	$-0.31 \pm 0.05 (\pm 0.28)$	2016	[41]
ABS	145 GHz	-1.7 ± 1.6	2018	[58]
SPTpol	95 + 150 GHz	$0.63 \pm 0.04 (\pm 1)$	2018	[97, 26]

1.5 Outline of Thesis

The rest of this dissertation is organized as follows. Chapter 2 details the POLARBEAR-1 and Simons Array experiments, along with a few landmark POLARBEAR-1 published results. Chapter 3 covers how the POLARBEAR-1 and POLARBEAR-2a telescopes are polarization calibrated, along with preliminary Jupiter and Tau A maps made with POLARBEAR-2a for the purposes of detector beam and polarization angle characterization. The design and laboratory

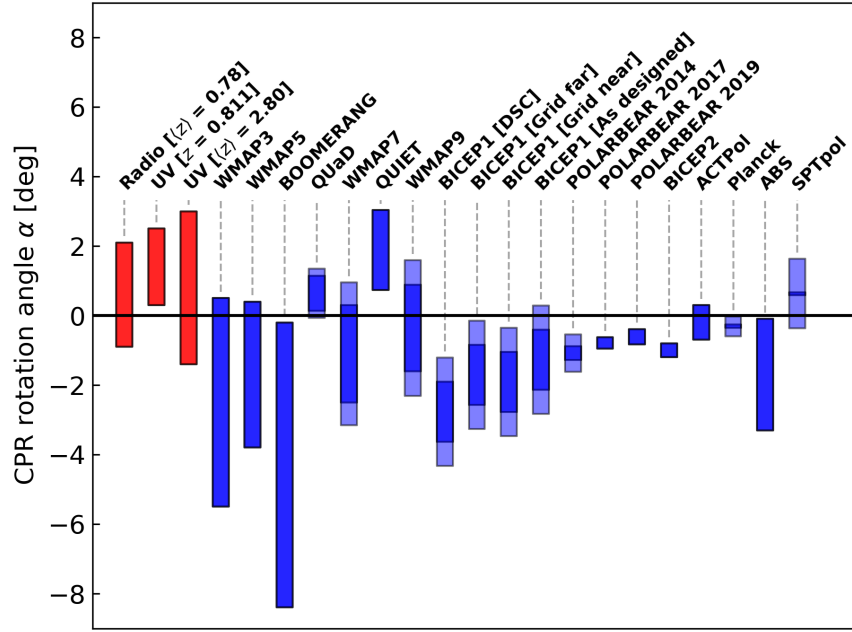


Figure 1.8: Compendium of constraints on CPR angle α from both radio and UV observations (red), as well as from CMB observations (blue). Statistical uncertainties are represented by solid bars while the quadrature sum of statistical and systematic uncertainties (where available) are represented by the entire solid plus shaded bars. Plotted data is from Table 1.1 and Table 1.2.

characterization of a novel ground-based absolute polarization calibrator for CMB experiments is described in Chapter 4, while Chapter 5 covers initial calibrator testing on both the POLARBEAR-1 telescope and the POLARBEAR-2b cryogenic receiver. Chapter 6 concludes this dissertation with a few summarizing remarks.

1.6 Acknowledgements

Figure 1.5 (top) has been submitted for publication of the material as it may appear in: S. Adachi, M.A.O.A. Faundez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, M.

Hasegawa, M. Hazumi, H. Hirose, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, S. Kikuchi, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, C. L. Reichardt, Y. Segawa, P. Siritanasak, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. “A measurement of the CMB E-mode angular power spectrum at subdegree scales from 670 square degrees of POLARBEAR data.” Submitted to The Astrophysical Journal. May 2020. The dissertation author made essential contributions to this work.

Chapter 2

POLARBEAR-1 and the Simons Array

POLARBEAR-1 and the Simons Array are CMB polarimetry experiments designed to measure both B-modes from gravitational lensing at small angular scales and primordial B-modes at large angular scales. Section 2.1 describes the qualifications of an ideal CMB observation site and the location chosen for these two experiments in the Chilean Atacama Desert. The science goals and resulting observation strategy for the POLARBEAR-1 experiment is discussed in section 2.2. The design of the POLARBEAR-1 experiment is detailed in Section 2.2 with major science results from its observation run between 2012 to 2016 presented in Section 2.3. The Simons Array is the successor experiment to POLARBEAR-1 with similar science goals but more sensitivity over additional frequency bands, and consists of three additional telescopes each housing one of three improved cryogenic receivers named POLARBEAR-2a, POLARBEAR-2b, and POLARBEAR-2c respectively. The specifications of this successor experiment and the deployment of the first receiver, POLARBEAR-2a, will be discussed in Section 2.4.

2.1 Chilean Observing Site at the James Ax Observatory

Determining the location for any ground-based telescope is heavily influenced by both its science goals and the intended observational frequency bands. CMB experiments observe

radiation in the sub-millimeter as the CMB blackbody spectrum peaks at a wavelength of ~ 2 mm, which unfortunately overlaps with the emission spectra of atmospheric water vapor. Thus, any water vapor in the atmosphere has the effect of degrading incoming CMB signal and increasing both loading and $1/f$ noise in detector timestreams.

Careful consideration in observation site can help mitigate the effects of this atmospheric contamination. For the case of CMB observations, an ideal observation site would be at very high altitude to minimize the atmospheric travel distance of incoming photons and have a very dry climate resulting in very low precipitable water vapor (PWV) to minimize the amount of water molecules present in the atmosphere. With these considerations in mind, POLARBEAR-1 was constructed at the James Ax Observatory on Cerro Toco in the Chilean Atacama Desert at an altitude of 17,000 ft (5200 m). The Atacama Desert is an ideal CMB observation site for several reasons. The mean PWV in the Atacama Desert is among the lowest in the world (< 1 mm on average) [62] making it the driest non-polar desert in the world [69]. Figure 2.1 depicts the atmospheric transmission versus frequency on Cerro Toco at various PWVs looking at zenith. The dips in transmission of the PWV emission spectra ultimately sets the band edges for broadband observations of the CMB and are generally avoided.

Located near the equator, the Atacama has access to roughly 80% of the sky which makes it an ideal location to not only target B-modes on large angular scales, but also to allow for significant opportunity for cross-correlation with other CMB experiments. Its proximity to the equator also allows for any patch of the sky to rotate relative to an observer on the ground over the course of a single day, providing an effective method for reducing systematics by observing the same patch of the sky at different parallactic angles. Additionally, its location in the Southern Hemisphere allows for less galactic foreground contamination compared to that of observations performed in the Northern Hemisphere. For similar reasons the Simons Array experiment [87] is also being constructed in the Atacama Desert, as is the upcoming Simons Observatory experiment [6] and potentially the CMB-S4 experiment [1].

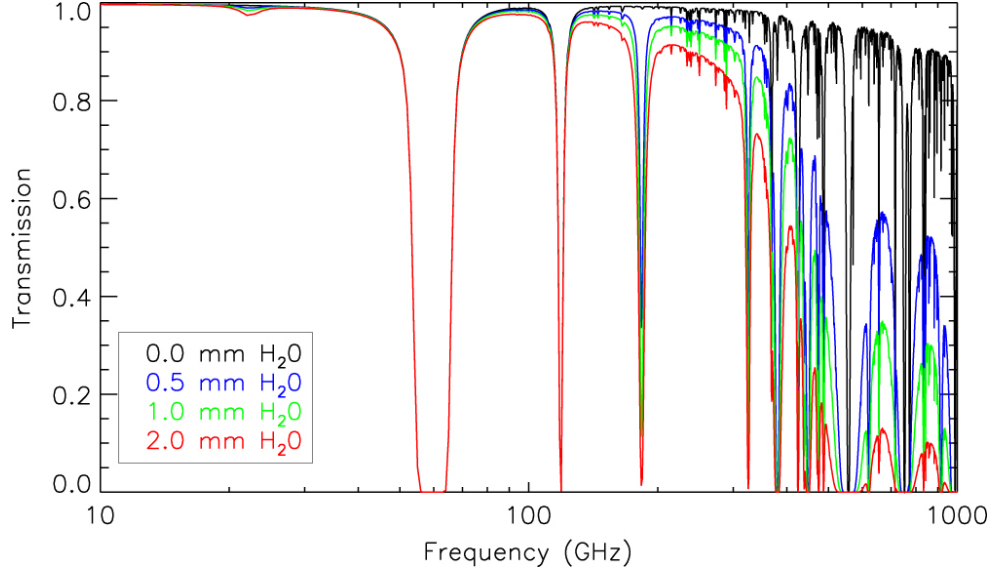


Figure 2.1: Atmospheric transmission at varying precipitable water vapor values as seen looking at zenith on Cerro Toco in the Chilean Atacama Desert, as generated by the *am* atmospheric model package [76]. Dips in transmission at 60/120/185/325/375 GHz drive the effective boundaries for CMB detector observation frequency windows and are generally avoided when designing detector observation bandwidths. Image from [36].

2.2 The POLARBEAR-1 Experiment

2.2.1 Science Goals and Scan Strategy

The primary science goals for the POLARBEAR-1 experiment are to measure both the gravitational lensing B-mode signal at arcminute angular scales ($\ell \sim 1000$) and the primordial gravitational wave B-mode signal at degree angular scales ($\ell \sim 100$), as described in Chapter 1. These two goals require different observing strategies and ultimately drive the overall design of the experiment.

To measure the gravitational lensing B-mode peak at small angular scales, POLARBEAR-1 observed ~ 30 square degrees over three patches of the sky called RA4.5, RA12, and RA23, each named corresponding to their approximate coordinate center in right ascension (RA). The three patch locations, shown in Figure 2.2, were chosen to minimize foreground contamination (locations distant from the galactic plane), to maximize observing time as seen from the observing

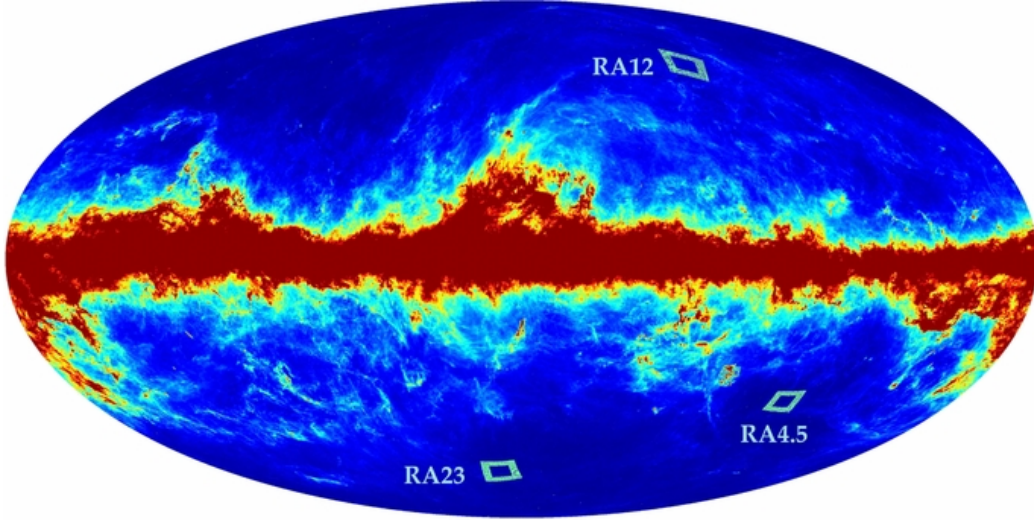


Figure 2.2: The POLARBEAR-1 observation patches overlaid on the full-sky 857 GHz intensity map generated by Planck [7]. Patches were chosen for low dust emission, overlap with other observations, and to allow nearly continuous CMB observations from the James Ax Observatory in Chile. Image from [10].

site in the Atacama Desert, and to provide significant overlap with existing data from other CMB experiments. Results from the sub-degree measurement of the B-mode power spectrum from observations of these patches are detailed in Section 2.3.1. To target the degree scale B-modes from primordial gravitational waves, a 670 square degree patch of the sky centered on $(RA, DEC)=(+0^h 12^m 0^s, -59^\circ 18')$, with significant overlap with experimental data from BICEP, the Keck Array, and SPTPOL, was observed with results similarly discussed in Section 2.3.1.

POLARBEAR-1 employs a series of constant elevation scans (CESs) to measure each of the sky patches. During a CES, the telescope is slewed to a particular elevation and scans back in forth in azimuth while the sky patch rotates into, and then out of, the telescope field of view. For the patches shown in Figure 2.2 this process takes about 15 minutes to measure an entire patch. This CES method has several motivations to mitigate systematic effects when measuring a patch. As the amount of atmosphere in the direction of the telescope line of sight is a function of elevation, observing at a constant elevation ensures equal atmospheric loading on all detectors throughout an observation. A number of other systematics and thermal loading, such

as variable cooling power of the cryogenic refrigerators described in Section 2.2.3, are also a function of elevation and mitigated employing a CES strategy. Additionally, as fluctuations in the atmosphere generally occur on time scales shorter than the duration of a single left or right going CES subscan, atmospheric noise becomes uncorrelated at a particular azimuth as the telescope is scanned back and forth as opposed to that of an observation strategy that remains at relatively constant azimuth.

2.2.2 Huan Tran Telescope

The POLARBEAR-1 cryogenic receiver is housed by the Huan Tran Telescope (HTT), which employs an off-axis Gregorian Dragone design and a 2.5-meter monolithic aluminum primary mirror as pictured in Figure 2.3. The secondary mirror is designed and placed such that the Mizuguchi-Dragone condition is satisfied, which minimizes the level of cross-polarization and astigmatism induced by the off-axis elements [31, 90]. The primary and secondary mirror coupled to the optical elements in the receiver provides a large diffraction-limited field of view of ~ 2.3 degrees. With a 2.5-meter primary mirror the resolution of the telescope at 150 GHz is 3.5 arcminutes at full-width half-maximum (FWHM), allowing probes of C_ℓ^{BB} up to multipoles of $\ell \sim 2500$ and sufficient measurement of the gravitational lensing peak at $\ell \sim 1000$. A primary guard ring surrounds the primary mirror to reduce sidelobe response in the detectors while a co-moving shield blocks out signal from the ground and far sidelobes. A ray-tracing of the optical path of light within HTT is also shown in Figure 2.3.

2.2.3 Cryogenic Receiver and Optics

The POLARBEAR-1 cryogenic receiver consists of a backend housing the focal plane, cold detector readout, and cooling refrigerators coupled to an optics tube consisting of a vacuum window, rotating half-wave plate, IR blocking filters, and three re-imaging lenses. This backend

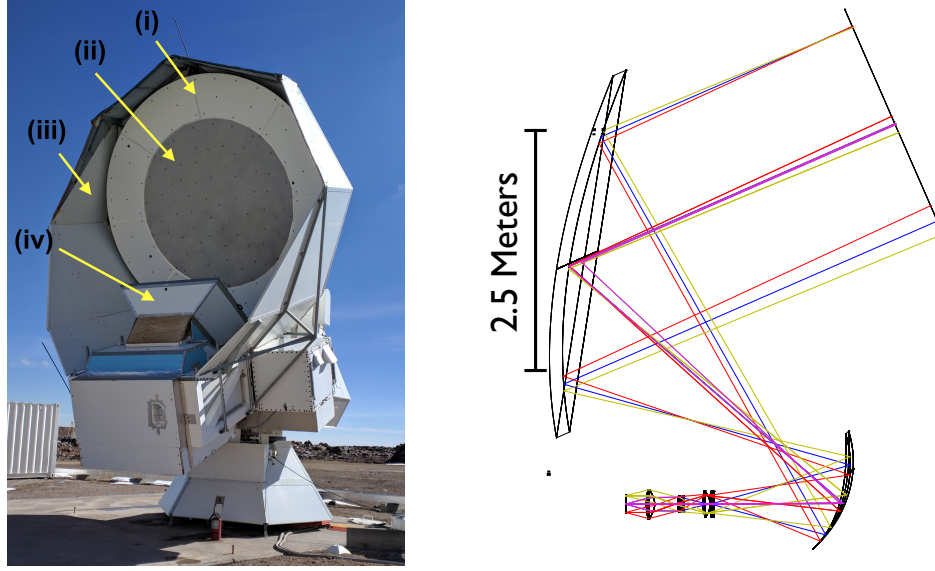


Figure 2.3: *Left:* The Huan Tran Telescope housing the POLARBEAR-1 receiver on the Cerro Toco plateau in the Chilean Atacama Desert. Labelled in this photo are the (i) primary guard ring, (ii) monolithic aluminum primary mirror, (iii) co-moving shield, and (iv) prime-focus baffle. The secondary mirror rests just inside of (iv). *Right:* Ray-tracing of the path light takes through the telescope optics. The cold re-imaging optics transform the focus created by the primary and secondary mirror to a flat, tele-centric focal plane. Images from [54].

plus optics tube configuration is shown in Figure 2.4.

The focal plane consists of 1,274 transition edge sensor (TES) bolometers coupled to double-slot dipole antennas distributed across seven silicon wafers. Two TES bolometers reside in a single pixel and are each connected to a double-slot dipole antenna that is sensitive to orthogonal linear polarizations with respect to one another. Each pixel is coupled to an anti-reflection coated hemispherical silicon¹ lenslet that re-focuses incoming light onto the antennas. Images of the fully assembled focal plane tower and individual TES bolometers are shown in Figure 2.5. Each TES bolometer is coupled to microstrip transmission lines with on-chip filters that create bandpass filters centered at 148 GHz with bandwidths of 38 GHz [54], as dictated by the atmospheric transmission windows depicted in Figure 2.1.

A series of frequency domain multiplexed superconducting quantum interference device

¹ All lenslets are made of silicon, except the wafer with white appearing lenslets in Figure 2.5 which are made from alumina.

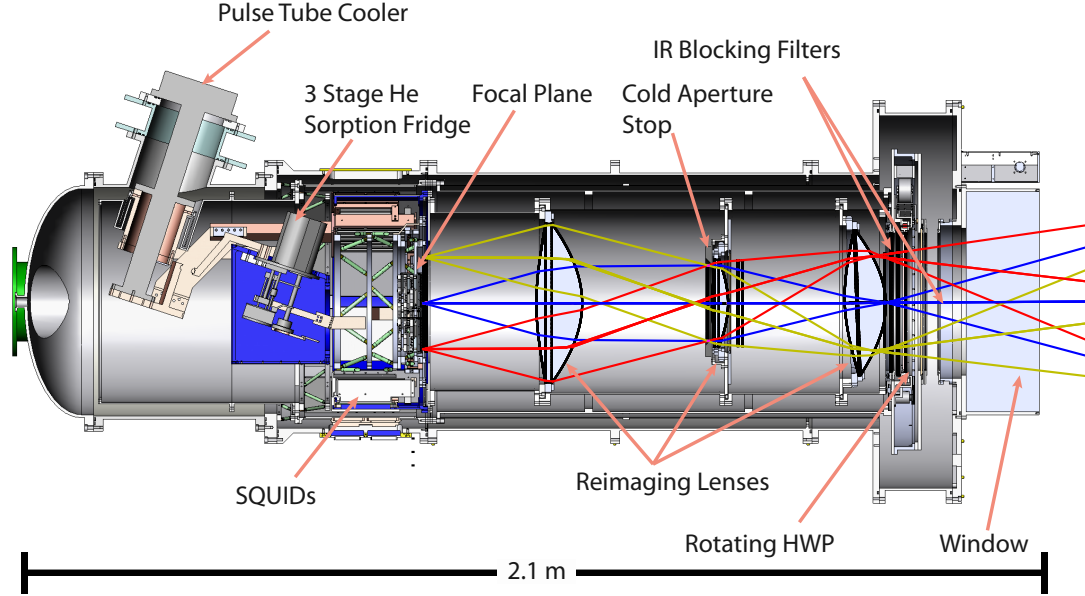


Figure 2.4: A cross-section CAD drawing of the POLARBEAR-1 receiver. Light enters from the right and passes through a series of IR blocking filters, a cold stepped rotating half-wave plate, a cold aperture stop, and several re-imaging lenses until it finally arrives at the focal plane. Image from [54].

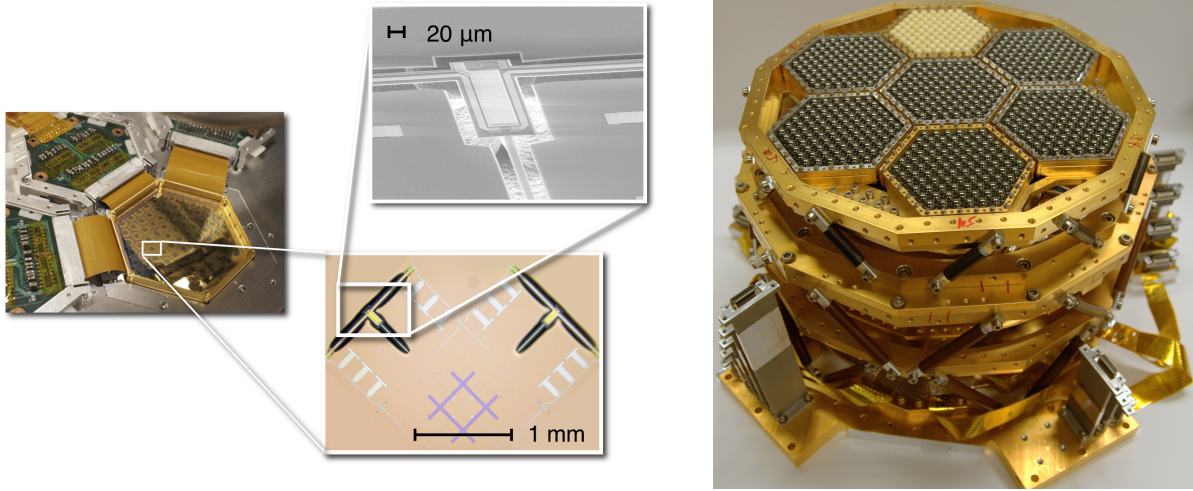


Figure 2.5: *Left:* The left image in this diagram is the back side of a POLARBEAR-1 wafer module. The bottom right image shows a zoom in of one of the pixels that contains two double-slot dipole antennas coupled to two bolometers. The top right image depicts an SEM close up of a single bolometer island. *Right:* The fully assembled POLARBEAR-1 focal plane, consisting of seven wafers as depicted in the left image. Each pixel consists of two bolometers as shown on the left coupled to double-slot dipole antennas and re-imaging silicon lenslets. All images in this figure are from [54].

(SQUID) amplifiers are used to read out the 1,274 TES bolometers on the focal plane. SQUIDs are extremely sensitive magnetometers and are ideal candidates to read out the extremely small electric currents induced by fluctuating optical power that pass through a bolometer. Each wire that connects between warm read out electronics and the cold focal plane increases the thermal loading on the focal plane and requires additional cooling power from cryogenic refrigerators. To minimize the thermal load induced by these read out wires, a multiplexing scheme is used in POLARBEAR-1 that allows for 8 TES bolometers to be read out simultaneously through a single wire. An LC filter in series with each TES bolometer designates a unique resonance frequency to each bolometer, which is used to communicate with the warm read out electronics via a comb of frequencies passed to the multiplexed bolometers. The spacing in resonant frequencies between adjacent channels on an 8 TES bolometer multiplexed comb are chosen to be logarithmically spaced within the bandwidth of the warm read out electronics in order to minimize electrical crosstalk between detectors [85].

Cryogenic cooling of the POLARBEAR-1 receiver is achieved through the use of two refrigerators. The first is a pulse tube cooler that provides continuous cooling to both the 50 K and 4 K stages within the receiver. The 50 K stage is the intermediate aluminum shell within the receiver and is thermally coupled to the cold half-wave plate (CHWP) and the IR blocking filter stack as shown in Figure 2.4. The 4 K stage consists of the inner-most aluminum shell and is thermally connected to the re-imaging lenses, cold aperture stop, focal plane, and SQUID amplifier read out. Cooling the lenses is necessary to reduce the amount of optical loading on the focal plane from thermal emission of the lenses themselves, while cooling the SQUIDs is necessary for operation at superconducting temperatures. The second source of cooling power in the receiver is a three-stage $^3\text{He}/^4\text{He}$ adsorption refrigerator mounted on the 4 K focal plane assembly that provides cooling of the focal plane down to 250 mK for up to 30 hours. It is important to operate CMB detectors at very low temperatures to keep the Johnson noise, which increases with the square root of temperature, sub-dominant to the inherent noise in the individual

arrival time of photons themselves called the “photon noise.”

The optics tube shown in Figure 2.4 houses the required optical elements within the receiver. The first optical element incoming light passes through (excepting the microwave-transparent 30 cm Zotefoam window) is a CHWP mounted to the 50 K shell that can be rotated in quantized steps. Rotation of the CHWP provides modulation of incoming polarized radiation and allows for separation of polarized CMB light from un-polarized atmosphere and polarized emission originating from optical elements beyond the CHWP. Light then passes through a series of IR blocking filters that act as low-pass filters to reject radiation at higher frequencies that would otherwise increase optical thermal loading on the focal plane. Three re-imaging lenses and hemispherical lenslets then re-focus incoming light onto each pixel on the focal plane. Each optical element within the receiver is anti-reflection coated to both increase overall optical efficiency and mitigate stray reflections that might contribute systematic effects in detector timestreams. In 2014 a warm continuously rotating half-wave plate (CRHWP) was installed at the prime focus of the HTT providing continuous polarization modulation at frequencies above the $1/f$ low frequency noise in order to allow the POLARBEAR-1 experiment to target large angular scale B-modes [89].

2.3 Significant POLARBEAR-1 Science Results

2.3.1 Degree and Sub-degree Angular Scale B-modes

The two primary science goals for the POLARBEAR-1 experiment was to measure the gravitational lensing B-mode power spectrum at small angular scales and to measure the primordial B-mode power spectrum at large angular scales. The POLARBEAR-1 collaboration published a measurement of the B-mode power spectrum at sub-degree scales (gravitational lensing) in 2017 [11] and at degree-scales (primordial peak) in 2019 [3].

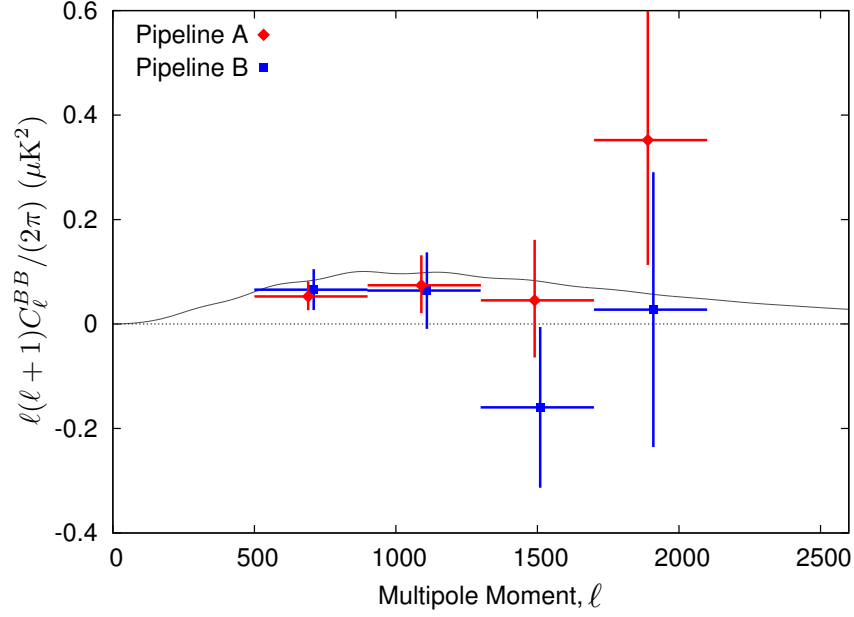


Figure 2.6: The measured POLARBEAR-1 B-mode power spectrum at sub-degree scales from the first two seasons of observations. The results from two parallel analysis pipelines A (red) and B (blue) are plotting along with the standard model C_ℓ^{BB} theory. Image from [11].

Sub-degree Angular Scale B-mode Measurement

POLARBEAR-1 observed the three sky patches in Figure 2.2 for two seasons between 2012 and 2014, resulting in $\sim 4,700$ hours of observations after data cuts, culminating in a measurement of the B-mode power spectrum at sub-degree angular scales as shown in Figure 2.6. The data rejects the null hypothesis of $C_\ell^{BB} = 0$ at 3.1σ . Two analysis pipelines were considered for the measurement in Figure 2.6, deemed pipeline “A” and “B”. Each pipeline implements a slightly different map making and power spectrum estimation procedure allowing for consistency checks and improved control over systematic errors. A more detailed account on the analysis pipeline and data processing for this published result can be found in [11].

The systematic uncertainties associated with the sub-degree angular scale B-mode measurement in Figure 2.6 is much less than the statistical uncertainty as shown in Figure 2.7. For the purposes of constraining the tensor-to-scalar ratio r and measuring the B-mode polarization signal it is clear that systematic uncertainties are sub-dominant to the statistical uncertainty of

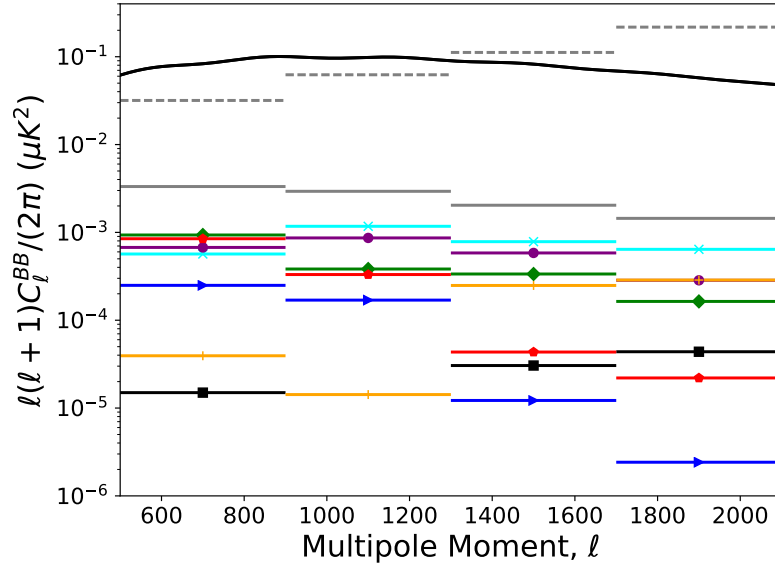


Figure 2.7: Estimated levels or upper bounds on instrumental systematic uncertainties in the four bins of the C_{ℓ}^{BB} power spectrum measurement from Figure 2.6. Individual effects (solid colors) and their combination (solid horizontal gray line) are displayed: combined uncertainty in instrument polarization angle and relative pixel polarization angles after self-calibration (purple circle), combined uncertainty in instrument boresight pointing model and differential pointing between the two detectors in a pixel (cyan cross), the drift of the gains between two consecutive thermal source calibrator measurements (red star), relative gain-calibration uncertainty between the two detectors in a pixel (green diamond), crosstalk in the multiplexed readout (blue arrow), differential beam shape (orange plus), and differential beam ellipticity (black square). For comparison, the binned statistical uncertainty from pipeline A (dashed horizontal line) is also shown, with standard model C_{ℓ}^{BB} plotted as the solid black line. Image and caption from [11].

the measurement. In the context of searching for Lorentz and parity violating physics in the CMB polarization power spectra, the fact that the polarization calibration uncertainty is nearly the dominant systematic, as shown in Figure 2.7, is worrisome. So long as the angle of rotation needed to force measured C_ℓ^{TB} and C_ℓ^{EB} correlations to be zero is of similar magnitude to that of the polarization angle uncertainty, no significant detection of physics departing from the standard model can be claimed.

Degree Angular Scale B-mode Measurement

POLARBEAR-1 measurements targeting the primordial gravitational wave B-mode signal on large angular scales took place between 2014 and 2016 after the addition of the CRHWP at the prime focus of the telescope [89]. The modulation provided by the CRHWP rotating at 2 Hz separated polarized CMB signal from large $1/f$ noise and allowed for measurements down to multipoles of $\ell \sim 50$. As mentioned in Section 2.2.1, the observation strategy consisted of measuring a 670 square degree patch of the sky with significant overlap of maps made from experiments at the south pole and employing a series of CESs at various elevation angles. The resulting B-mode power spectra measured between $\ell \sim 50$ to $\ell \sim 600$ from these three seasons of observations is shown in Figure 2.8. This measurement rejects the null $C_\ell^{BB} = 0$ hypothesis at 2.2σ and places a 95% confidence level upper limit on the tensor-to-scalar ratio of $r < 0.90$ [3].

The total uncertainty associated with the data reported in Figure 2.8 is dominated by statistical noise, with the largest systematic error being the uncertainty in the ground structure subtraction as shown in Figure 2.9. It is clear that the uncertainty in polarization angle calibration is far from being the dominant systematic in measuring the degree scale B-mode power spectrum in this measurement. However, as the next generation of CMB experiments place tighter constraints on the tensor-to-scalar ratio r , it will soon be a limiting factor as seen in Figure 1.7. The uncertainty in polarization angle calibration reported here is certainly too large to place meaningful constraints on Lorentz and parity violating physics as can be seen by the POLARBEAR-1 measurement

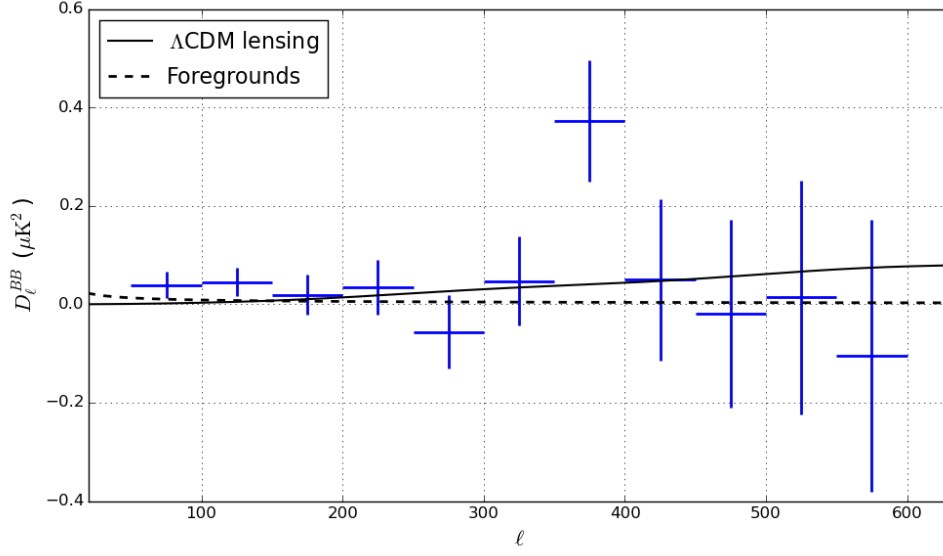


Figure 2.8: The B-mode power spectrum measured at degree scales with the POLARBEAR-1 experiment from the third to fifth seasons of observation. The solid (dashed) black line represents the best-fit cosmological (foreground) model. Image from [3].

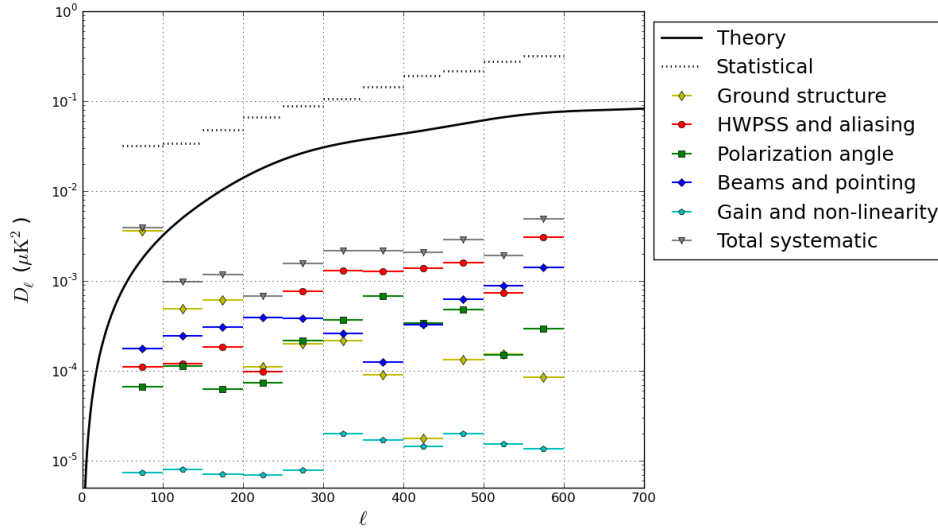


Figure 2.9: Systematic contributions to the B-mode power spectra as reported in 2.8. The dominant error in the B-mode power spectrum is the uncertainty in the ground structure subtraction. Statistical error is shown by the dotted black lines for each bin and is the dominant source of uncertainty in this measurement. Image from [3].

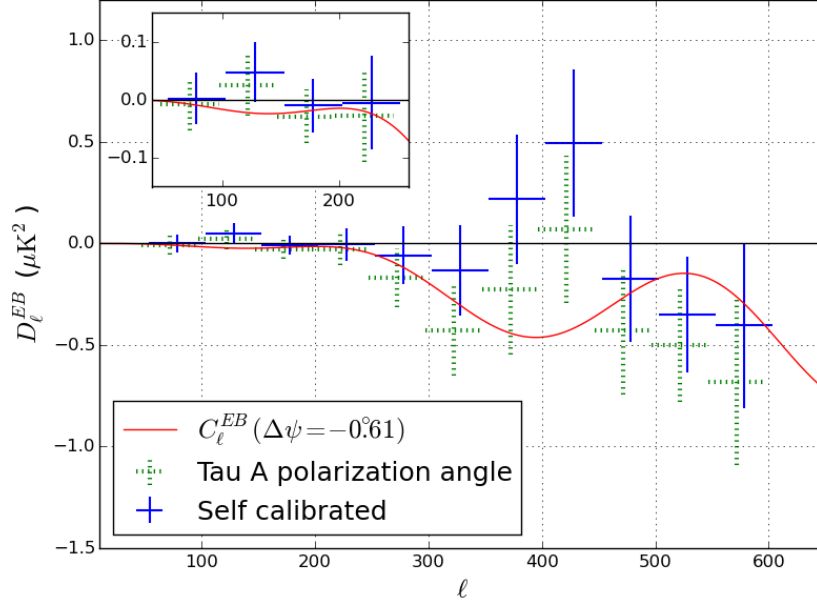


Figure 2.10: The EB power spectrum as measured by the POLARBEAR-1 experiment after applying an angle rotation from calibration to Tau A (green) and then from self-calibration [53] (blue). After self-calibration, the measured EB power spectrum is consistent with null. The C_ℓ^{EB} theory spectrum after applying a -0.61 degree rotation is shown in red. Image from [3].

of C_ℓ^{EB} shown in Figure 2.10. At a glance POLARBEAR-1 appears to measure a non-zero C_ℓ^{EB} power spectrum and is suggestive of a non-zero CPR measurement. Even when polarization angle calibration using Tau A is performed, the “corrected” C_ℓ^{EB} spectrum is consistent with a rotation angle α equal to $\alpha = -0.61^\circ \pm 0.22^\circ$. However, as the polarization angle systematic error from calibration to Tau A is of order ~ 1 degree, the -0.61 degree rotation is assumed to be an overall instrument polarization angle miscalibration and not the result of CPR. As such, the C_ℓ^{EB} spectrum is corrected to be zero by rotating the power spectrum by this assumed global miscalibration in what is called self-calibration [53]. Detector polarization angle calibration using measurements of Tau A will be discussed in Chapter 3.

As current CMB experiment measurements show that the uncertainty in polarization angle calibration is on par with the levels of observed non-zero C_ℓ^{EB} , it appears that we are on the cusp of possessing the capacity to probe Lorentz and parity violating physics from observations of

the polarized CMB. Combined with the ever decreasing upper limit on r , it is clear that a more accurate polarization angle calibration methodology is required for the next generation of CMB experiments.

2.3.2 Constraints on Cosmic Birefringence and Equivalent Primordial Magnetic Field Strength

It was shown in Section 1.4.1 that cosmic birefringence could arise in our universe if photons were coupled to some pseudo-scalar field p_α (from Equation 1.18). This coupling produces Lorentz and parity violating non-zero TB and EB correlations not predicted by the standard model, but only if the spatial average of the scalar field $\langle p_\alpha \rangle$ is not zero. Whether the value of $\langle p_\alpha \rangle$ is zero or non-zero, any fluctuations in the pseudo-scalar field generates a spatially varying cosmic birefringence, causing the CPR angle α to become a function of observation direction $\mathbf{n}$. This “anisotropic cosmic birefringence” generates spurious B-modes and creates non-trivial four-point correlations between E- and B-modes with angular dependence characterized by a rotation power spectrum $C_L^{\alpha\alpha}$, and can be described by an equivalent PMF Faraday rotation $\alpha(\mathbf{n})$ given by Equation 1.24.

To obtain an expression for the rotation power spectrum $C_L^{\alpha\alpha}$, we follow the logic in [12, 39]. The effect of anisotropic cosmic birefringence is to add a phase factor $e^{\pm 2i\alpha(\mathbf{n})}$ to the CMB polarization, transforming the Stokes Q and U parameters in Equation 1.12 to

$$Q(\mathbf{n}) \pm iU(\mathbf{n}) = (\tilde{Q}(\mathbf{n}) \pm i\tilde{U}(\mathbf{n}))e^{\pm 2i\alpha(\mathbf{n})}, \quad (2.1)$$

where $\tilde{Q}$ and $\tilde{U}$ are the theoretical CMB polarization maps, and Q and U are the observed Stokes parameters. This expression is rotation invariant and can be decomposed into E- and B-modes as

$$[E \pm iB](\ell) = \int d\mathbf{n} [Q(\mathbf{n}) \pm iU(\mathbf{n})] e^{\mp 2i\phi_1} e^{-i\ell \cdot \mathbf{n}}, \quad (2.2)$$

where ϕ_1 is the angular separation between $\mathbf{n}$ and $\boldsymbol{\ell}$. A Taylor expansion of this expression reveals that the off-diagonal elements of the two-point correlation functions of E- and B-modes are proportional to the rotation field $\alpha(\mathbf{n})$. The CMB polarization quadratic estimator is then

$$\alpha_{EB}(\mathbf{L}) = A_{EB}(L) \int \frac{d^2\boldsymbol{\ell}}{(2\pi)^2} E(\boldsymbol{\ell}) B(\boldsymbol{\ell}') \frac{2\tilde{C}_\ell^{EE} \cos 2\phi_{\ell\ell'}}{C_\ell^{EE} C_{\ell'}^{BB}}, \quad (2.3)$$

where $\mathbf{L} = \boldsymbol{\ell} + \boldsymbol{\ell}'$, $\phi_{\ell\ell'}$ is the angular separation between $\boldsymbol{\ell}$ and $\boldsymbol{\ell}'$, $\tilde{C}_\ell^{EE}$ is the theoretical, un-rotated primordial EE power spectrum, C_ℓ^{EE} and C_ℓ^{BB} are the measured EE and BB power spectra, and $A_{EB}(L)$ is a normalization factor. Analogous to Equation 1.15, we then derive the rotation power spectrum $C_L^{\alpha\alpha}$ from the four-point correlation of E and B from [12]

$$\langle \alpha_{EB}(\mathbf{L}) \alpha_{EB}^*(\mathbf{L}') \rangle = (2\pi)^2 \delta(\mathbf{L} - \mathbf{L}') \left(C_L^{\alpha\alpha} + N_{EB}^{(0)}(L) + \text{higher-order terms} \right), \quad (2.4)$$

where $N^{(0)}$ is the Gaussian contribution to the four-point function.

POLARBEAR-1 placed the first ground-based constraints on the anisotropic cosmic birefringence and equivalent PMFs at sub-degree angular scales in 2015 [12]. The rotation power spectrum $C_L^{\alpha\alpha}$ from POLARBEAR-1's first observing season is shown in Figure 2.11, which shows no detection of any anisotropic rotation signal as the coadded data is consistent with zero. A dimensionless amplitude parameter A_{CB} of the measured rotation power spectrum can be defined in relation to a reference scale-invariant spectrum with amplitude 10^{-4} rad^2 (0.44 deg^2). The POLARBEAR-1 upper limit set on A_{CB} from its first season of observations is $A_{CB} < 3.1$ at 95% confidence, which translates to an equivalent PMF strength on 1 Mpc scales of $B_{1\text{Mpc}} < 93 \text{ nG}$.

In addition to the constraints placed on anisotropic cosmic birefringence and PMFs from four-point correlations in the first season of POLARBEAR-1 observations, similar constraints can be placed from the two-point correlation C_ℓ^{BB} . PMFs can generate B-mode polarization and contribute to C_ℓ^{BB} as the stress energy in the PMF sources vector and tensor perturbations in the

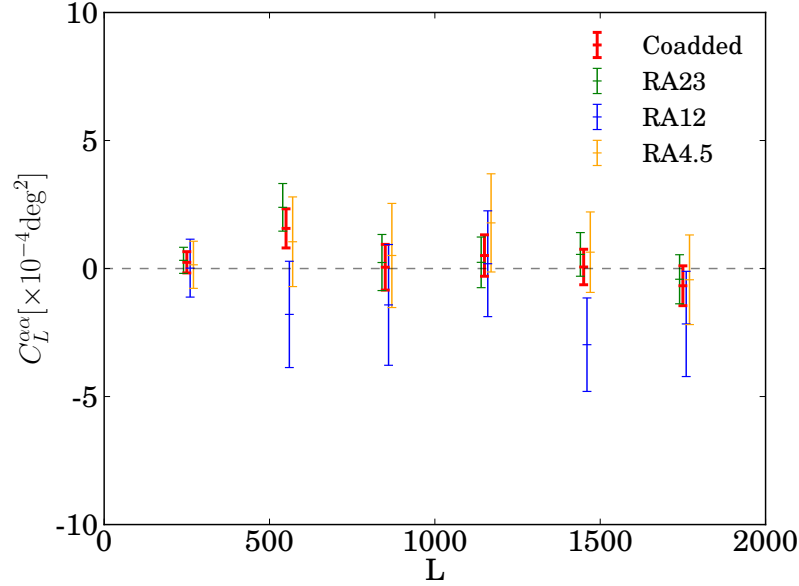


Figure 2.11: The anisotropic cosmic rotation power spectra as measured from the first season of POLARBEAR-1 observations. First season data observed three sky patches: RA23 (green), RA12 (blue), and RA4.5 (yellow) as defined in Figure 2.2. The coadded power spectrum from the three patches (red) is consistent with zero. Figure is from [12].

metric [59]. Using the measured C_ℓ^{BB} power spectrum, upper limits on PMF strength can be placed using the fact that the PMF induced B-mode power spectrum is characterized by three parameters: $B_{1\text{Mpc}}$, the relative scale factor between the epoch of neutrino decoupling and PMF generation $\beta = \ln(a_\nu/a_{\text{PMF}})$, and the spectral index n . POLARBEAR-1 places an upper limit on the PMF strength on 1 Mpc scales from two-point correlations of $B_{1\text{Mpc}} < 3.9 \text{ nG}$ to 95% confidence levels as shown in Figure 2.12.

2.4 POLARBEAR-2 and the Simons Array

Many CMB experiments, including POLARBEAR-1, operate detectors such that the photon noise is the dominant source of noise in a measurement. In this case, the photon noise dictates a fundamental lower limit on the noise levels CMB detectors can achieve. A consequence of operating detectors in this regime is that the only way to increase sensitivity to CMB B-mode

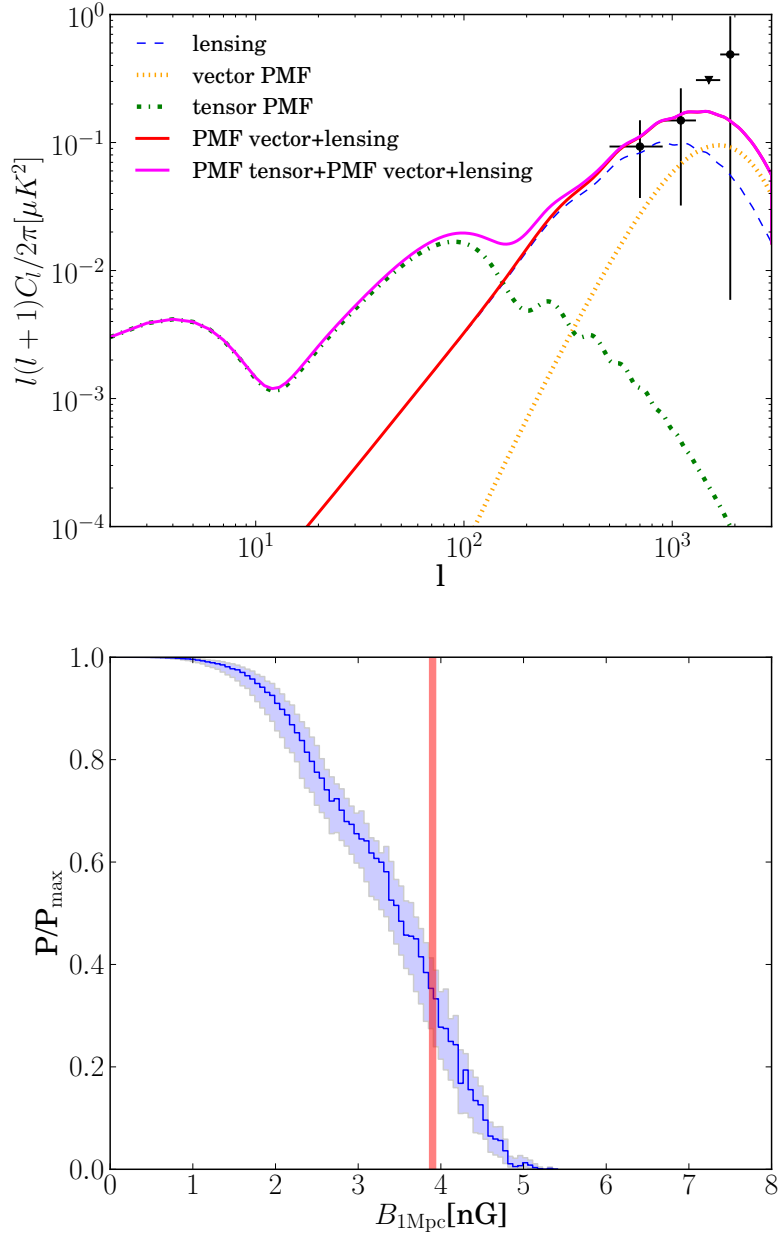


Figure 2.12: *Top:* The B-mode polarization power spectrum sourced by a scale-invariant PMF. The passive tensor and compensated vector modes generated by PMFs are shown in green and orange respectively. The gravitational lensing B-mode signal is shown in blue. The red curve shows the sum of lensing plus vector B-modes while the magenta curve shows the sum of all three components. The PMF signal shown here assumes $B_{1Mpc} = 2.5$ nG, $n = -2.9$, and $a_v/a_{PMF} = 10^9$. Data points from the POLARBEAR-1 first season B-mode power spectrum are also shown. *Bottom:* The posterior distribution function of amplitude B_{1Mpc} for PMFs using the POLARBEAR first season C_ℓ^{BB} measurement. The red line indicates the 95% confidence level upper limit at $B_{1Mpc} < 3.9$ nG. Shaded blue areas represent systematic effects. Both images from [12].



Figure 2.13: Photo of the three telescopes that comprise the Simons Array. The left telescope houses the POLARBEAR-2a receiver and is currently operable. The right telescope will soon house the POLARBEAR-2b receiver, while the center telescope is the original HTT housing the POLARBEAR-1 receiver and will eventually be retrofitted for the POLARBEAR-2c receiver. Photo courtesy of Praween Siritanasak.

polarization signals is to either observe the CMB for a longer period of time or with more detectors.

The Simons Array is the successor experiment to the POLARBEAR-1 experiment that achieves greater sensitivity and CMB map depth with the implementation of an order of magnitude increase in the number of detectors compared to that of POLARBEAR-1. This is achieved through the use of three cryogenic receivers, called POLARBEAR-2a, POLARBEAR-2b, and POLARBEAR-2c respectively, mounted on three separate telescopes based on the HTT design, as pictured in Figure 2.13. Additionally, the Simons Array observes the CMB in several frequency bands allowing for better separation of CMB signal and contaminating foregrounds, as well as allowing for the search of Lorentz and parity violating physics from effects like CPR and PMFs as described in Section 1.4. Specifically POLARBEAR-2a and POLARBEAR-2b will observe the sky in dual frequency bands centered at 90 GHz and 150 GHz, while POLARBEAR-2c will observe in frequency bands centered on 220 GHz and 270 GHz. The science goals of the Simons

Array are similar to that of the POLARBEAR-1 experiment: aiming to place tighter constraints on the gravitational lensing B-mode signal at small angular scales and the primordial gravitational wave B-mode signal at large angular scales (and thus also placing tighter constraints on the tensor-to-scalar ratio r). The multi-chroic capability of the Simons Array receivers also allows for tighter constraints to be placed on the sum of the neutrino masses as well as on the effects of any potential Lorentz and parity violating physics in our universe. The design of the new generation of POLARBEAR-2 receivers that will be capable of achieving these desired science goals is described in the following sections.

The POLARBEAR-2a receiver was characterized at The High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan and deployed to the Chilean Atacama plateau observation site and installed on one of the telescopes in October 2018. Data analyzed by the author from the deployment of POLARBEAR-2a is detailed in Chapter 3, and details about deployment of the receiver and first light can be found in [50].

2.4.1 POLARBEAR-2a, -2b, and -2c Cryogenic Receivers

The overall design of the three POLARBEAR-2 receivers, pictured in Figure 2.14, is similar to that of the POLARBEAR-1 receiver described in Section 2.2.3 with a few notable differences. The most important difference to enable more sensitive searches for B-modes at all angular scales is a sizeable increase in the number of detectors within each receiver. Each receiver houses 7,588 bolometers on their respective focal planes resulting in a total of 22,764 bolometers across the entire Simons Array. Each bolometer is connected to a sinuous antenna [32] that allows for simultaneous measurement of two orthogonal linear polarizations of incoming light in two separate frequency bands at once. An image of a sinuous antenna pixel with four connected bolometers is shown in Figure 2.15. The sinuous antennas in the POLARBEAR-2a and -2b receivers are designed for observation in the 90 GHz and 150 GHz bands, while the POLARBEAR-2c receiver sinuous antennas are designed for 220 GHz and 270 GHz band observations. Each

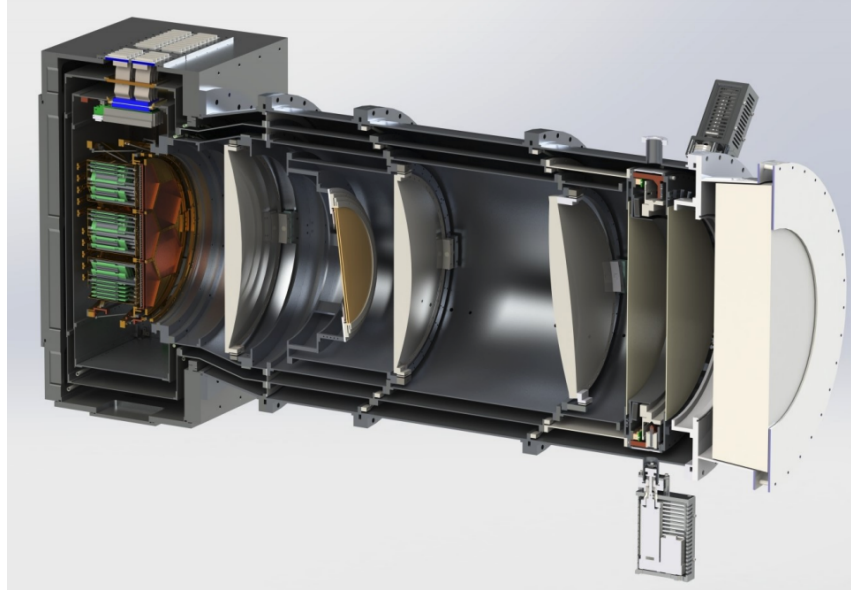
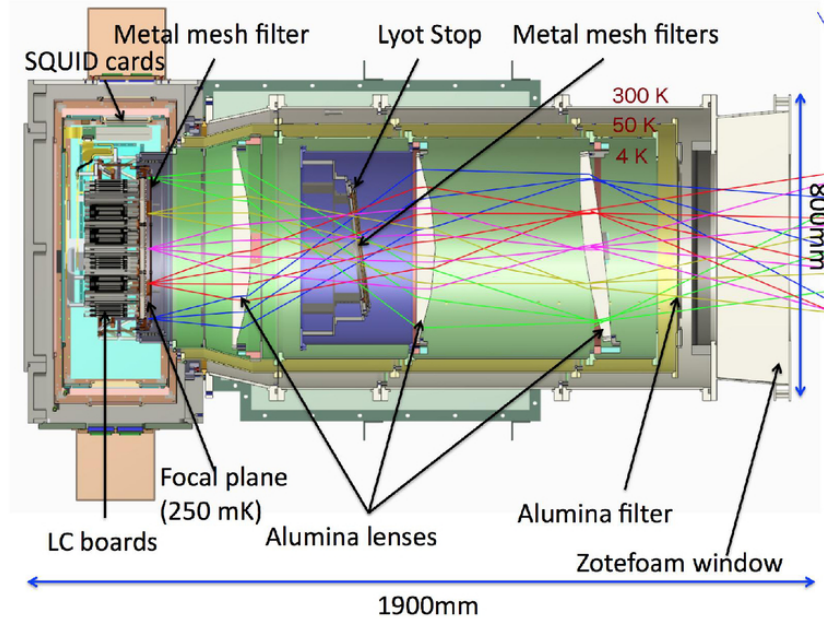


Figure 2.14: *Top:* CAD cross-section depiction of the POLARBEAR-2a receiver with ray tracings through the receiver optics. Image from [46]. *Right:* CAD cross-section of the POLARBEAR-2b and POLARBEAR-2c receiver design. The design is similar to that of the POLARBEAR-2a receiver, with the exception of a cryogenic CRHWP placed just inside the Zotefoam window. Image from [45].

pixel's observation band is set by on-chip band-defining filters. The POLARBEAR-2 receivers have about a six-fold increase in the number of detectors each over the POLARBEAR-1 receiver. To read out the 7,588 bolometers on each POLARBEAR-2 receiver, SQUIDs are similarly used but with a multiplexing factor of 40 instead of 8. The increase in multiplexing factor is necessary to minimize the thermal loading from wires needed to read out the drastic increase in the amount of detectors. Further details on the read out and focal planes used in the Simons Array across the POLARBEAR-2 receivers can be found in [19, 35, 45].

The POLARBEAR-2 receivers are cryogenically cooled using the same refrigeration technology as POLARBEAR-1. Two pulse tube coolers are used to cool the backend and optics tube separately, with the 50 K stages cooling the intermediate aluminum shell and the CRHWP in POLARBEAR-2b and -2c and the 4 K stages cooling the focal plane tower and all optical elements. A similar three-stage $^3\text{He}/^4\text{He}$ adsorption refrigerator is mounted to each focal plane and is used to cool the focal plane to temperatures of ~ 300 mK with similar hold times to that of the POLARBEAR-1 refrigerator.

The optical stack of the POLARBEAR-2 receivers as shown in the bottom of Figure 2.14 consists the optical Zotefoam window, IR blocking filters, three large re-imaging lenses, a Lyot stop, a low-pass metal mesh filter directly in front of the focal plane, and finally a hemispherical alumina lenslet coupled to each sinuous antenna [84]. The re-imaging lenses coupled to the telescope optics provide a tele-centric focal plane with a diffraction limited field of view of ~ 4.5 degrees. The POLARBEAR-2b and -2c receivers also contain a cold magnetically levitating CRHWP placed between the Zotefoam window and IR blockers while POLARBEAR-2a will have an ambient temperature CRHWP installed at the prime focus baffle [43]. The modulation from the CRHWPs pushes the polarized $4f$ signal to frequencies away from the large low frequency $1/f$ noise that come from effects such as transient atmospheric fluctuations during an observation. Each optical element is double anti-reflection coated to account for reflections in both observing bands and to maximize optical efficiency. In POLARBEAR-2a each curved optical element is

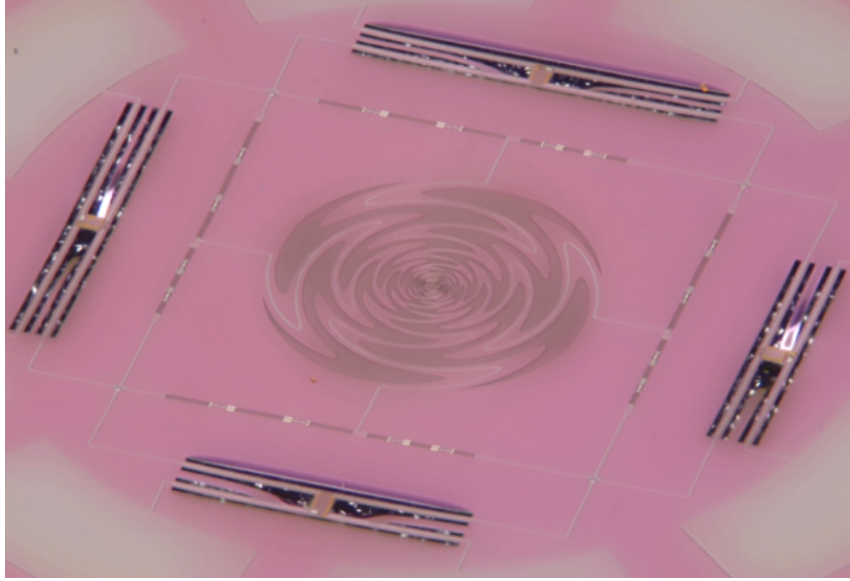


Figure 2.15: Image of a sinuous antenna pixel on a POLARBEAR-2a wafer. Four bolometers are connected to the antenna with on-chip band-defining filters to measure two frequency bands at two linear polarizations. Image from [18].

anti-reflection coated using a two-layer epoxy resin [81] while each flat optical element is sprayed with a porous-polyimide sheet [47]. A more detailed account of the POLARBEAR-2 optics can be found in [67].

2.5 Summary

This chapter has provided an overview of the POLARBEAR-1 and Simons Array experiments. The benefits of the Chilean observation site along with the resulting science scan strategies from this location were discussed. Significant published results from POLARBEAR-1 were presented including measurements of the B-mode power spectrum at degree and sub-degree scales as well as constraints placed on Lorentz and parity violating physics from cosmic birefringence and equivalent PMF strength from observations of the CMB. The Simons Array design and science goals were described, which expands the POLARBEAR-1 experiment to three telescopes with new POLARBEAR-2a, -b, and -c receivers that provide an order of magnitude increase in the

number of detectors and sensitivity and allows for better foreground separation through the use of dichroic pixels. The next chapter will discuss how these experiments' detector polarization angles and beam shapes are calibrated and will detail the limitations on the precision of the current best celestial polarization calibration source, Taurus A.

2.6 Acknowledgements

Figure 2.1 is a reprint of the material as it appears in: J. Errard, P. A. Ade, Y. Akiba, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, J. Delabrouille, M. Dobbs, A. Ducout, T. Elleflot, G. Fabbian, C. Feng, S. Feeney, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, O. Jeong, N. Katayama, J. Kaufman, B. Keating, Z. Kermish, R. Keski-talo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, F. Matsuda, T. Matsumura, N. J. Miller, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, G. Puglisi, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, D. E. Schenck, B. D. Sherwin, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, A. Tikhomirov, T. Tomaru, N. Whitehorn, B. Wilson, A. Yadav, and O. Zahn. "Modeling Atmospheric Emission for CMB Ground-Based Observations." *The Astrophysical Journal*, 809(1):63, Aug 2015. The dissertation author made essential contributions to this work.

Figure 2.2 is a reprint of the material as it appears in: P. A. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, D. Flanigan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S.

Moyerman, M. J. Myers, M. Navaroli, H. Nishino, A. Orlando, H. Paar, J. Peloton, D. Poletti, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, D. E. Schenck, B. D. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. “A measurement of the cosmic microwave background B-mode polarization power spectrum at sub-degree scales with POLARBEAR.” *The Astrophysical Journal*, 794(2):171, May 2014. The dissertation author made essential contributions to this work.

Figures 2.6 and 2.7 are reprints of the materials as they appear in: P. A. R. Ade, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, K. Crowley, A. Cukierman, R. Dunner, M. Dobbs, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. C. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, M. L. Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, Y. Minami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, P. L. Richards, C. Ross, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, T. Tomaru, C. Tucker, N. Whitehorn, and A. Zahn. ”A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Subdegree Scales from Two Years of POLARBEAR Data.” *The Astrophysical Journal*, 848(2):121, 2017. The dissertation author made essential contributions to this work.

Figures 2.8, 2.9, and 2.10 have been submitted for publication of the materials as they may appear in: S. Adachi, M. A. O. Aguilar Faundex, K. Arnold, C. Baccigalupi, B. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, A. Cukierman, M. Dobbs. H. El Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, Y. Inoue, G. Jaehnig, O. Jeong,

D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. KrachmanIlnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Lindner, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, Y. Zhou. “A Measurement of the Degree Scale CMB B-mode Angular Power Spectrum with POLARBEAR.” Submitted to The Astrophysical Journal. Oct 2019. The dissertation author made essential contributions to this work.

Figures 2.11, 2.12 (top), and 2.12 (bottom) are reprints of the materials as they appear in: P. A. R. Ade, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, A. Gilbert, N. Goeckner-Wald, J. Groh, W. L. Holzapfel, Y. Hori, L. Howe, A. H. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, Y. Li, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. J. Myers, M. Navaroli, D. Poletti, G. Puglisi, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, D. E. Schenck, B. D. Sherwin, M. Shimon, I. Shirley, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, A. Suzuki, J.-I. Suzuki, B. Wilson, A. Yadav, A. Zahn, and O. Zahn. “POLARBEAR constraints on cosmic birefringence and primordial magnetic fields.” Physical Review D, 92(12):1550–7998, 2015. The dissertation author made essential contributions to this work.

Figure 2.14 (top) is a reprint of the material as it appears in Y. Inoue, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. A. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman,

K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskital, T. Kisner, A. Kusaka, M. L. Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, K. Mizukami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermond, Y. Segaw, B. D. Sherwin, I. Shirley, P. Siritanasak, N. Stebor, R. S. A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirol, T. Tomaru, N. Whitehorn, A. Zahn, and O. Zahn. POLARBEAR-2: an instrument for CMB polarization measurements. SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 991411:1–8, 2016. The dissertation author made essential contributions to this work.

Chapter 3

Calibration of the POLARBEAR-1 and POLARBEAR-2a CMB Experiments

We saw in Chapter 1 and Figures 2.7 and 2.9 that overall calibration of a CMB experiment is critically important when trying to measure both the primordial and gravitational lensing B-mode signal, when placing limits on the tensor-to-scalar ratio r , or when attempting to place meaningful constraints on the amount of cosmic birefringence or PMFs. Experiment detector calibration generally falls into one of four categories: *i*) gain calibration dictating the responsivity of a detector to a fluctuating sky signal, *ii*) beam shape calibration to measure the angular resolution and side lobe response of a detector, *iii*) pointing offset calibration that determines where on the sky the detector is actually pointed, and *iv*) detector polarization angle calibration that sets the determined angle of incoming polarized light.

Gain calibration is generally determined via observations of a thermal source with well characterized temperature, the procedure of which can be found in Chapter 3 of [20]. Characterizations of detector beam shapes and pointing offsets are derived from observations of known point sources such as planets within our solar system. Astrophysical polarization calibrations is usually performed via observations of Taurus A, a polarized celestial source that will be discussed

in detail in Section 3.1. Section 3.2 goes over the procedure of transforming detector timestreams into maps of the Stokes I, Q, and U parameters and how to then derive a polarization P map. Polarization calibration of POLARBEAR-1 detectors determined from observations of Taurus A is detailed in Section 3.3, while Section 3.4 presents preliminary maps of Taurus A and Jupiter from the first year of commissioning of the POLARBEAR-2a telescope.

3.1 Taurus A

Taurus A (henceforth “Tau A”), also known as the Crab Nebula or Messier 1, is the remnant of supernova SN1054, which occurred in the year 1054 and was observed by early civilizations and recorded in detail by Chinese astronomers [42]. Located at right ascension $05^h 34^m 31.94^s$ and declination $+22^\circ 00' 52.2''$, the supernova was a spectacle to behold as it was nearly as bright as the moon and appeared during the daytime for several weeks. A composite image taken in the visible spectrum of Tau A by the Hubble Space Telescope¹ is shown in Figure 3.1. A rapidly rotating pulsar ($T \approx 33$ ms) that resides at the center of the nebula is surrounded by a polarized nebula that provides the strongest source of synchrotron emission in our galaxy [64]. The total flux from Tau A follows a power law that decreases with frequency. Between frequencies of about 1-100 GHz the power law spectral index has been measured to be -0.296 ± 0.06 while at higher frequencies the spectral index trends towards -0.698 ± 0.018 [64]. The total flux also appears to be decreasing at a rate of $0.167\% \pm 0.015\%$ per year [16] due to the expansion of the supernova remnant. A compendium of measurements of the total intensity flux of Tau A at various frequencies is shown in Figure 3.2. Because Tau A has been so extensively studied across the electromagnetic spectrum, it is perhaps the most popular calibration target for astronomical experiments due to its extremely accurate pulsar timing and well characterized intensity and polarization.

¹<https://www.nasa.gov/feature/goddard/2017/messier-1-the-crab-nebula/>

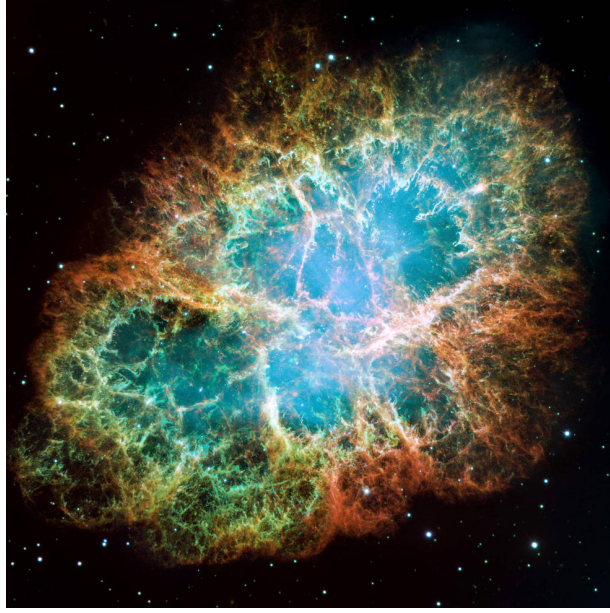
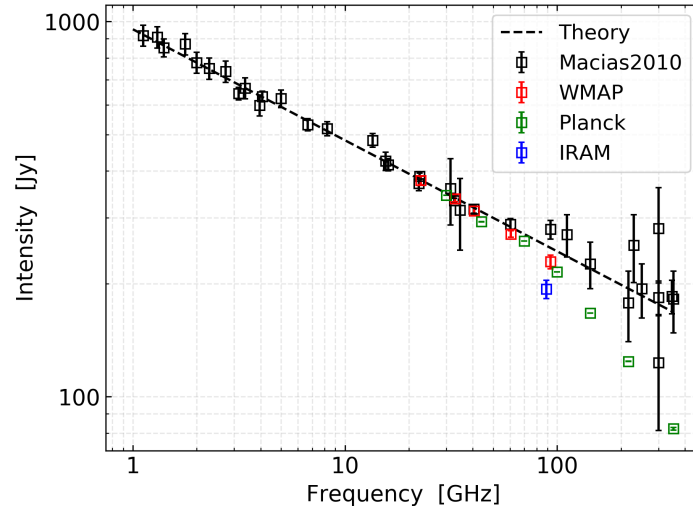


Figure 3.1: Composite visible light image of the Crab Nebula (Tau A) taken by NASA's Hubble Space Telescope. Image courtesy of NASA.



In the context of observations of the polarized CMB, Tau A presents itself as the brightest source of polarized microwave radiation at arcminute angular scales, making it a potentially ideal candidate for polarization calibration of CMB detectors. Tau A's polarization structure was first measured in the context of a CMB polarization calibrator by the XPOL polarimeter on the IRAM 30-meter telescope in 2010 [16]. With a beam size of about half an arcminute, the XPOL polarimeter resolves the extended 7 arcminute by 5 arcminute nebula and found that the polarization across the nebula is not entirely uniform. Convolved with a 5 arcminute beam (the approximate beam size of a CMB detector observing at 90 GHz), the smoothed polarization field is reported to be at an average angle of $149.9^\circ \pm 0.2^\circ_{stat} (\pm 0.5^\circ_{tot})$ in equatorial coordinates [16]. Since this initial measurement, the polarization angle of Tau A has been measured (with larger error) by several CMB experiments at varying frequencies with data shown in Table 3.1 and plotted in Figure 3.3. A combined analysis of existing Tau A polarization angle measurements suggests an improvement to the overall uncertainty from 0.5° [16] to 0.33° [17], or as low as 0.27° [80].

While Tau A remains one of the best available astrophysical CMB polarization calibrators, it possesses several drawbacks as we look towards detector polarization calibration of the next generation of CMB experiments. One of the most notable issues is that [16] reveals the complicated polarization structure within the nebula itself. Detectors observing at low frequencies smooth the extended Tau A structure with their large beam sizes, but as detectors observing at higher frequencies begin to resolve structure within the nebula with their smaller beam sizes it becomes increasingly difficult to define the value of the polarization angle to compare against other measurements. Another potential issue is that, while the polarization angle appears to be unchanged between 90 GHz and 150 GHz, this is not guaranteed to be true across all frequencies or even at all times. Furthermore, as the nebula itself is expanding at a rate of about 1500 km/s (or $\sim 0.5\%$ of the speed of light) there is no guarantee how long a calibration to Tau A might be valid.

Table 3.1: Compendium of Tau A polarization angle measurements from various CMB experiments. Statistical uncertainties are listed after the measurement followed by systematic uncertainties in parenthesis (where available). All measurements are reported in equatorial coordinates.

Experiment	ν [GHz]	Polarization angle [deg]	Citation
Planck	30	$148.84 \pm 0.54(\pm 0.50)$	[92]
Planck	44	$149.45 \pm 0.32(\pm 0.50)$	
Planck	70	$150.61 \pm 0.23(\pm 0.50)$	
Planck	100	$150.36 \pm 0.11(\pm 0.62)$	
Planck	143	$150.88 \pm 0.13(\pm 0.62)$	
Planck	217	$149.36 \pm 0.12(\pm 0.62)$	
Planck	353	$149.72.37(\pm 0.62)$	
NIKA	150	$142.0 \pm 0.7(\pm 2.3)$	[80]
WMAP	23	$149.1 \pm 0.10(\pm 1.50)$	[94]
WMAP	33	$149.9 \pm 0.10(\pm 1.50)$	
WMAP	41	$150.3 \pm 0.20(\pm 1.50)$	
WMAP	61	$149.9 \pm 0.40(\pm 1.50)$	
WMAP	93	$148.9 \pm 0.70(\pm 1.50)$	
IRAM	93	$149.9 \pm 0.20(\pm 0.50)$	[16]
ABS	145	150.7 ± 1.4	[58]
ACTPol	146	150.7 ± 0.6	[71]
POLARBEAR	150	$150.4 \pm 0.2(\pm 0.8)$	[11]

Moreover the current uncertainty in the polarization angle of Tau A is not accurate enough to place meaningful constraints on CPR from Lorentz or parity violating physics, as evidenced by the uncertainty in the Tau A-calibrated POLARBEAR-1 measurement of non-zero C_ℓ^{EB} presented in Section 2.3. As there exists no better astrophysical calibration source that acts as a point source across a broad range of detector frequencies and beam sizes, the demand for a well characterized artificial polarization calibrator is well warranted. Additionally, any CMB experiment that is calibrated with an artificial source more accurately than Tau A can currently provide can in return then re-calibrate Tau A and other polarized celestial sources for the CMB community as a whole.

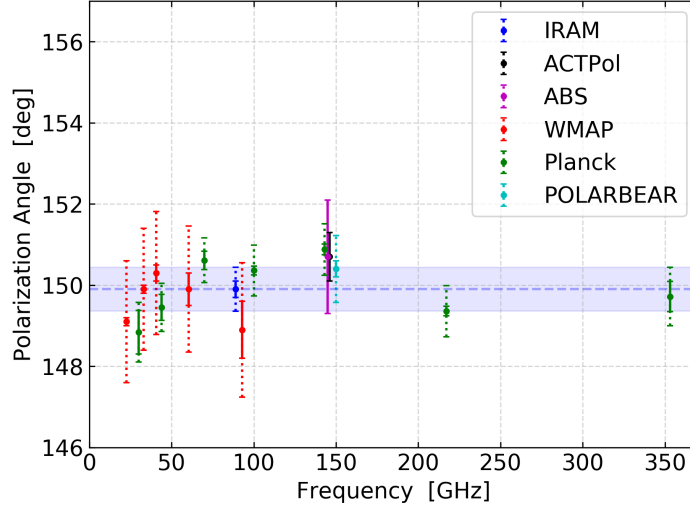


Figure 3.3: Measurements of the Tau A polarization angle by the IRAM (blue) [16], ACTPol (black) [71], ABS (purple) [58], WMAP (red) [94], Planck (green) [92], and POLARBEAR-1 (cyan) [10] experiments. The NIKA experiment [80] is not plotted as it is a clear outlier. Solid error bars represent statistical error while dotted error bars show the total systematic plus statistical error. The dashed blue line and shaded regions represent the IRAM measurement center value and total error. Data from Table 3.1.

3.2 Map Making Procedure

This section describes the analytical process of transforming raw detector timestreams from an observation of a polarized celestial source into two dimensional real space maps of the I, Q, and U Stokes parameters, using POLARBEAR-2a observations of Jupiter and Tau A during its initial calibration season as an in-depth example [50]. Maps are typically displayed in celestial coordinates of right ascension (RA) and declination (DEC). Once intensity maps have been made for each polarization sensitive bolometer (PSB) pixel-pair, they can be coadded into a single map for each wafer or across the entire focal plane. If the data is polarization modulated in the time domain by a CRHWP as with POLARBEAR-1 data, Q and U maps can be constructed from a single detector and coadded across the focal plane. Without time domain polarization modulation as with initial POLARBEAR-2a data, Q and U maps can be estimated from a single observation provided there is either sufficient sky rotation throughout the duration of the observation or if the

source is observed at many detector angles. POLARBEAR-2a has seven observing wafers that are rotated with respect to one another, with two pixel angle orientations per wafer, to provide the necessary modulation to construct Q and U maps from a single observation. These maps become much more accurate as many observations of a source are coadded at varying parallactic angles or through the use of a CRHWP.

3.2.1 I, Q, U, and Polarization Maps from Pixel-pair Differencing

Pair Differencing

A PSB oriented at angle ϕ observing the sky with gain g and polarization efficiency $\rho = (1 - \epsilon)/(1 + \epsilon)$ will measure a power timestream d with noise n given by

$$d = g(I + \rho(Q \cos 2\phi + U \sin 2\phi)) + n. \quad (3.1)$$

The Stokes I, Q, and U parameters can be extracted from an observation of a celestial source using a pair of PSBs that are spatially co-located. As a single PSB is sensitive to only one polarization angle, pairs of orthogonal PSBs called “pixels” with bolometers labelled “top” and “bottom” are used to measure the polarization along either axis of the PSB pair. Without a CRHWP, a single pixel is not able to measure polarization oriented at 45° with respect to itself. To measure all possible orientations of incoming polarized light, a second pixel is placed at a respective angle of 45° spatially near the first pixel. These pairs of pixels are referred to as Q and U pixels and timestreams from both are necessary to measure sky Q and U Stokes parameters.

To extract the Q and U sky signal from detector timestreams, consider a pair of orthogonal PSBs from a single pixel that we will refer to as t and b . Following Equation 3.1, the power

incident on each PSB is then

$$\begin{aligned} d_t &= g_t(I_t + \rho_t(Q_t \cos 2\phi_t + U_t \sin 2\phi_t)) + n_t \\ d_b &= g_b(I_b + \rho_b(Q_b \cos 2\phi_b + U_b \sin 2\phi_b)) + n_b. \end{aligned} \quad (3.2)$$

If the top and bottom PSBs are fabricated such that $\phi_t - \phi_b = 90^\circ$, Equation 3.2 can be more generally written as

$$\begin{aligned} d_t &= g_t(I_t + \rho_t(Q_t \cos 2\phi + U_t \sin 2\phi)) + n_t \\ d_b &= g_b(I_b - \rho_b(Q_b \cos 2\phi + U_b \sin 2\phi)) + n_b, \end{aligned} \quad (3.3)$$

where ϕ is the angle of the pixel itself. Ideally the gain and polarization efficiencies of the top and bottom PSBs would be equally matched such that $g_t = g_b = g$ and $\rho_t = \rho_b = \rho$. Additionally, if the antenna beams are rotationally symmetric then $I_t = I_b = I$, $Q_t = Q_b = Q$, and $U_t = U_b = U$. In reality, the top and bottom bolometer gains g_t and g_b in any given pixel are not equal and are individually measured by observing a chopped, un-polarized thermal source with known temperature (often referred to as a “stimulator”) before and after any observation and linearly interpolated throughout the observation. The bolometer time constants (discussed more in Section 5.2.1) are also measured with the stimulator and deconvolved from each PSB timestream before proceeding. Assuming rotationally symmetric beams with $I_t = I_b = I$, $Q_t = Q_b = Q$, $g_t = g_b = g$, and $\rho_t = \rho_b = \rho$, the top and bottom PSB pixel-pair timestreams are summed and differenced to obtain the total intensity and polarized timestreams respectively, given by

$$\begin{aligned} d_{sum} &= \frac{1}{2}(d_t + d_b) = \frac{gI + n_t + n_b}{2} \\ d_{diff} &= \frac{1}{2}(d_t - d_b) = g\rho(Q \cos 2\phi + U \sin 2\phi) + (n_t - n_b). \end{aligned} \quad (3.4)$$

with $I = I_t + I_b$, $Q = Q_t + Q_b$, and $U = U_t + U_b$. The total intensity I is generally much larger than the additive noise $n_t + n_b$ for bright calibration sources such as Jupiter or Tau A. For un-polarized sources the polarized response d_{diff} is zero excepting noise and systematic fluctuation. Sources

that are only slightly polarized can result in very small values of d_{diff} , but one major advantage of this pair-differencing technique is that common-mode noise between n_t and n_b is eliminated in d_{diff} . Example PSB common-mode noise sources include telescope motion vibration, focal plane temperature variations, and atmospheric fluctuations throughout an observation. In general, PSB pixel-pair parameters are likely not perfectly equal. Mismatches in the gains or polarization efficiencies will leak intensity into polarization and vice-versa. Beam shape or bandpass mismatch between PSBs will also mix intensity and polarization when performing the sum and difference of timestreams. Observing astronomical targets such as planets to measure the exact shape of the beam, performing FTS measurements to determine detector bandpasses, and calibrating gains to the stimulator before and after observations reduces this systematic uncertainty from intensity and polarization leakage but leaves a residual 1/f noise.

I, Q, U, and Polarization Maps

To generate an intensity map, consider d_{sum} for a pair of PSBs observing a bright calibration source such that $d_{sum} \approx I$. The intensity map for a single pixel for a single observation is then simply the two-dimensional matrix that is generated by binning the d_{sum} timestream according to the azimuth and elevation timestreams and the desired bin width or map pixel size. In this case the binning operation is the mean of the d_{sum} points that fall into each of the bins. The coadded intensity map for multiple pixels over more than one observation is calculated by taking the inverse-variance weighted average of all the constituent intensity maps. The weight w for each pixel map is determined by the inverse-variance of the source-masked polynomial-filtered d_{sum} timestream. Letting i denote the i th map pixel in the intensity maps, j the j th observation, and k the k th focal plane pixel in an observation, the coadded intensity map $\bar{I}_i$ is given by inverse-variance weighted average

$$\bar{I}_i = \frac{\sum_j \sum_k w_{ijk} d_{sum,ijk}}{\sum_j \sum_k w_{ijk}} \quad (3.5)$$

where w_{ijk} is the weight and $d_{sum,ijk}$ is the pixel sum for the k th focal plane pixel in the j th observation in the i th map pixel. It is important to note that the individual intensity maps that make up the coadded intensity map must each be centered on the desired astronomical target in order for accurate coaddition. A d_{diff} intensity co-added map of a polarized source can be constructed analogously to Equation 3.5 by replacing d_{sum} with d_{diff} .

To generate Q and U maps let us assume that $g = 1$, $\rho = 1$, and that polarized signal dominates noise in Equation 3.4². Let's also define the angle between a detector's orientation and the parallactic angle of the source at the time of observation to be ϕ' . Coadding PSB pixel-pair difference timestreams from multiple observations with varying parallactic source angles, let the k th pixel in the j th observation observe the source in the i th map pixel at relative detector-parallactic angle ϕ'_{ijk} . Then, we can generate inverse-variance weighted coadded Q and U maps given by

$$\begin{aligned}\overline{Q}_i &= \frac{\overline{SS}_i \cdot \overline{DC}_i - \overline{CS}_i \cdot \overline{DS}_i}{\overline{CC}_i \cdot \overline{SS}_i - \overline{CS}_i \cdot \overline{CS}_i} \\ \overline{U}_i &= \frac{\overline{CC}_i \cdot \overline{DS}_i - \overline{CS}_i \cdot \overline{DC}_i}{\overline{CC}_i \cdot \overline{SS}_i - \overline{CS}_i \cdot \overline{CS}_i}.\end{aligned}\tag{3.6}$$

²Or assume that the gain and polarization efficiency have been properly calibrated to the stimulator.

Here, $\overline{CC}_i$, $\overline{SS}_i$, $\overline{CS}_i$, $\overline{DC}_i$, and $\overline{DS}_i$ are given by

$$\begin{aligned}
\overline{CC}_i &= \frac{\sum_j \sum_k w_{ijk} \cos^2(2\phi'_{ijk})}{\sum_j \sum_k w_{ijk}} \\
\overline{SS}_i &= \frac{\sum_j \sum_k w_{ijk} \sin^2(2\phi'_{ijk})}{\sum_j \sum_k w_{ijk}} \\
\overline{CS}_i &= \frac{\sum_j \sum_k w_{ijk} \cos(2\phi'_{ijk}) \sin(2\phi'_{ijk})}{\sum_j \sum_k w_{ijk}} \\
\overline{DC}_i &= \frac{\sum_j \sum_k w_{ijk} \cos(2\phi'_{ijk}) d_{diff,ijk}}{\sum_j \sum_k w_{ijk}} \\
\overline{DS}_i &= \frac{\sum_j \sum_k w_{ijk} \sin(2\phi'_{ijk}) d_{diff,ijk}}{\sum_j \sum_k w_{ijk}}
\end{aligned} \tag{3.7}$$

where $d_{diff,ijk}$ is the pixel-pair difference timestream for the k th focal plane pixel in the j th observation in the i th map pixel. Note that the denominators in Equation 3.6 are zero for a single value of the relative detector-parallactic angle ϕ' . To remedy this fact and make more accurate maps, a polarized celestial source is typically observed and coadded at many parallactic angles across multiple observations with several detector orientations across a focal plane. Equation 3.6 and Equation 3.7 are transcribed from the POLARBEAR-1 analysis pipeline and a similar quantitative analysis solving for Q and U Stokes parameter maps can be found in Section 3.2 of [91]. An in depth example of making I, Q, and U maps from POLARBEAR-1 observations can be found in [79].

Once I, Q, and U maps have been generated it is simple to obtain maps of the polarization intensity P and polarization fraction Π by calculating

$$\begin{aligned}
P_i &= \sqrt{Q_i^2 + U_i^2} \\
\Pi_i &= \frac{P_i}{I_i}
\end{aligned} \tag{3.8}$$

for each pixel in the map and re-plotting. A polarization angle map α_i is calculated by

$$\alpha_i = \frac{1}{2} \text{atan2}(U_i, Q_i). \quad (3.9)$$

There are several ways to define the polarization angle α of a polarized celestial source from a polarization angle map, but the most common method is to calculate the sum of Q and U in pixels at radius r_i that lie within some radius R from the center of the source to calculate

$$\alpha = \frac{1}{2} \text{atan2} \left(\sum_i^{r_i < R} U_i, \sum_i^{r_i < R} Q_i \right). \quad (3.10)$$

Pre-processing of the Sum and Difference Timestreams

Before I, Q, U, and polarization maps can be made a number of data processing operations must first be applied to the sum and difference timestreams d_{sum} and d_{diff} for a pair of PSBs. The pre-processing methods applied to the data resulting in the maps presented in Section 3.4.1 are detailed in this section using a POLARBEAR-2a observation of Tau A as a detailed example.

First, the two timestreams are gain calibrated and deconvolved from their respective time constants as measured by observations of the stimulator before and after a science or calibration scan. After stimulator calibration, d_{sum} and d_{diff} are each separated into left- and right-going subscans (henceforth referred to as “L/R subscans”) according to when the telescope azimuth is decreasing (left-going) or increasing (right-going). This separation is performed to check for systematics correlated with the telescope scan direction and the L/R separated timestreams are re-combined later in the analysis. A few seconds at the beginning and end of each L/R subscan timestream is then masked to mitigate excess noise induced by the acceleration of the telescope at the azimuthal turnaround points. Each L/R subscan is subsequently filtered by a third- or fifth-order³ polynomial which acts as a high-pass filter against low-frequency systematics such

³Depending on how much drift there is in the TOD higher order polynomial filters may be applied.

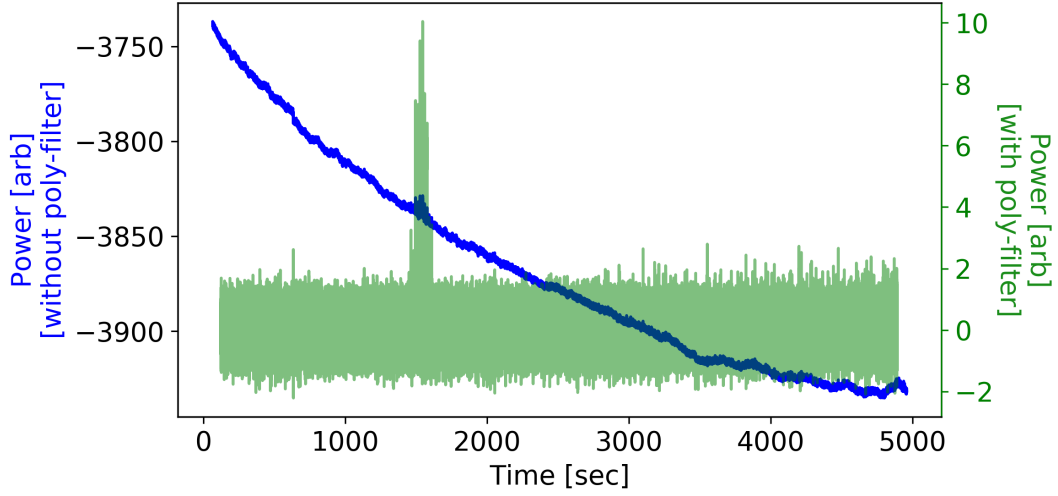


Figure 3.4: A sample PSB pair d_{sum} timestream from a POLARBEAR-2a Tau A observation before (blue) and after (green) applying a fifth-order polynomial filter. Tau A can be seen around $T = 1600$ seconds.

as focal plane temperature variations or sky transients (small clouds, etc). Figure 3.4 shows an example POLARBEAR-2a PSB pair d_{sum} observation of Tau A before and after polynomial filtering. Once the polynomial filter has been applied to each L/R subscan, they are re-combined and sorted according to the detector timestamps.

Before continuing with the analyses, there is a crucial systematic hidden in Figure 3.4. Polynomial filtering is significantly degraded by spikes in optical power, such as those L/R subscans where optical signal from the celestial target is much greater than the detector noise. An example of this signal degradation in both timestream and map space is shown in the top of Figure 3.5. To minimize this systematic effect, the pre-filtered L/R subscan timestreams are masked within 15 arcminutes of the center of the source as determined by a 2D Gaussian fit to the timestream data. The masked subscans are fit to a polynomial filter as described above, which is then subtracted from the un-masked subscans. The effect of the source-masked polynomial filter is depicted in the bottom of Figure 3.5.

After the d_{sum} and d_{diff} timestreams have been source-masked polynomial-filtered, maps

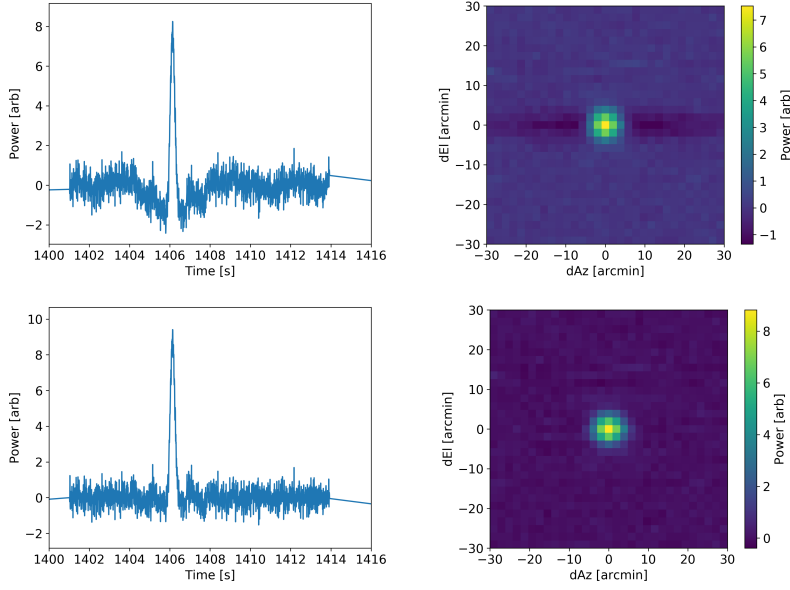


Figure 3.5: *Top:* A zoom in of a fifth-order polynomial-filtered L/R subscan from Figure 3.4 (left), with filtering artifacts visible as power dips near the peak of the source. The corresponding intensity map (right) shows artifacts visible as dark stripes near the source in the azimuthal direction. *Bottom:* The same plots as above but with source-masked polynomial filtering applied.

of I, Q, U, and P can be generated according to Equation 3.5 and Equation 3.6. Additionally, detector parameters such as the individual beam sizes and physical focal plane offsets can be gleaned by fitting another 2D Gaussian to the processed d_{sum} timestream. Detector characterization results from these analyses are presented in Section 3.4.

3.2.2 Detector Angles from Tau A Observations

When making maps of a polarized source employing the map making procedure detailed in the previous section, each detector angle is assumed to be some value. If the detectors have been previously calibrated, those values are typically used when calculating the offset between the detector angle and parallactic angle of the source. If no polarization calibration has been performed then design angle values are used in the map making procedure. In the latter scenario, the resulting polarized map can be used to in turn polarization calibrate the detectors if the source being measured has a known polarization map. In this section we discuss the process of

calibrating detector angles from a measured polarized source map.

Let us consider calibrating CMB detector angles to Tau A by making polarized maps and comparing them to maps made from the IRAM measurements [16]. Revisiting Equation 3.4 and assuming polarized signal is much larger than the noise, let us define an angle Θ to take into account not only the angle of the detector θ_{det} with respect to vertical ($\pi/2 - \theta_{det}$) but also the parallactic angle of the source $\theta_{pa}(t)$ and the angle of any half-wave plate $\theta_{HWP}(t)$ (if one is used, otherwise $\theta_{HWP}(t) = 0$) to obtain

$$d = g((I + x_i) + \rho(Q \cos 2\Theta + U \sin 2\Theta)) \quad (3.11)$$

where

$$\Theta = (\pi/2 - \theta_{det}) + 2\theta_{HWP}(t) + \theta_{PA}(t). \quad (3.12)$$

θ_{pa} is a function of time, changing both over the course of an observation and between observations. θ_{HWP} is common to all detectors and also changing with time with a known value when paired with an optical encoder. When comparing the measured map to the IRAM generated map, g becomes the relative gain between the CMB and IRAM experiments. The nuisance parameter x_i accounts for un-polarized intensity drifts in the atmosphere between each subscan i .

Simulated detector timestreams are made for each detector by convolving each measured beam shape with the IRAM beam, applying each pointing offset to the data, then “scanning” the IRAM Tau A I, Q, and U maps. The simulated timestreams are then fit to the observed timestreams combined over many observations (for maximum θ_{pa} coverage) for the three parameters: g , ρ , and finally the individual detector angles θ_{det} .

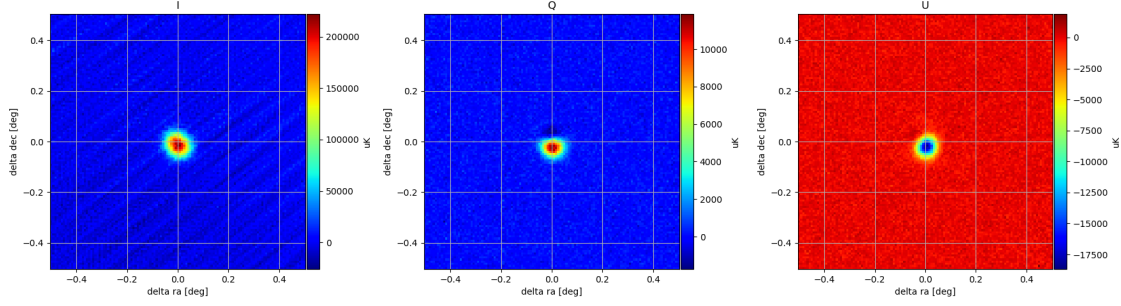


Figure 3.6: I (left), Q (middle), and U (right) maps made from a single observation of Tau A by the POLARBEAR-1 telescope. The color scale is in temperature units of μK .

3.3 POLARBEAR-1 Observations of Tau A

POLARBEAR-1’s primary absolute polarization calibration comes from observations of Tau A⁴. The scan strategy for observing Tau A consisted of tracking the source and raster scanning 5.5 degrees back and forth in azimuth, with small elevation steps in between each azimuthal subscan until the entire focal plane observed the source. Scanning the entire focal plane using 2 arcminute steps and a scan velocity of 0.2 degrees per second on the sky takes roughly one hour and was performed several times per week during regular observations. Stimulator calibrations were performed before and after each observation to obtain the detector gains and time constants to be interpolated throughout an observation.

In POLARBEAR-1’s third to fifth observing seasons, 2014 to 2016, Tau A was observed 289 times. Observations that are cut from the following analyses include observations where Tau A was less than 30 degrees from the sun (resulting in increased sidelobe response), observations where the PWV was higher than 4 mm, observations that did not have a before and after stimulator measurement, and observations with focal plane temperatures outside of standard operating range. After implementing these cuts, 190 observations remained. Individual I, Q, and U maps are then made for the remaining observations, which are then coadded into final “full-season” maps. An example I, Q, and U map from one observation that passed data cuts is shown in Figure 3.6.

⁴Though the final absolute polarization calibration is determined from self-calibration [53], assuming the absence of CPR-inducing effects.

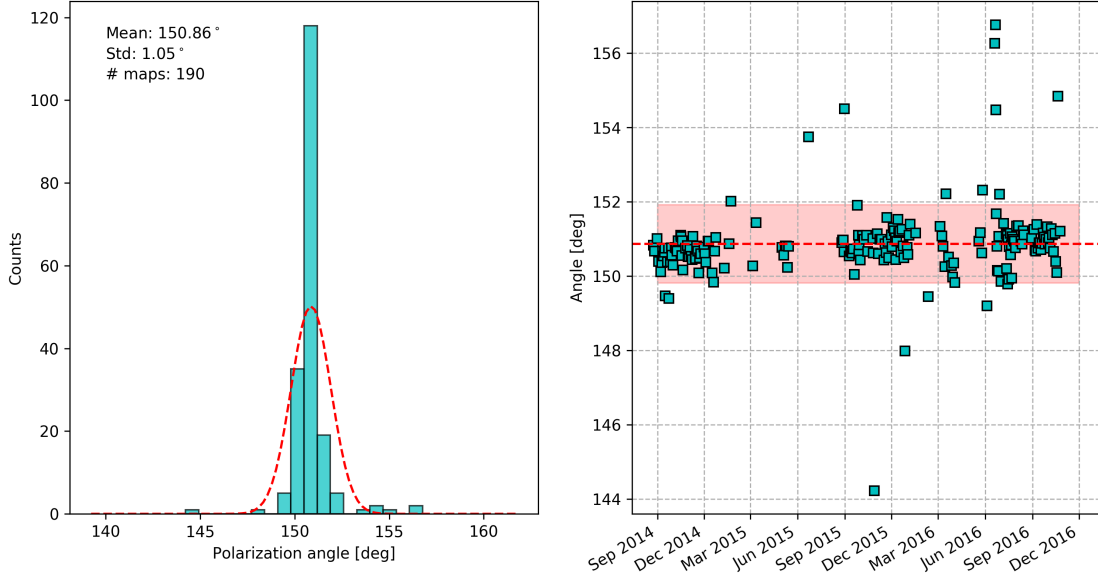


Figure 3.7: *Left:* Histogram of Tau A polarization angles as measured from 190 POLARBEAR-1 observations across three seasons, with an overall measured angle of $150.86^\circ \pm 1.06^\circ$. A fitted Gaussian histogram is plotted as a dashed red line. *Right:* The same Tau A polarization angles plotted as a function of time. The dashed red line and shaded red box represent the mean and standard deviation of the data respectively.

Once maps were made for each of the 190 observations, the polarization angle of Tau A was calculated using Equation 3.10 and summing Q and U values within a 10 arcminute radius of the map centers. The calculated Tau A angles for these three seasons of POLARBEAR-1 observations are shown in Figure 3.7, with an average value of $150.86^\circ \pm 1.06^\circ$. Note that outliers in the distribution are deviant due to non-zero Q and U backgrounds for those measurements, which result in a systematic bias in the calculated polarization angle when integrating Equation 3.10 out to 10 arcminutes. The POLARBEAR-1 derived Tau A polarization angle presented here is in good agreement with the IRAM measurements of $149.9^\circ \pm 0.5^\circ$.

Each observation's I, Q, and U map is coadded according to Equation 3.5 and Equation 3.6 resulting in the three season overall Tau A map shown in Figure 3.8 [48], and is in good agreement with the IRAM Tau A maps [16]. The map's color scale gives the polarized intensity magnitude, the contours give the overall intensity magnitude, and the headless vectors represent the polarization angle with magnitude proportional to vector length.

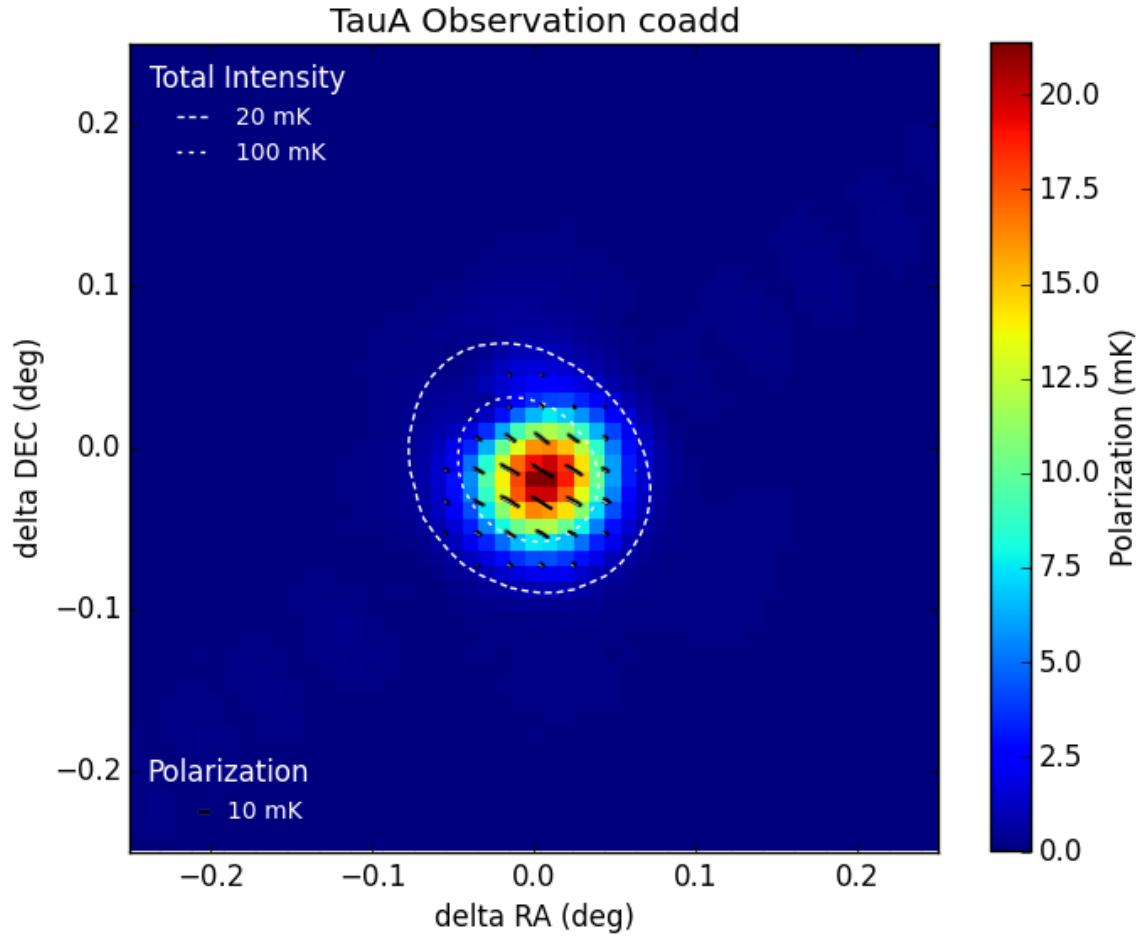


Figure 3.8: Polarization map of Tau A from three seasons of POLARBEAR-1 observations. Tau A intensity is plotted as dashed contours and polarization intensity is plotted as headless vectors with length proportional to its magnitude. Image courtesy of Greg Jaehnig, from [48] (with polarization vectors darkened by the author).

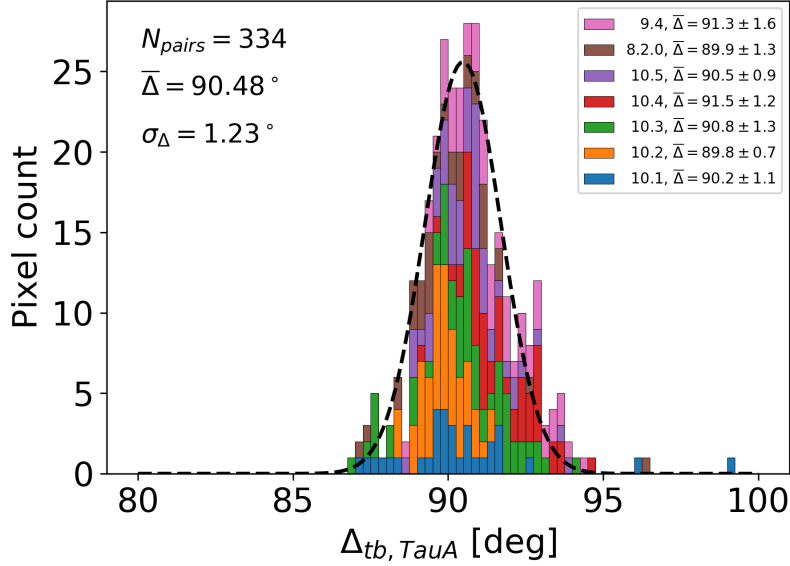


Figure 3.9: PSB pixel-pair polarization angle differences $\Delta_{tb, \text{TauA}}$ in POLARBEAR-1 as derived from three seasons of Tau A observations. The dashed black line is a 1D Gaussian fit to the histogram with fit values in the top left. The seven POLARBEAR-1 wafers are noted in the legend along with per-wafer 1D Gaussian fit parameters. Data used in this figure from [48].

The measured detector timestreams are compared to their respective simulated IRAM timestreams according to Section 3.2.2 to fit for and determine individual detector angles. To check the accuracy of this calibration, the polarization angle difference between orthogonal top and bottom PSB pairs on a pixel $\Delta_{tb, \text{TauA}}$ is calculated and compared to the expected pair difference value of 90° as any global rotation of a focal plane wafer should affect each bolometer equally having no impact on the orthogonality of PSB pairs. The PSB angle pair differences are shown in Figure 3.9 with a 1D Gaussian fitted average value of $90.48^\circ \pm 1.23^\circ$ [3], in good agreement with the design value of 90° . Further details on the making of the three season coadded Tau A map and calculating the individual detector polarization angles and efficiencies can be found in Chapter 3 of [48].

3.4 POLARBEAR-2a Observations

The POLARBEAR-2a receiver was deployed to the Chilean Atacama Desert in October 2018 and achieved first light in January 2019. The first year of observations was dedicated primarily to cryogenic optimization and telescope characterization. Observations of a thermal stimulator confirmed optical response, gain, and time constants in detectors while a polarized coherent source was observed to confirm hardware map parameters such as pixel observation bands and Q or U pixel distinctions. Observations of planets such as Jupiter confirmed detector beam widths, pointing offsets, observation bands, and helped determine the focus of the receiver over time. Tau A observations confirmed polarized response in detectors and verified polarization map analysis pipelines. The following sections will detail observations of Tau A and Jupiter during initial commissioning. Further detail on the first year of commissioning data can be found in [50].

3.4.1 Tau A I, Q, U, and P Maps

POLARBEAR-2a observed Tau A in a very similar raster scan fashion as POLARBEAR-1, with similar azimuthal scan speed and elevation steps but with a ~ 9 degree map width due to the increased field of view. During commissioning, there were six observations of Tau A that were also calibrated to the stimulator both before and after the scan. To determine individual bolometer data cuts, the power spectral density (PSD) $p(f)$ for each d_{diff} timestream was calculated and then fit to a power law of the form

$$p(f) = N_w^2 (1 + (f_{knee}/f_s)^\beta), \quad (3.13)$$

where N_w is the white noise floor, f_{knee} is the knee frequency of the PSD, f_s is the sample frequency of the timestream, and β is the degree of the power law. N_w , f_{knee} , and β are fit as free parameters and the latter two parameters are used to determine which bolometers are cut from an

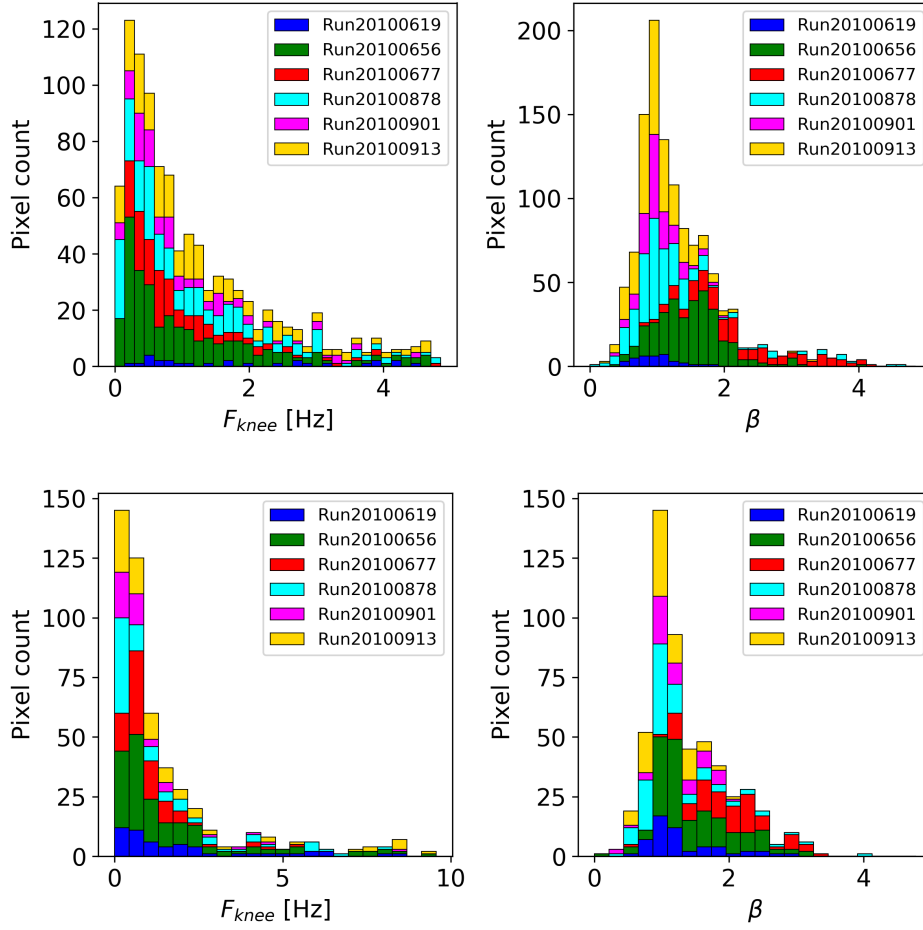


Figure 3.10: The PSD f_{knee} (left column) and β (right column) parameters for six POLARBEAR-2a observations of Tau A for both 90 GHz (top row) and 150 GHz (bottom row) bolometers.

observation. For the six observations of Tau A, the values for f_{knee} and β across the focal plane for both 90 GHz and 150 GHz bolometers are shown in Figure 3.10. Bolometers with $f_{knee} > 2$ Hz or $\beta > 2.5$ are cut from the coaddition, as are bolometers with a reduced $\chi^2 < 3$. Entire observations were cut if they were too close to the sun, had extremely poor yield, or excessive noise. After individual bolometer and observation cuts, $O(500)$ bolometers were coadded across two Tau A observations to generate the I, Q, and U maps shown in Figure 3.11. All maps presented here are in units of arbitrary power as the conversion to temperature from observations of the stimulator and Jupiter had not been calculated at the time of making these maps. The shape of

the intensity map is as expected for both 90 GHz and 150 GHz and the overall sign of the Q and U maps is in agreement with the IRAM measurement. The polarization P map with overlaid polarization vectors is shown in Figure 3.12. Using Equation 3.10 to sum over Q and U values in a 10 arcminute radius the overall polarization angles at 90 GHz and 150 GHz are calculated to be $149.5^\circ \pm 0.5^\circ$ and $152.2^\circ \pm 1.7^\circ$ respectively, in good agreement with the expected value from POLARBEAR-1 and IRAM measurements. The larger error in the 150 GHz measurement is due to increased noise in the 150 GHz detector timestreams compared to their 90 GHz counterparts, an issue that is actively being addressed as field commissioning for POLARBEAR-2a continues.

The I, Q, U, and P maps presented in this section provides confirmation of POLARBEAR-2a's ability to measure polarized response in observations of a celestial source. With the coaddition of more Tau A maps at varying parallactic angle in the coming months and the addition of a CRHWP at the prime focus baffle, POLARBEAR-2a is in a promising position to move forward with detector polarization angle calibration and CMB science observations.

3.4.2 Jupiter Pointing Offsets, Beam Shapes, and Intensity Maps

POLARBEAR-2a observed Jupiter during commissioning with a similar scan strategy as that of Tau A observations. Like the Tau A analysis, bolometer data were cut based on the PSD fits to the individual d_{diff} timestreams with similar f_{knee} and β cutoffs. The PSD fit parameter values for four POLARBEAR-2a Jupiter observations are shown in Figure 3.13. None of the four observations analyzed were cut based on coadded intensity maps. After individual bolometer cuts, the coadded intensity maps for Jupiter are shown in Figure 3.14. The fact that Jupiter is not only much brighter than Tau A but also that Jupiter is effectively a point source for both the 90 GHz and 150 GHz detectors (whereas Tau A is an extended 7 arcminute by 5 arcminute source) is reflected in the visibly high map signal-to-noise and that the 90 GHz and 150 GHz beam sizes are visually apparent.

Because Jupiter acts as a point source for both 90 GHz and 150 GHz detectors (with

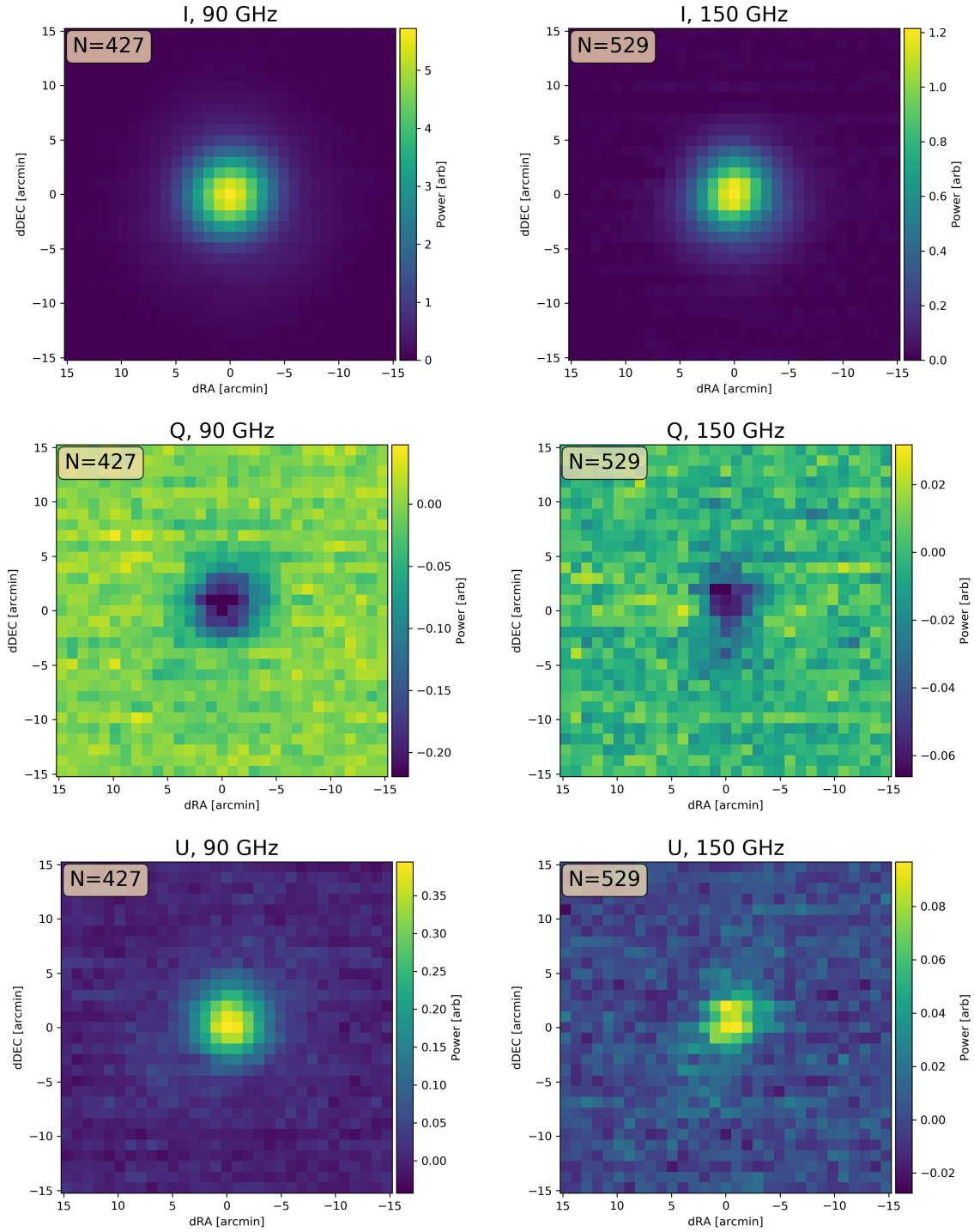


Figure 3.11: I (first row), Q (second row), and U (third row) coadded maps of two POLARBEAR-2a observations of Tau A, for both 90 GHz (left column) and 150 GHz (right column) detectors. After data cuts, a total of 427 90 GHz bolometers and 529 150 GHz bolometers are present in the coadded maps.

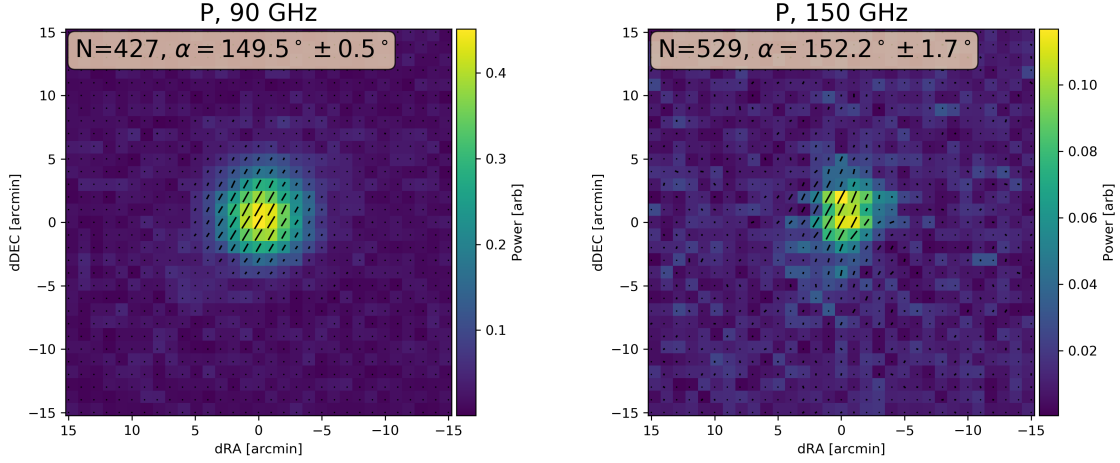


Figure 3.12: Polarization intensity (in arbitrary power units) coadded map from two POLARBEAR-2a observations of Tau A, for both 90 GHz (left) and 150 GHz (right) detectors. The overlaid vectors represent the polarization angle for each map pixel with length proportional to polarization magnitude. Both 90 GHz and 150 GHz polarization angles of $149^\circ \pm 0.5^\circ$ and $152.2^\circ \pm 1.7^\circ$ are in agreement with the IRAM measured angle [16].

detector beam sizes of ~ 5 arcminutes and ~ 3.5 arcminutes respectively), it is a great source to calibrate both the detector pointing offsets on the focal plane as well as the detector beam shapes. These two quantities can be obtained by fitting a 2D Gaussian to the source-masked polynomial-filtered d_{sum} timestreams, where the center of the fits and standard deviations are the detector pointing offsets and beam shapes respectively. One example for this type of detector characterization is shown for a single POLARBEAR-2a observation of Jupiter in Figure 3.15. The left side of this figure shows the measured detector offsets in which the layout of detectors across the focal plane is visually apparent. The beam FWHM in both the major and minor axes for detectors in this observation are shown on the right and the distinction between the beam sizes of 90 GHz and 150 GHz detectors are both clearly seen and approximately the expected values. Both the pointing offsets and beam shapes are used in many other analyses, and are necessary in determining the individual detector polarization angles when simulating a polarized source timestream as described in Section 3.2.2.

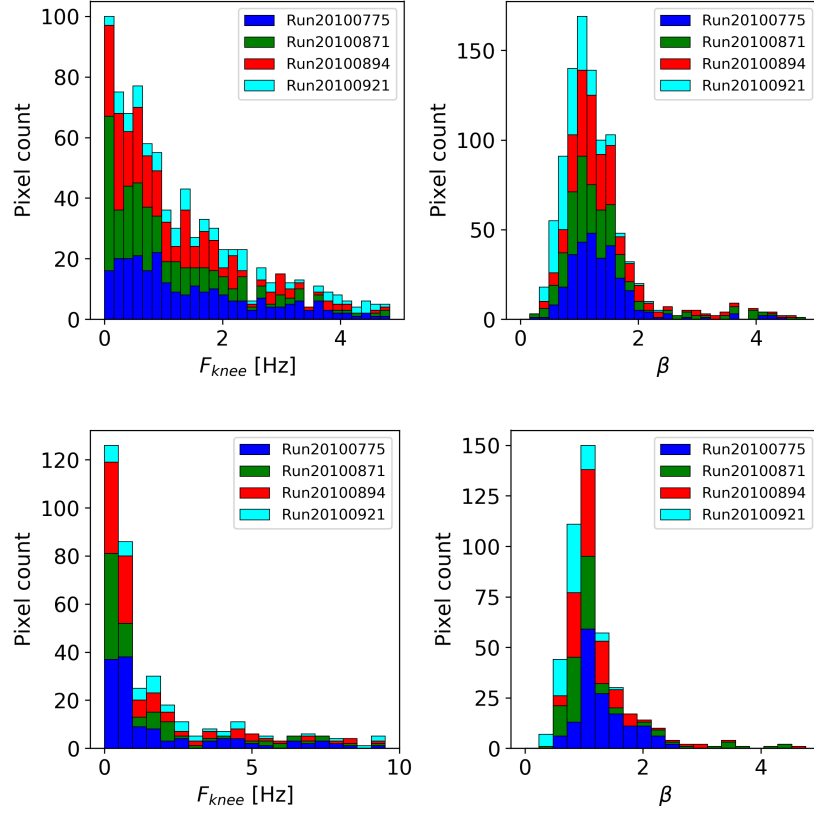


Figure 3.13: The PSD f_{knee} (left column) and β (right column) parameters for four POLARBEAR-2a observations of Jupiter for both 90 GHz (top row) and 150 GHz (bottom row) bolometers.

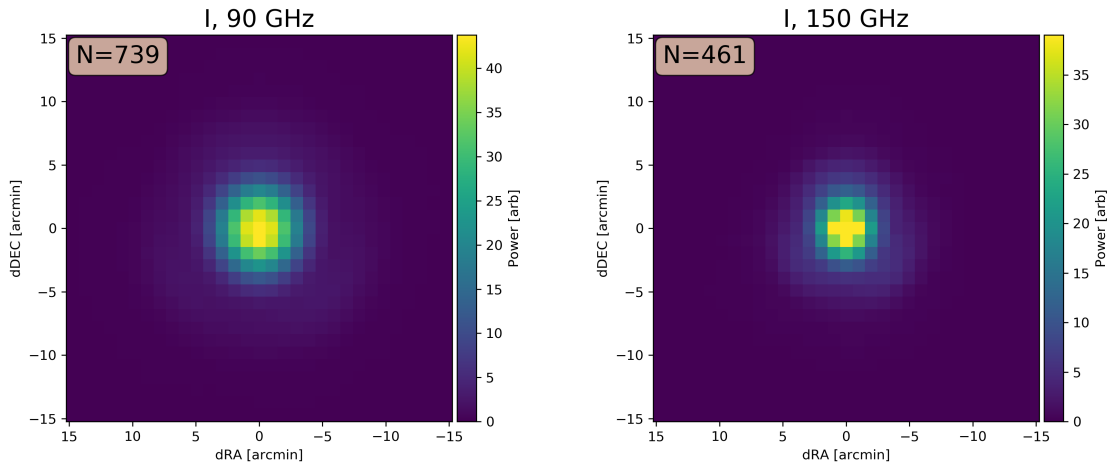


Figure 3.14: Coadded intensity maps of five observations of Jupiter with POLARBEAR-2a for 90 GHz (left) and 150 GHz (right) bolometers.

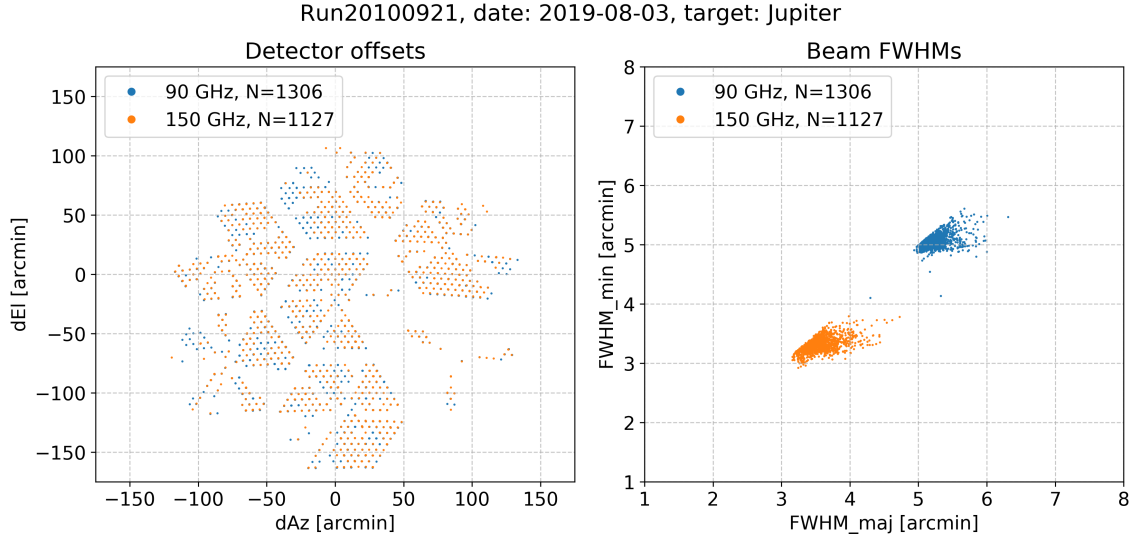


Figure 3.15: Detector pointing offsets (left) and beam shapes (right) for one POLARBEAR-2a observation of Jupiter. After data cuts, 1306 90 GHz bolometers and 1127 150 GHz bolometers remain.

3.4.3 Focusing the Receiver

POLARBEAR-2a first light occurred in January 2019 from observations of Venus and confirmed the receiver’s ability to see a bright unpolarized point source. Over the course of field commissioning the receiver was pistonned in ~ 1 cm increments along the boresight axis four times in the same direction in an attempt to focus the receiver. To check the progression of the focus of the receiver, detector beam shapes are calculated from both Jupiter and Tau A observations between each of the pistonings, with results shown in Figure 3.16. From observing the trend of the beam shape with each pistonning, it is clear that the receiver became progressively more in focus with each pistonning of the receiver. However, a few more pistonings may still be necessary to ensure that the exact focus has been reached.

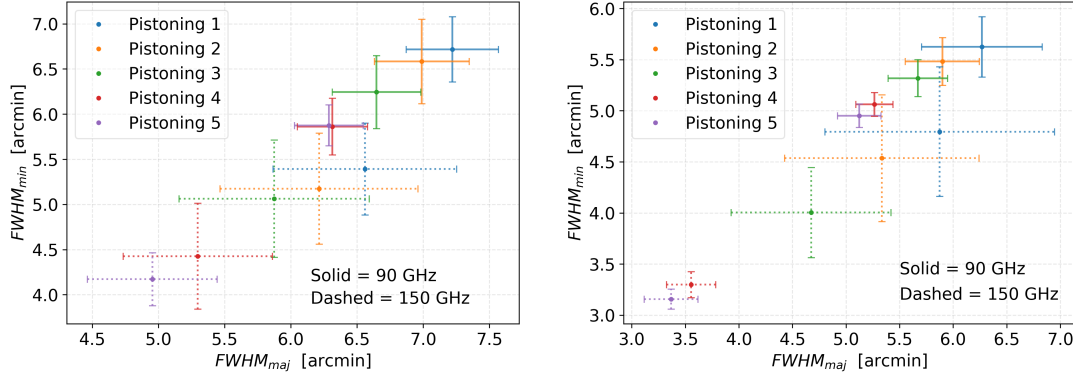


Figure 3.16: Overall beam shape for five POLARBEAR-2a observations of Tau A (left) and Jupiter (right) for both 90 GHz (solid lines) and 150 GHz (dotted lines) detectors. Values and error bars are determined by the inverse variance weighted average and standard deviations of the beam shapes for the observation. Each observation was performed at a different receiver position while trying to focus the receiver, with each pistonings increasing the receiver distance by 1 cm.

3.5 Summary

This chapter focused on observations of the polarized Taurus A nebula for the purposes of polarization calibration of CMB experiments, with example data from the POLARBEAR-1 and POLARBEAR-2a experiments. The process of turning detector time-ordered data into I, Q, U, and P maps was discussed, as well as how to calculate the polarization angle from an observation of a polarized source. Preliminary maps from the first year of commissioning of the POLARBEAR-2a telescope confirmed polarized response of Tau A in agreement with current measurements and validated the beam shape and focus of the telescope from observations of Jupiter. The polarization angle calibration error from observations of Tau A was shown to be of the order $0.5^\circ - 1^\circ$. While this level of uncertainty is currently not limiting constraints on the tensor-to-scalar ratio r , there is a necessity to improve polarization angle calibration precision by about an order of magnitude to improve constraints on CPR-inducing physics. The next chapter will detail the design of an artificial polarization calibration source with the goal of calibrating CMB experiment detector angles to better than 0.1° to enable searches for new Lorentz and parity

violating physics in the CMB polarization.

Chapter 4

Design and Characterization of a Ground-Based Absolute Polarization Calibrator

As we have seen in Chapter 1 and Chapter 3, current polarization calibration standards for modern CMB experiments are only accurate to about half of a degree. Measurements listed in Table 1.2 show that this level of systematic error on absolute calibration angle is not currently sufficient to place meaningful upper limits on the CPR angle α , let alone to claim significant detection. Additionally, pressure to better calibrate CMB detector angles amounts as modern CMB experiments push the upper bound on the tensor-to-scalar ratio r ever lower and will soon be at odds with the current equivalent B-modes generated by detector misalignment as shown in Figure 1.7. Therefore, innovative methods that depart from the standard celestial polarization calibrator must be developed if we are to push the limits on detecting evidence for either parity-violating physics or even primordial gravitational waves in our universe. In this chapter, we focus on ground-based polarization calibrators as a near-term solution to this growing need for more accurate polarization calibration.

Several ground-based absolute polarization angle calibrators have been designed and tested with current CMB experiments [65, 96, 52, 9, 58]. Many existing calibration sources are specifically designed to operate on their respective experiment and cannot be cross-checked using other experiments. Initial source polarization vector referencing also typically requires input from the experiment itself. Here we focus on the methodology and design of a rotating polarized source operating at microwave frequencies with a co-rotating, polarizing wire grid that was designed to avoid the aforementioned issues using a portable, self-contained design that internally references the local gravitational vector without input from the experiment. The science goal for this calibrator is to have the ability to calibrate a CMB detector angle to better than 0.1° .

The rotating polarized source detailed in this chapter (henceforth referred to as POLCAL) underwent two design iterations referred to as “POLCAL phase one” and “POLCAL phase two”. Section 4.1 covers the design and laboratory characterization of the POLCAL phase one iteration while Section 4.2 covers the design modifications and their motivations, as well as the laboratory characterization of the second phase of POLCAL.

4.1 POLCAL Phase One

4.1.1 Design and Hardware

Rotating Chopped Polarized Source

As nearly every CMB experiment includes a wide observation band centered near 150 GHz (where the CMB blackbody spectrum peaks), POLCAL phase one utilizes a 76 GHz Gunn oscillator coupled to a frequency doubler. The Gunn oscillator is further coupled to a Sage Millimeter¹ WR-06 pyramidal horn antenna in order to transmit a linearly polarized signal. The power output of the oscillator was measured to be 0.75 mW integrated across the beam (described

¹Sage Millimeter, Inc. Torrance, CA. www.sagemillimeter.com

in Section 4.1.3) by connecting the waveguide output of the frequency doubler to the waveguide input of a microwave power meter. The Gunn oscillator with doubler and horn antenna are mounted on a motorized rotation stage with a 0.001° precision encoder readout in order to rotate POLCAL's linearly polarized signal by precisely known angles. A co-rotating aluminum cylinder coated with Berkeley Black composite material [78] is mounted around the Gunn oscillator to mitigate stray reflections. To further ensure linear polarization purity of the source, a co-rotating polarizing wire grid is mounted to the end of the blackened aluminum cylinder to a lockable 0.002° precision stage to allow fine adjustment of the wire grid polarization axis with respect to the horn antenna. As the angle of the horn antenna itself is difficult to determine, a precision-ground aluminum plane attached to the wire grid allows for precise calibration of the wire grid to the local gravitational vector as described in Section 4.1.2. The Gunn oscillator circuit, aluminum cylinder with wire grid, and rotation stage system (henceforth referred to as “the source”) are shown in Figure 4.1. In order to differentiate the linearly polarized source signal from ground signal and other systematics, a chopper wheel is installed between the polarizing wire grid and the front of the enclosure. Two photodiodes placed with respect to the chopper blades at 0° and 45° , which correspond to 0° and 90° in phase space due to the chopper consisting of two blades, act as quadrature encoders.

Polarizing Wire Grid

The polarizing wire grid used in POLCAL was manufactured at UC San Diego using the “grid-winder” described in [68] to wrap tungsten wire around a square aluminum frame. Though using the Gunn oscillator in combination with a pyramidal horn provides polarized radiation, it is difficult to precisely measure the angle of the pyramidal horn. Mounting a polarizing wire grid with an attached precision aluminum plane (shown as “plane C” in Figure 4.3) in front of the pyramidal horn allows for a macroscopic surface to measure the angle of the wire grid with respect to the local gravitational vector. To measure the angle of the tungsten wires with respect

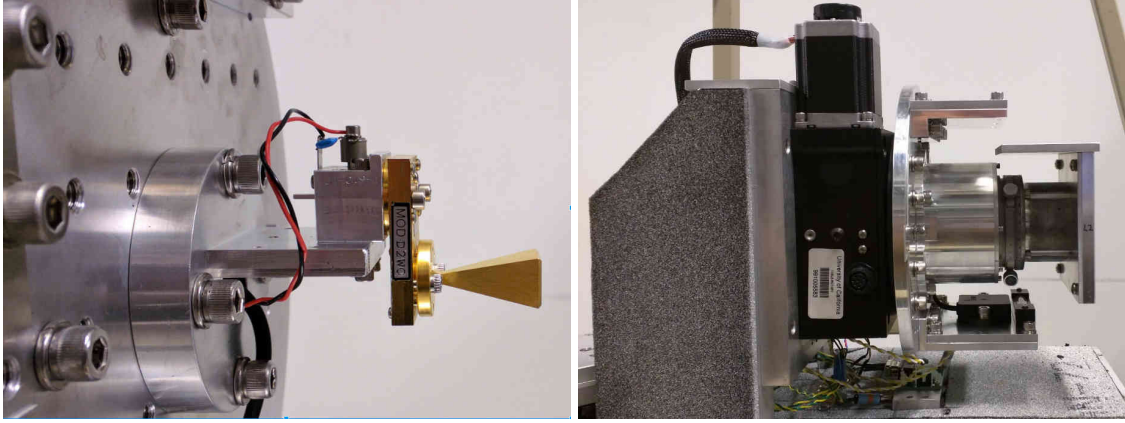


Figure 4.1: *Left:* The Gunn oscillator + doubler + pyramidal horn circuit mounted on the rotation stage. *Right:* The co-rotating blackened aluminum cylinder with adjustable co-rotating polarizing wire grid mounted around the Gunn oscillator circuit.

to the wire grid frame, the slopes of 40 random tungsten wires were measured with respect to the slope of the frame using a microscope and dual-axis translation stage as shown in Figure 4.2. The average angle offset between the 40 wires and the frame was measured to be $0.025^\circ \pm 0.005^\circ$. As it is the frame that is aligned with the local gravitational vector, the measured 0.025° wire offset is accounted for later in analysis.

Enclosure and Pointing

POLCAL's motorized rotation stage is mounted inside a rectangular aluminum enclosure in order to provide ruggedness for handling and protection from the harsh environment at 5200 m in the Atacama Desert. All inner-facing aluminum is coated with Eccosorb² AN-72 to mitigate potential reflections. A circular window is cut out of the front-facing side of the enclosure to allow propagation of the source signal with a diameter set to be 1.5 times larger than the beam FWHM to reduce any diffraction effects that might interfere with the beam. Two weather-tight materials are used for the window: high density polyethylene foam, effectively transparent at 150 GHz, and Eccosorb MF-110 plastic, measured to attenuate a 150 GHz signal by 15.4 ± 0.6 dB per centimeter of thickness. Four modular MF-110 windows with thicknesses 0.635 cm each

²Emerson & Cuming Microwave Products, a unit of Laird Technologies. Chesterfield, MO. www.eccosorb.com

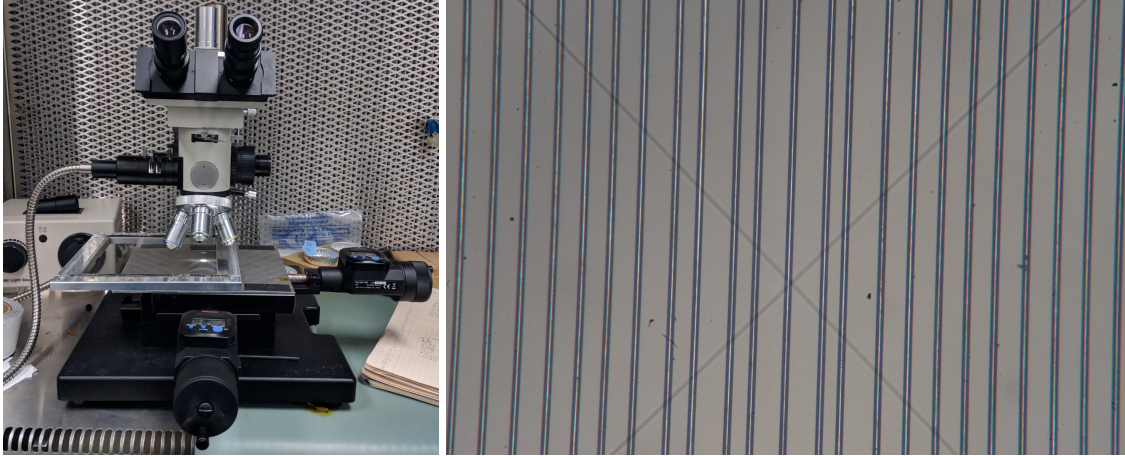


Figure 4.2: *Left:* The microscope and dual-axis translation stage used to measure the angles of the wire grid wires and frame. *Right:* View through the microscope showing some of the wire grid's tungsten wires. The slopes of 40 wires were measured with respect to the measured slope of the edge of the frame to determine the wire-frame angle offset.

provide variable attenuation up to 39 dB.

The enclosure is mounted on an 0.001° precision adjustable azimuthal yaw stage which, in combination with a finder scope mounted on top of the enclosure, can be adjusted for rough pointing towards the telescope. Underneath the yaw stage are two perpendicular one-axis 0.004° precision tilt stages for fine-tuned initial horizontal polarization angle adjustment and vertical pointing. The enclosure and tilt and yaw stages are mounted to a 23 kg Meade³ Giant Field Tripod to provide a sturdy base. The Gunn oscillator power output varies with temperature by -0.4 dB/C° and can be stabilized with self-regulating heating pads placed on the outside of POLCAL enclosure. A thermometer is placed near the Gunn oscillator and measured throughout a calibration scan in order to account for the varied output power. The systematic error corresponding to the temperature dependent Gunn oscillator power is detailed in Appendix ??.

Discussion and images of the full calibrator setup while deployed on an initial engineering test run on the POLARBEAR-1 telescope in the Atacama Desert, Chile in March 2017 can be found in Section 5.1.

³Meade Instruments. Irvine, CA. www.meade.com

4.1.2 Calibration to the Local Gravity Vector

The initial polarization angle of the source is calibrated to the local gravity vector to better than the 0.1° science target by using a 0.006° accuracy bubble level in combination with four precision-ground aluminum planes located within the enclosure. POLCAL is first pointed azimuthally toward the target using the yaw stage beneath the enclosure. Planes A, B, C, and D, as labeled in Figure 4.3, are then leveled by adjusting the two perpendicular, one-axis tilt stages beneath the enclosure, the rotation stage motor position, the polarizing grid's yaw stage, and the micrometer dials on the two-axis tilt stage respectively. The enclosure is then pointed downwards towards the target by using the vertical one-axis tilt stage until the target appears in the optical finder scope. Plane D is then re-leveled and POLCAL's output polarization plane is determined with respect to the local gravity vector by comparing the initial and final values of the two-axis tilt stage micrometer dials. A two-axis 0.01° precision digital tiltmeter is placed on plane D and continuously monitored throughout a measurement to account for any shifts in source calibration angle due to winds, vibrations, or other effects that might permanently shift POLCAL enclosure.

Control Software and Data Acquisition

Both the chopper and rotation stage stepper motors are controlled via a Moxa⁴ NPort 5450 serial device server. The chopper stepper motor is commanded to a single rotation frequency throughout the duration of a measurement while the rotation stage stepper motor is commanded to perform a “scan”, defined as a $0^\circ \rightarrow 360^\circ$ rotation of the source at a specified step size and integration time per step. The integration time is determined by the desired signal-to-noise of the detector response which, for POLCAL coupled to the POLARBEAR-1 telescope, was calculated to be five seconds to ensure a signal-to-noise of over 100. An MCCDAQ⁵ USB-1208FS data acquisition device (DAQ) is used to record the output of the two chopper encoders and a 360°

⁴Moxa. Chesterfield, MO. www.moxa.com

⁵Measurement Computing Corporation. Norton, MA. www.mccdaq.com

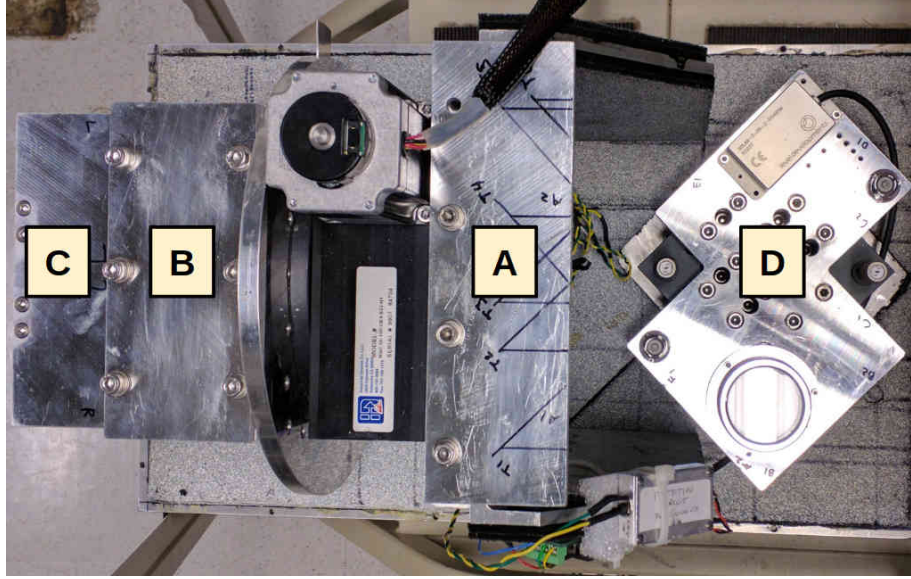


Figure 4.3: The four precision-ground aluminum planes used for calibrating to the local gravity vector. Planes A, B, and C are fixed with respect to the enclosure, rotation stage, and co-rotating wire grid respectively. Plane D is mounted on a 0.001° precision two-axis tilt stage with micrometer dials (fixed with respect to the enclosure) to allow horizontal and vertical adjustment of the plane. Angle measurements of each combination of micrometer dial value were made using a digital tilt meter to determine the angle at each micrometer dial value.

analog tilt stage mounted on the rotation stage for redundant mid-measurement angle validation. The DAQ also monitors an enclosure-mounted encoder coupled to the rotation stage that is used to initialize the source polarization axis before performing a scan.

4.1.3 Laboratory Characterization

Rotating Polarized Signal Model

Detector response is continuously recorded as the POLCAL source performs repeated scans. The detector timestream is separated according to the POLCAL source angle and then demodulated to determine the power incident on the detector. The demodulated signals are fit to the model according to Equation 4.2 to recover the initial offset angle ϕ between the initial POLCAL source and detector polarization planes. If the initial calibrator source polarization plane is referenced to the local gravity vector as described in Section 4.1.2, then ϕ becomes the

absolute detector polarization angle orientation with respect to the local gravity vector.

The ideal demodulated detector signal $S(\theta)$ is expected to follow a cosine curve described by a model of the form

$$S_{ideal}(\theta) = A \cos(2(\theta - \phi)) + B, \quad (4.1)$$

where A is the detector signal amplitude, θ is the source angle, ϕ is the initial angle offset between the source and the detector, and B is a DC offset term. The $\cos 2\theta$ term arises due to the fact that the detector observes two full polarization vector rotations of the POLCAL source as it is rotated between 0° and 360° . If the source is poorly collimated about its rotation axis, Equation 4.1 must be modified to account for the resulting precession and can be accounted for by adjusting the model as

$$S(\theta) = \left(A \cos(2(\theta - \phi)) + B \right) \left(C \cos(\theta - \psi) + 1 \right), \quad (4.2)$$

where C and ψ are the precession amplitude and phase. Figure 4.4 shows an example demodulated detector power timestream from laboratory characterization (described later in Section 4.1.3). Note that this model is only valid for experiments with no modulating optical elements such as a CRHWP. The CRHWP modulated model is discussed in Section 5.2.2.

Characterization with a Room Temperature Diode

A room-temperature, broadband Pacific Millimeter⁶ 110-170 GHz detector diode coupled to a WR-06 pyramidal horn antenna, identical to the POLCAL horn antenna, was used in conjunction with a low-noise voltage preamplifier to characterize the POLCAL polarization signal. The detector and horn antenna were mounted on a dual-axis linear translation stage consisting of two perpendicular linear stages coupled to separate stepper motors to precisely control the position of the detector relative to POLCAL. Eccosorb AN-72 was placed around both POLCAL and detector beams to mitigate reflections and ensure beam purity.

⁶Pacific Millimeter Products. Golden, CO. www.pacificmillimeter.com

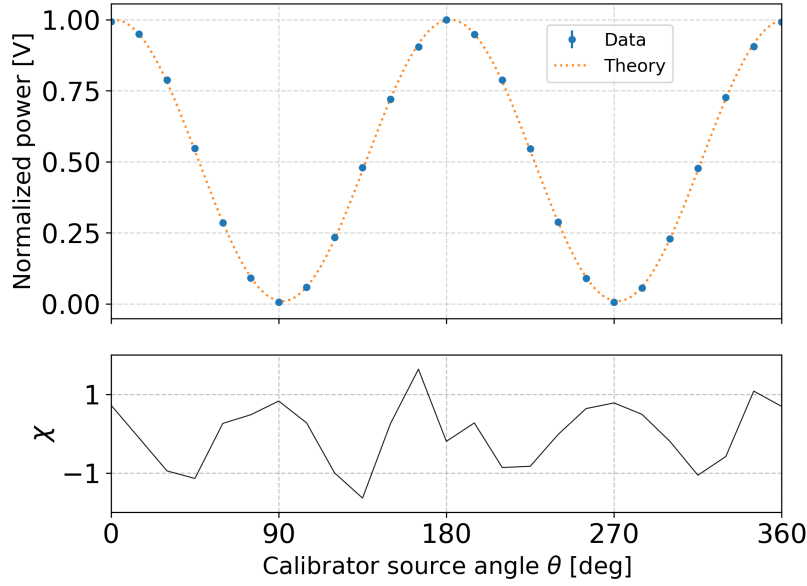


Figure 4.4: *Top:* Normalized, demodulated laboratory detector response (blue) for one example calibrator scan fitted to the model in Equation 4.2 (orange). Normalized error bars represent statistical error only. *Bottom:* Weighted residual between the data and the model with $\chi = (S_{data} - S_{fit})/\sigma_{data}$.

The consistency of POLCAL’s ability to measure the offset angle ϕ between the initial source and detector polarization planes was determined by fixing the position of the detector on the dual-axis linear translation stage and performing repeated $0^\circ \rightarrow 360^\circ$ scans of the source. Calibrator consistency tests were performed on six separate days with varying source and detector setups. After cutting scans with obvious glitches in their respective timestreams, the demodulated detector signal timestreams from 1012 scans taken over the six days were fitted according to the model given in Equation 4.2. Figure 4.5 demonstrates that the offset angle ϕ was measured to within $\pm 0.049^\circ$ over these 1012 scans, confirming POLCAL’s repeatability to within the 0.1° goal.

Measurements of the POLCAL beam were made by fixing the POLCAL source angle and measuring the detector output at various positions using the dual-axis linear translation stage. The beam maps were produced by raster scanning 9 cm by 9 cm in 0.635 cm steps at a source

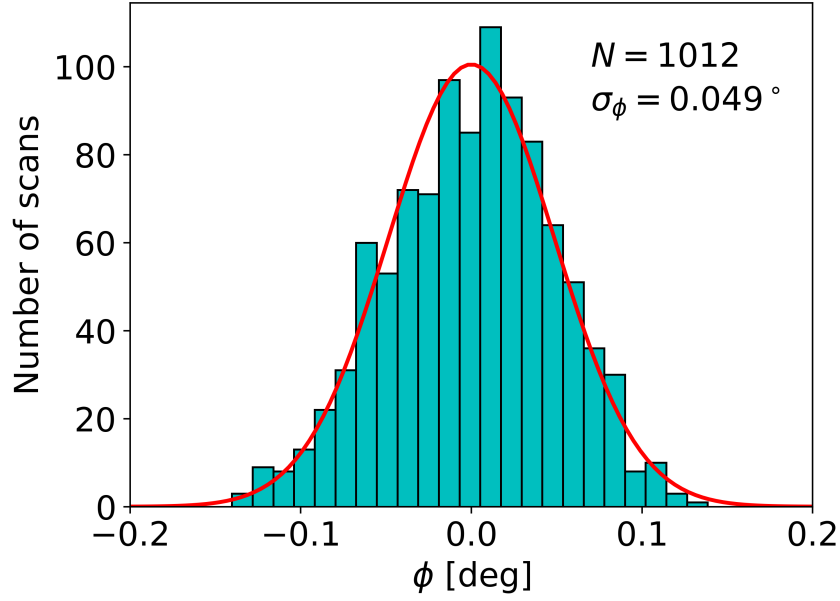


Figure 4.5: Histogram of POLCAL repeatability between 1012 scans. ϕ represents the misalignment angle between the initial source and detector polarization axes (ϕ_{mean} has been subtracted out of the data to center the histogram on zero) and was measured with an error of $\sigma_\phi = 0.049^\circ$ over the 1012 scans.

distance from the detector of 47 cm (which translates to a 10.7° by 10.7° map in 0.77° steps) and are shown in Figure 4.6. All beam map measurements were taken in the far-field of both horn antennas (each of which have a far-field distance of 22.5 cm) and are fitted to a two-dimensional Gaussian function. From beam maps made at calibrator source angles of 0° and 180° , the fitted beam center for the two angles revealed a 0.5° source horn antenna axis misalignment with the POLCAL source rotation axis as described by Equation 4.2. Figure 4.6 also shows the measured E- and H-plane beam profiles in units of dB.

4.1.4 Systematic Error Estimation

Table 4.1 details relevant systematic uncertainties involved in a measurement of absolute detector angle polarization using POLCAL on the POLARBEAR-1 telescope. The total calibrator polarization angle error is calculated to be $\pm 0.013^\circ$ (statistical) and $\pm 0.055^\circ$ (systematic). The statistical errors arise from bubble-level measurements of the system while calibrating to the

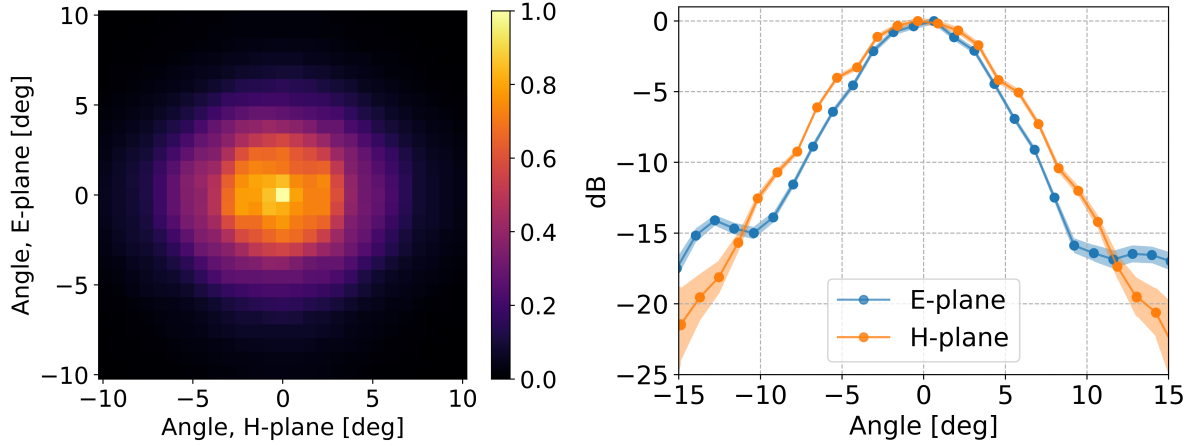


Figure 4.6: *Left:* Beam map of the source and room-temperature detector diode. The two axes represent the E- and H-planes for the two horns and are plotted in degrees. The scale of the heat map is normalized to the maximum beam map value. *Right:* Measured E- and H-plane beam profiles with errors given by the respective shaded regions.

local gravity vector while the systematic errors are estimated by propagating the corresponding systematic model through the analysis pipeline.

The systematic errors reported in Table 4.1 are estimated for deployment of POLCAL on the POLARBEAR-1 telescope as follows.

Electrical Crosstalk

POLARBEAR-1 bolometers are read out using frequency domain multiplexed superconducting quantum interference devices (SQUIDs), with eight bolometers read out per SQUID card. It is assumed that neighboring bolometers on any particular SQUID card experience electrical crosstalk of 2% [10] and that the two bolometers are spaced on the focal plane such that they are not both within the main lobe of the POLCAL beam.

When one bolometer leaks signal power to another in the form of electrical crosstalk the measured polarization angle of the affected bolometer will shift, assuming the two bolometers have differing polarization angles. This angle shift occurs as the resulting measured power of the affected bolometer becomes the sum of the optical power that it would normally measure and the

Table 4.1: Calculated and estimated statistical and systematic errors.

Statistical uncertainties	Angle
Wire-grid misalignment	0.006°
Rotation stage backlash	0.006°
Pre-pointing gravity vector leveling	0.006°
Post-pointing	0.006°
Wire-grid wire wrapping	0.005°
Quadrature sum	0.013°
Systematic uncertainties	Angle
Electrical crosstalk	0.05°
Ground reflections	0.015°
Calibrator beam deformities	<0.01°
Gunn diode temperature stability	<0.01°
Birefringent MF-110 attenuators	<0.01°
Quadrature sum	0.055°

crosstalk-leaked optical power of a bolometer out of phase with itself. To quantify the resulting angle uncertainty from electrical crosstalk we consider two theoretical bolometers, B1 and B2. B1 is assumed to be located at the center of the POLCAL beam on the focal plane while B2 is assumed to be located on the edge of the POLCAL beam such that it observes 10% of the power that B1 does (in reality the spacing of frequency domain neighbors on the focal plane and the POLCAL beam size ensures that this number is much less than 10%). The relative angle between B1 and B2 is assumed to be 45° , the angle at which electrical crosstalk effects are at a maximum. The timestreams for B1 and B2 are simulated for one 0° to 360° scan of the POLCAL source, adding 2% of the B2 signal to the B1 timestream. The model from Eq. 4.2 is fit to the resulting B1 timestream and the angle error uncertainty is estimated to be the difference between the initial modeled angle and the fitted angle ϕ , with a resulting worst-case scenario uncertainty of 0.05° .

Ground Reflections

Radiation that reflects off of the ground between POLCAL and the POLARBEAR-1 telescope will be polarized in the horizontal direction with respect to the reflection surface. The magnitude of the reflected polarized signal varies with the POLCAL source angle and has the effect of skewing measured bolometer polarization angles, as bolometers will measure both the intended POLCAL signal (the phase of which is initialized to the local gravitational vector) and the reflected signal (the phase of which depends on the angle of the surface that reflects the POLCAL signal). A bolometer measuring the sum of these two optical signals with differing phases causes the apparent measured polarization angle of the bolometer to be shifted. The severity of the resulting angular uncertainty depends heavily on the distance between POLCAL and the telescope and the FWHM of the telescope beam.

To quantify the effect of polarized ground reflections on angular uncertainty we consider the following scenario. POLCAL is assumed to be at a distance of 400 meters from the POLARBEAR-1 telescope. The ground is assumed to have a worst-case scenario reflection coef-

ficient of 1. The POLARBEAR-1 primary mirror has a diameter of 2.5 meters and is estimated to be elevated 7 meters above the ground while the POLCAL source is estimated to be elevated 1.1 meters above the ground. The POLARBEAR-1 beam is assumed to be Gaussian with a 3.5 arcminute FWHM (with a $1/\theta^3$ tail) while the POLCAL beam is assumed to be Gaussian with a 34° FWHM. The ground between POLCAL and the telescope is assumed to be linearly increasing in slope. Ray traces produced under these assumptions show that source radiation directed downward with an angle between $8'$ and $19'$ with respect to the ground intercept the telescope primary mirror. The timestream of an arbitrary bolometer is simulated by adding the power from reflected radiation to the expected timestream for a 0° to 360° rotation of the POLCAL source. The difference between the input bolometer orientation and the Eq. 4.2 fitted angle ϕ is considered to be the resulting angular uncertainty. For the assumptions listed above, the effect of reflections on angular uncertainty is calculated to be 0.013° and is rounded up to a more conservative 0.015° .

At a POLCAL-telescope distance of 400 meters ground reflections are not a dominant systematic error due to large reflectance angles when compared to the telescope beam FWHM of 3.5 arcminutes. This effect becomes much more pronounced at large POLCAL-telescope distances when the reflectance angle becomes comparable to the telescope beam FWHM and must be physically mitigated or else accounted for in analysis.

Beam Deformities

While the POLCAL beam is assumed to be a uniform Gaussian with a FWHM of 34° , in reality there are deviations from Gaussian across the beam and slightly differing E- and H-plane beam profiles as shown in Figure 4.6. If the POLCAL source is poorly collimated about its rotation axis, then source beam deviations show up as power deviations in bolometer timestreams that, when fit to Eq. 4.2, result in a systematic error for polarization angle ϕ . To quantify this effect, detector timestreams were simulated as POLCAL rotates between 0° and 360° for a conservative

mis-collimation of 1° . The statistical error of the beam measurement from Figure 4.6 corresponds to a 0.005° shift in ϕ and a conservative 0.01° systematic error is reported in Table 4.1.

Gunn Diode Temperature Stability

Gunn diode oscillator output power typically varies with operating temperature. If the temperature of the POLCAL source varies over the course of a 0° to 360° scan then the variation in source power leads to variations in the detector timestreams which affect fitted angles ϕ . This effect is most prominent if the temperature steadily increases or decreases throughout a calibration scan. The power-temperature variability of the POLCAL source was measured to be $-0.04 \text{ dB}/^\circ\text{C}$. One scan takes about six minutes (assuming 5° scan resolution and an integration time of five seconds per POLCAL source angle) and temperature variation on this timescale for the measurement in Figure 4.5 does not exceed 0.1°C . A conservative 0.2°C variation corresponds to a 0.0075° systematic error and a 0.01° systematic error is reported in Table 4.1. Thermometers mounted near the Gunn oscillator allow for substantial reduction of this systematic in the field as the temperature of the source can be accounted for in the detector timestreams.

Birefringent MF-110 Attenuation

MF-110 sheets used for signal attenuation were machined to a thickness of $0.25''$. In the process of machining, mechanical stress can induce a small amount of birefringence leading to a systematic angle error. Measurements of ϕ both with the MF-110 and without it yield an error less than the statistical error reported in Table 4.1. This error is reduced to less than 0.01° by rotating the MF-110 sheet and measuring ϕ at several MF-110 orientations.

4.2 POLCAL Phase Two

While POLCAL's initial design is sufficient for polarized CMB experiments operating at 150 GHz, a number of modifications were made to the design to accommodate future experiments such as the Simons Array and the Simons Observatory which operate in multiple frequency bands to better disentangle CMB signal from foreground contamination. Other improvements were also made to the phase one design to minimize systematics and ease of use. This section details the modifications and their motivations, as well as the re-performed laboratory characterization for what is known as POLCAL phase two.

4.2.1 Modifications to the Polarized RF Source Circuit

A number of modifications were made to the phase one polarized RF source circuit, which consisted only of the 76 GHz Gunn oscillator coupled to a frequency doubler, modulated by a physical chopper wheel and attenuated with physical MF-110 slabs. The phase two design replaces the Gunn oscillator, the physical chopper wheel, and adds RF circuit elements to attenuate the signal. Each modification is detailed in the following section, with images of the completed phase two polarized RF source circuit shown in Figure 4.7

Replacing the Gunn Diode Oscillator

As modern CMB experiments move towards the usage of multi-chroic detectors, polarized calibration sources used to calibrate absolute detector orientation in these experiments must possess multi-frequency band calibration capability. To accommodate this need, POLCAL's 76 GHz Gunn diode oscillator was replaced with a tunable 75-115 GHz Gunn diode oscillator [23] to cover an observation band centered on 90 GHz. This tunable oscillator can be modularly coupled to the same frequency doubler used in the POLCAL phase one design for calibration at frequencies between 150-230 GHz to cover most of both 150 GHz or 220 GHz centered

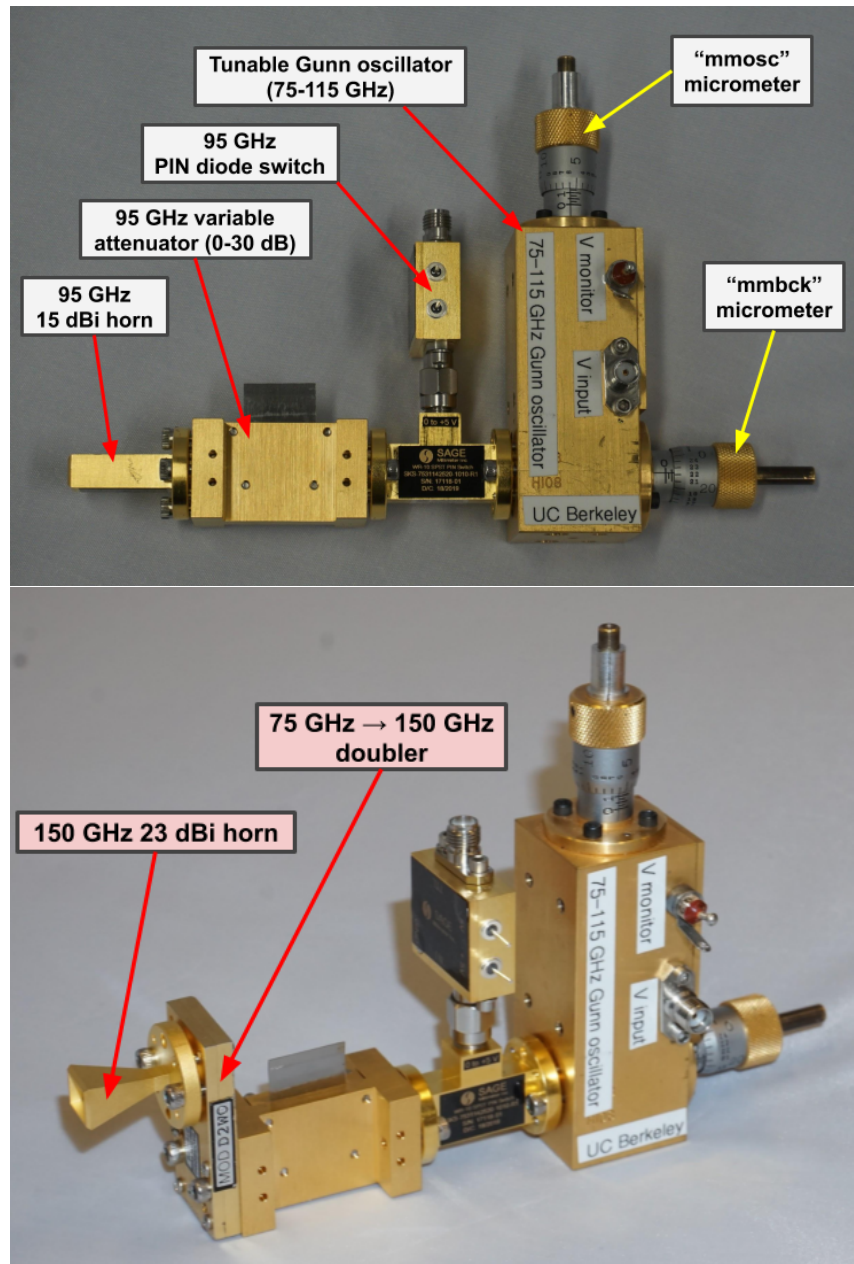


Figure 4.7: *Top:* The 75-115 GHz tunable Gunn oscillator RF source in POLCAL. From right to left, the RF source elements are now: tunable 75-115 GHz Gunn oscillator, PIN switch diode, variable RF attenuator, pyramidal horn. The micrometers labelled “mmosc” and “mmbck” on the Gunn oscillator vary the output frequency and power respectively. *Bottom:* The source with the doubler attached after the PIN switch diode to allow source frequencies of 150-230 GHz. A separate mount is used for this emission band to ensure that the source output horn is aligned with the axis of rotation of the motorized rotation stage due to the geometry of this particular doubler.

observation bands. Unfortunately, this particular frequency doubler was only designed for a bandwidth of 150-152 GHz and there is significant signal attenuation above 152 GHz (though in practice there is enough signal up to 170 GHz to be seen by CMB detectors as will be shown later in this chapter). Future modifications to POLCAL might consider replacing this frequency doubler with a wider bandwidth version. The design of the multi-chroic RF source in POLCAL is meant to be modular such that additional Gunn diode oscillators operating at different base frequencies can be swapped out to calibrate additional observation bands.

Replacing the Physical Chopper Wheel

The largest source of error in both calibration accuracy and mechanical failure for the phase one POLCAL design was the physical chopper wheel used. As the RF horn attached to the Gunn diode oscillator has a wide beam width, reflections and diffraction dominate signal systematics as the chopper wheel moves into and out of the beam. Additionally, the size of the chopper wheel was physically limited both by the enclosure size and requiring that the enclosure aperture be 1.25 times the size of the 17° FWHM of the source horn to avoid further diffraction effects. The balance between these two physical limitations resulted in a duty cycle of less than 50% in which the POLCAL source beam was fully blocked or open, increasing both the required integration time and the difficulty to separate systematic effects.

To solve the aforementioned issues the physical chopper wheel was replaced with a Sage Millimeter RF PIN switch diode⁷. Instead of modulating the source signal by physically blocking the source beam, modulation of the source signal can be achieved with a PIN switch by feeding a TTL square wave signal at the desired chop frequency to the PIN switch. When properly biased, an input “high” signal ($> 3V$) makes the PIN switch act as an RF open circuit and blocks RF power, while a “low” signal ($< 3V$) puts the switch into a closed state and allows RF power to pass through unimpeded. It is important to note that, in practice, the open state of the PIN

⁷Sage Millimeter item # SKU:SKS-7531142520-1010-R1

switch isn't a true open but rather a ~ 25 dB attenuation of the input RF signal. This means that the "off" state of the source may still appear in detector timestreams. However, when fitting demodulated timestreams to Equation 4.2, only the relative amplitudes between the "on" and "off" source state are required (assuming systematics are relatively constant over the course of a calibration scan). The input square wave to the PIN switch is generated by an Arduino Uno⁸ with a modulation frequency chosen by the user before a calibration scan. The PIN switch has a switching time of a few nanoseconds (much lower than expected detector time constants of order tens of milliseconds) and can modulate POLCAL signal between 0-1000 Hz reliably as a near perfect square wave. The previous physical chopper was only capable of modulation up to ~ 15 Hz and slower chopping speeds were effectively meaningless as the chop wasn't a true square wave due to the non-zero beam width of the source. Images of the upgraded tunable Gunn diode oscillator and RF PIN switch diode are shown in Figure 4.7.

Adding Inline RF Attenuation

The only two sources of attenuation in the phase one POLCAL design were a series of four modular MF-110 plates and physical distance from the telescope. In some situations, such as testing in a laboratory where you cannot increase the distance appreciably, more attenuation is desired. To that end, a variable RF attenuator (0-30 dB attenuation) was added inline between the PIN switch diode and the emitting pyramidal horn. The micrometer labelled "mmbck" in Figure 4.7 can be used to attenuate the power output of the Gunn oscillator even further.

4.2.2 Modifications to the POLCAL Enclosure and Pointing

Increasing Exit Aperture Size

The most significant modification to the POLCAL enclosure was a re-design of the front facing aperture. The phase one design set the diameter for the exit aperture to be 1.5 times larger

⁸Arduino. Somerville, MA. store.arduino.cc/usa/arduino-uno-rev3

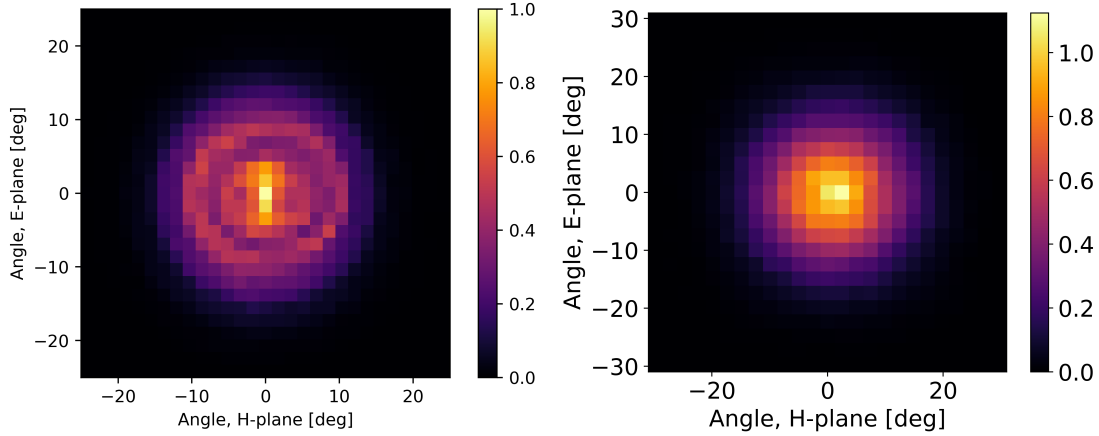


Figure 4.8: *Left:* A beam map measured with phase one POLCAL’s smaller exit aperture. The diffraction from the smaller aperture is visually apparent, as is the truncation of the beam at about 10° . *Right:* Beam map measured with phase two POLCAL’s larger exit aperture. The replacement of the physical chopper wheel with the PIN switch diode allows the aperture to be much larger, significantly decreasing diffraction and truncation of the source’s beam.

than the source beam FWHM. However, as the source is significantly brighter than the expected signal that CMB detectors are designed to observe, reflections and diffraction off of the exit aperture edges were much more prominent than expected. After the physical chopper wheel was replaced with the PIN switch diode, the constraints on aperture size from the physical chopper wheel were lifted and the aperture was expanded to be significantly larger than the size of the new multi-chroic source’s largest beam FWHM. Figure 4.8 depicts beam maps taken with the old and the new aperture size to show the reduction in diffraction and reflection effects.

Replacing the Polarizing Wire Grid

With the increased exit aperture size, POLCAL’s polarizing wire grid needed to be re-designed and constructed to fill the entire aperture to mitigate unwanted systematics involved with rotating the polarized rotation stage. Figure 4.9. shows the upgraded multi-chroic microwave source along with the expanded, beam-filling polarizing wire grid both with and without the enclosure front plate attached. An extra Eccosorb coated aluminum plane was also added to surround the RF source horn to both mitigate reflections and to block view of internal electronics

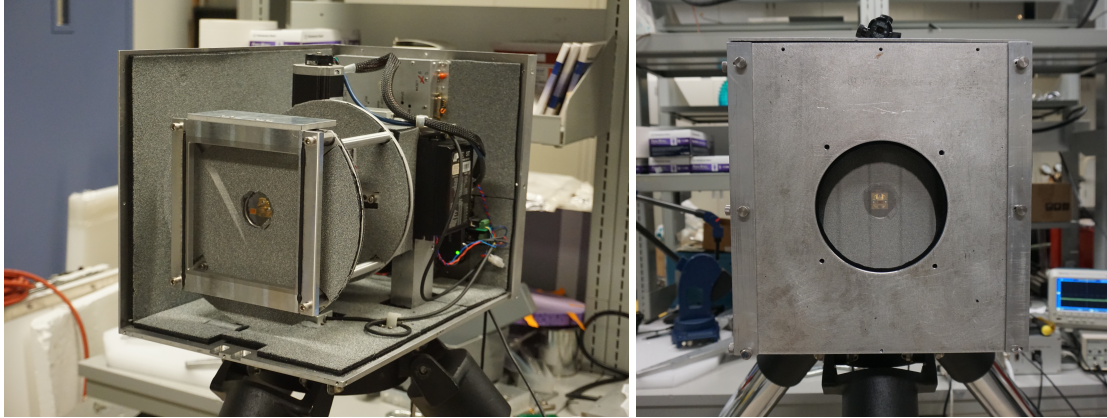


Figure 4.9: The enlarged polarizing wire grid designed to fill the entire expanded aperture for POLCAL. The increase in distance between the source horn and the edge of the wire grid also mitigated potential reflections and diffraction off of the wire grid frame. POLCAL is pictured without (left) and with (right) the new enclosure front plate with exit aperture.

by the telescope.

Adding Digital Tiltmeters

No major changes were made to the method of calibrating POLCAL to the local gravitational vector as described in Section 4.1.2 other than adding a second digital tiltmeter on top of the motorized rotation stage to act as a redundant measurement of the output polarization angle of the source during a calibration run.

4.2.3 Laboratory Characterization

The methodology of laboratory characterization of the POLCAL phase two design iteration follows the model and procedure described in Section 4.1.3 relatively unchanged, except that the analyses are performed for repeated calibration scans at multiple source frequencies. The laboratory testing setup was also improved by enclosing the entire setup in a makeshift Eccosorb room to mitigate reflections and stray radiation. Pictures of this setup are shown in Figure 4.10.

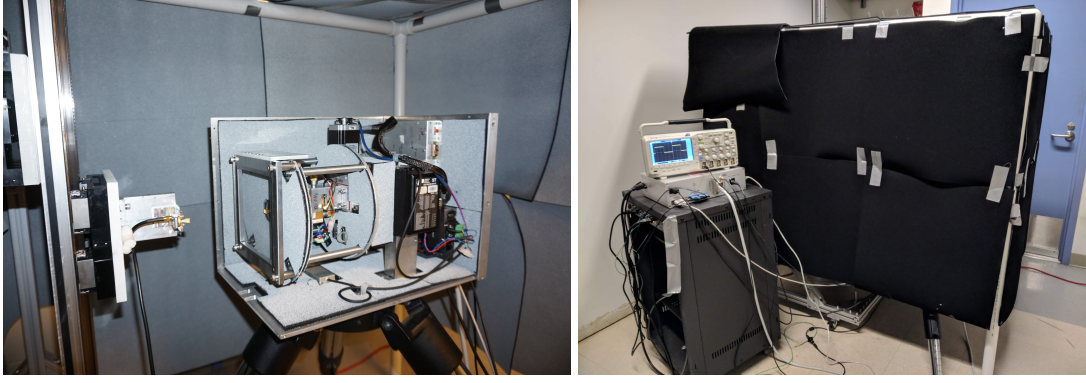


Figure 4.10: Images of the testing setup used to characterize POLCAL phase two in this section. A pseudo-RF room was constructed from PVC pipe and Eccorsorb sheets to mitigate stray reflections and radiation. *Left:* The room temperature diode mounted to the dual-axis translation stage is shown in the left of this image with POLCAL on the right. The enclosure is opened for display purposes only. *Right:* The pseudo-RF room during a measurement.

Phase Two Repeatability

Following the analysis procedure described in Section 4.1.3, Figure 4.11 shows the repeatability of recovering the initial offset angle between the source and detector polarization planes between multiple calibration scans at multiple frequencies within the POLCAL emission band. As with the case in phase one testing, scans at any given frequency were taken over multiple days and various source distances to test for any time-varying or leveling-procedure systematics. From Figure 4.11 it is clear that the repeatability of the new tunable, PIN switch modulated polarized RF source is as accurate as the simpler phase one source, with a repeatability error $\sigma_{\phi_{total}}$ of $\sigma_{\phi_{total}} = 0.046^\circ$. This is consistent with the goal of calibrating CMB experiment detector angles to better than 0.1° to improve current calibration standards in the search for parity-violating physics from CPR in our universe.

Phase Two Beam Maps

Likewise, the methodology for measuring beam maps for POLCAL phase two remains unchanged from the phase one procedure described in Section 4.1.3. Beam maps and E- and H-plane beam profiles were measured at multiple frequencies within the tunable source bands

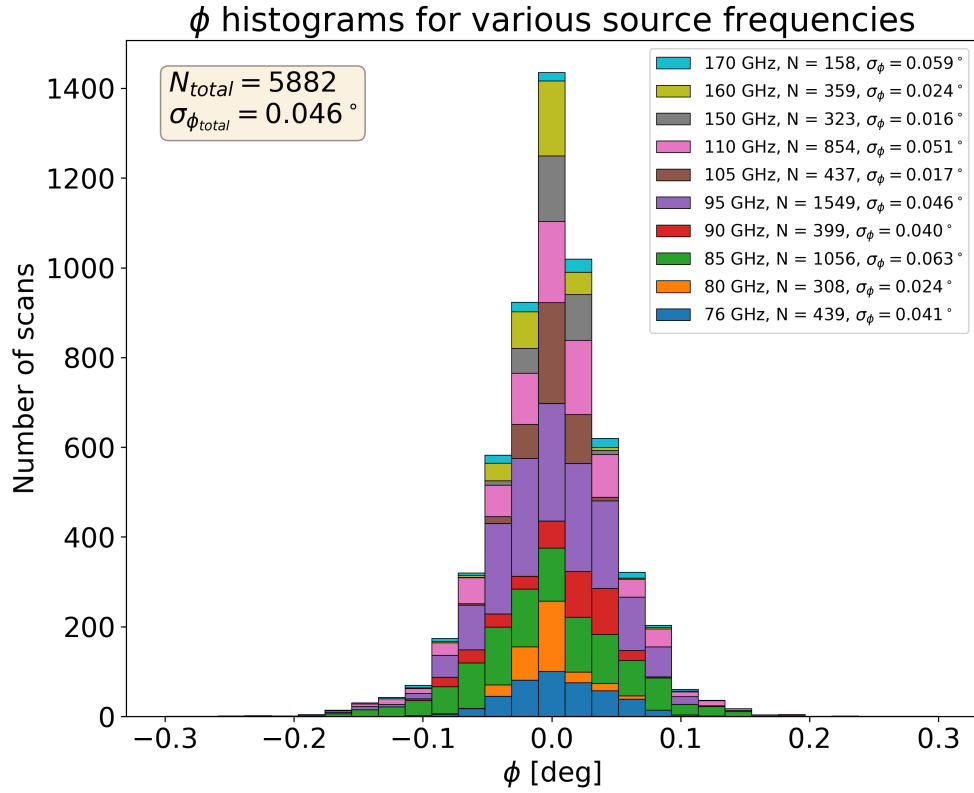


Figure 4.11: Stacked histogram of repeatability between calibration scans using POLCAL phase two at various frequencies. The error in recovering the initial offset angle for all individual POLCAL frequencies is less than 0.1° , with the total error of the stacked histogram over 5882 total scans being $\sigma_{\phi_{total}} = 0.046^\circ$ (better than the POLCAL phase one repeatability error of 0.049° reported in Figure 4.5).

and are shown in Figures 4.12, 4.13, and 4.14. A summary plot of the E- and H-plane FWHM measurements is shown across both the 95 GHz and 150 GHz bands in Figure 4.15.

4.3 Summary

This chapter describes the design and laboratory characterization of a ground-based absolute polarization calibrator that was commissioned to meet demands to increase the precision of polarization calibration on CMB experiments to place tighter constraints on the tensor-to-scalar-ratio r as well as to reduce upper limits on the CMB TB and EB correlations to allow for searches of evidence of CPR effects from Lorentz or parity violating physics. The repeatability of calibration was shown to be precise to better than 0.1° using a room-temperature detector diode throughout both the 90 GHz and 150 GHz operational bands and the respective beam shapes were shown to be free from systematic anomalies. The next chapter will present results from calibrator testing on both the POLARBEAR-1 telescope and the POLARBEAR-2b receiver.

4.4 Acknowledgements

Section 4.1 is an updated reprint of material as it appears in: M. F. Navaroli, K. D. Crowley, G. P. Teply, N. Galitzki, J. P. Kaufman, B. Keating, and K. S. Arnold. “Design and characterization of a ground-based absolute polarization calibrator for use with polarization sensitive CMB experiments.” *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, page 80. SPIE, Jul 2018. The dissertation author was the primary author of this work.

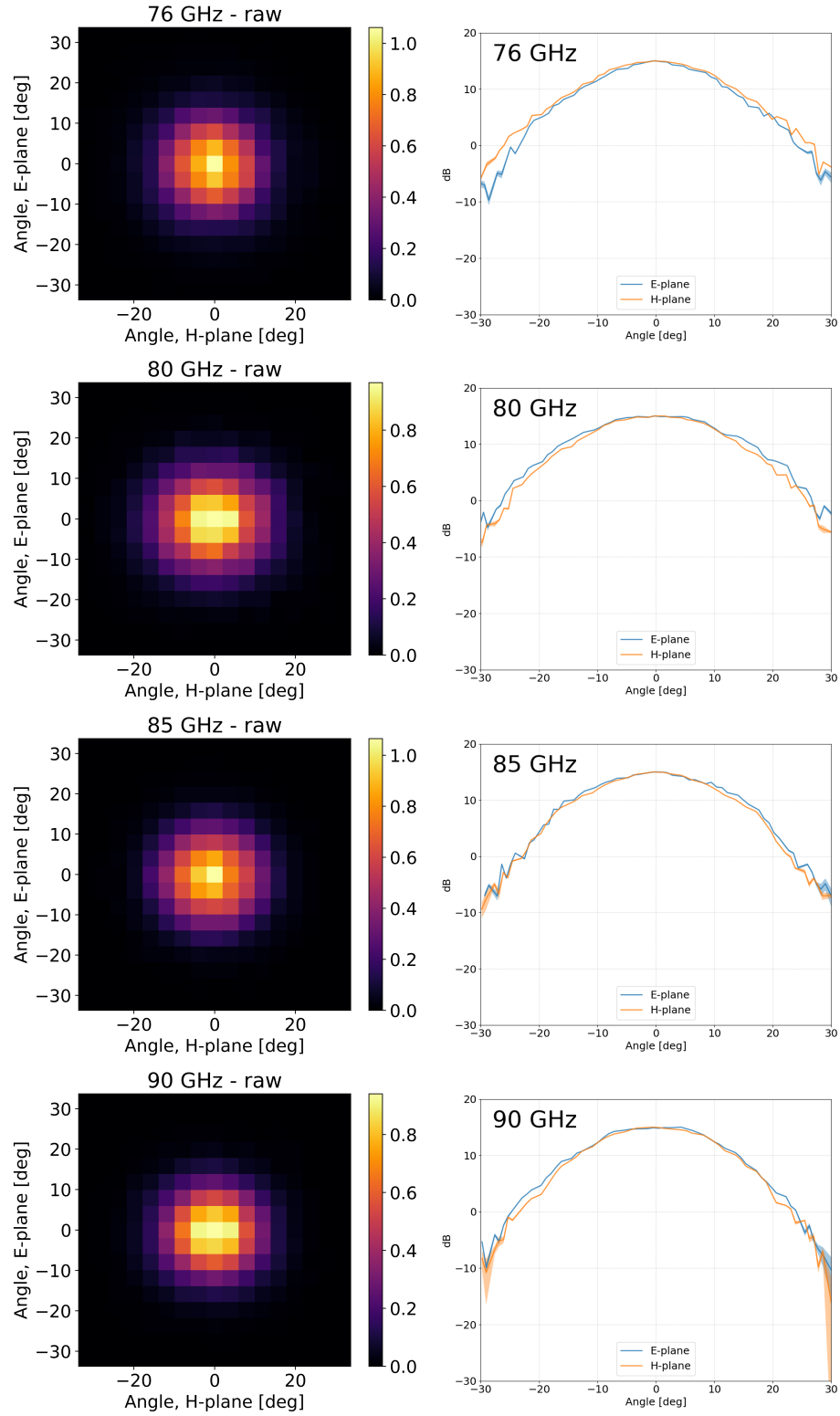


Figure 4.12: Beam maps and E- and H-plane beam profiles measured in the 95 GHz band. Measurements were made at source frequencies of 76, 80, 85, and 90 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.

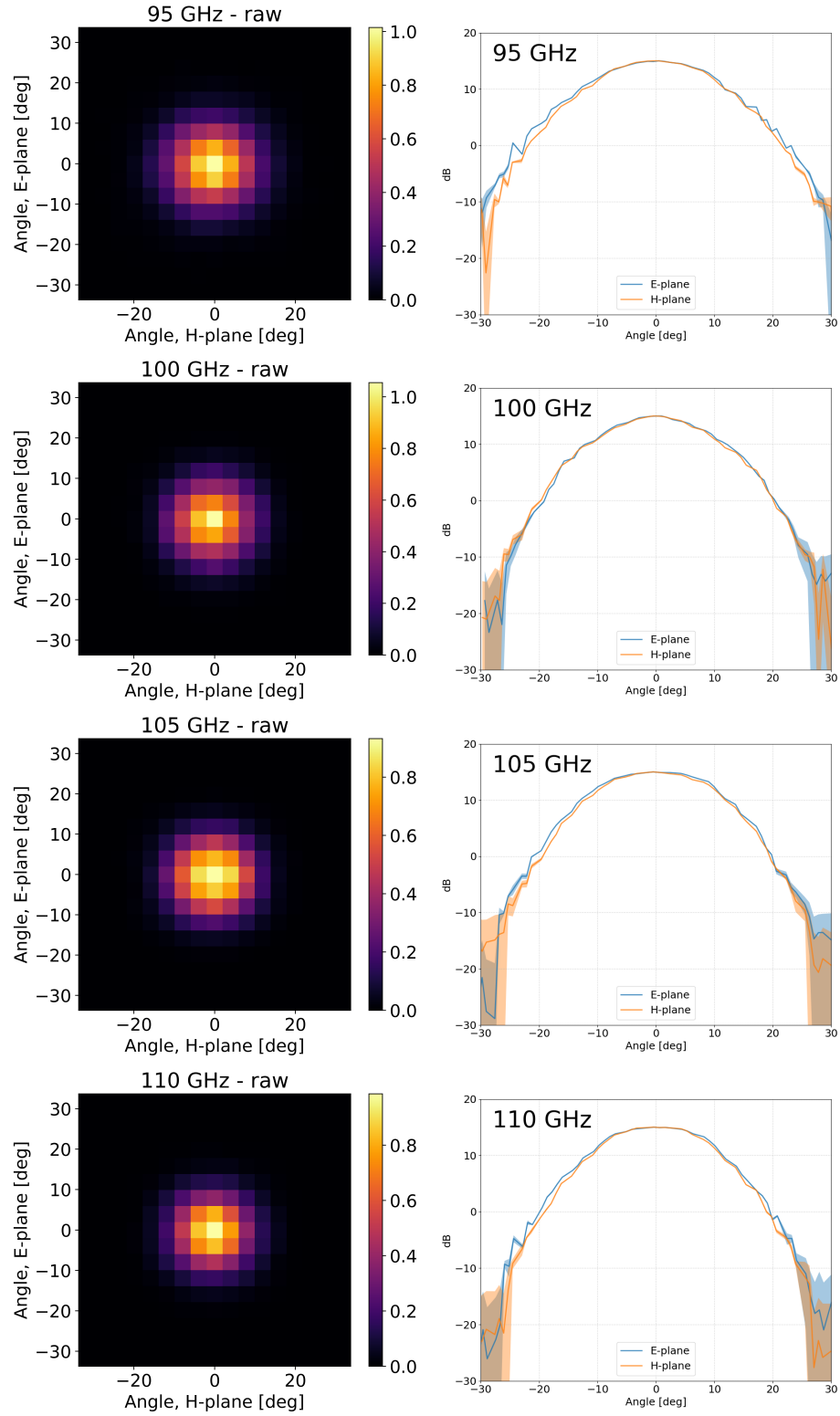


Figure 4.13: Beam maps and E- and H-plane beam profiles measured in the 95 GHz band. Measurements were made at source frequencies of 95, 100, 105, and 110 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.

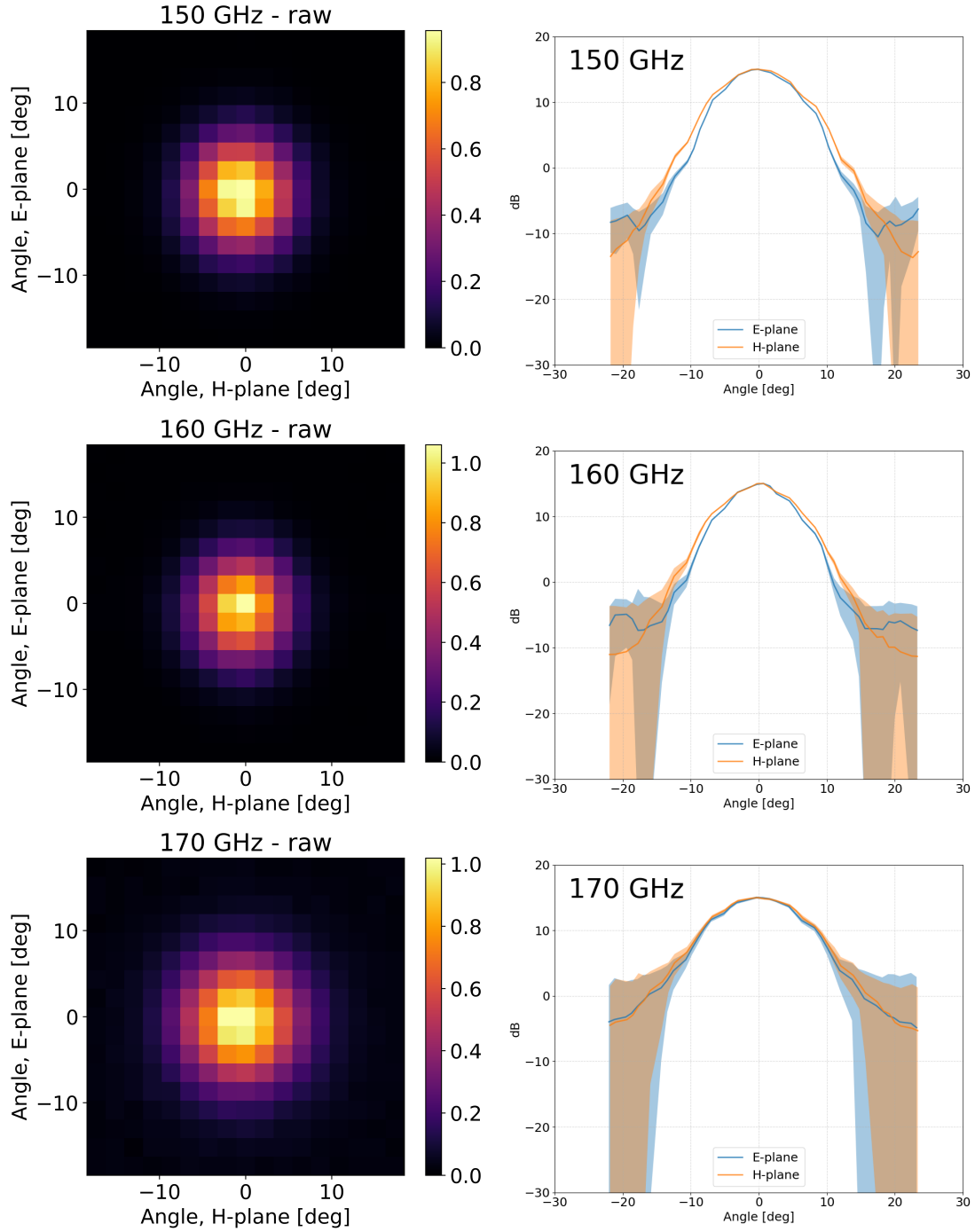


Figure 4.14: Beam maps and E- and H-plane beam profiles measured in the 150 GHz band. Measurements were made at source frequencies of 150, 160, and 170 GHz. Shaded regions in the beam profiles represent the statistical error in the respective measurement.

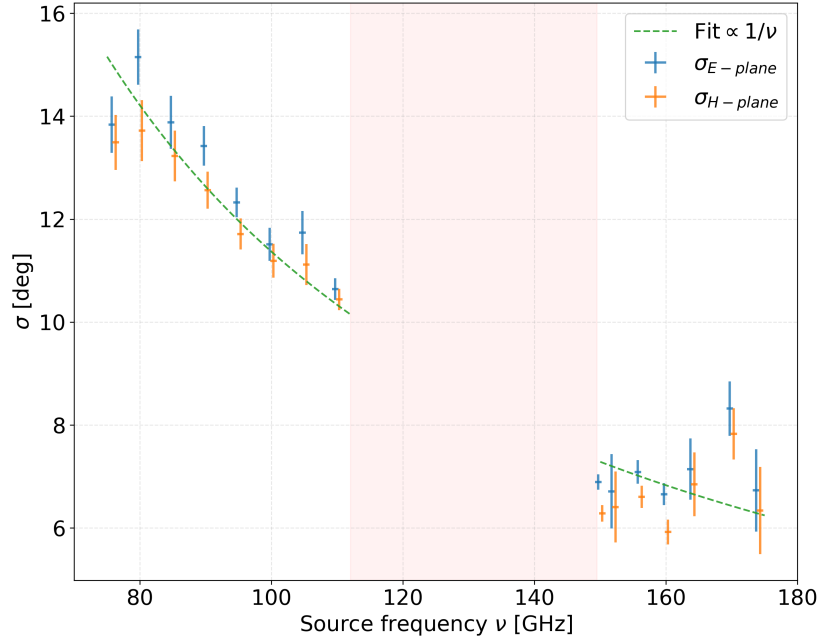


Figure 4.15: E- and H-plane FWHM fitted values (blue and orange, respectively) plotted against POLCAL source frequency (offset by ± 0.5 GHz for visual purposes). Fit values come from 2D Gaussian fits to the maps and beam profiles in Figures 4.12, 4.13, and 4.14. The shaded red area shows output frequencies unavailable to the POLCAL source. The expected inverse proportionality of beam FWHM to frequency is shown in green.

Chapter 5

Results From POLCAL Polarization

Calibration on the POLARBEAR-1

Experiment and POLARBEAR-2b

Receiver

While the previous chapter detailed the design and laboratory characterization of the absolute polarization calibrator called POLCAL, this chapter will focus on results from performing POLCAL calibration scans on actual CMB experiment cryogenic receivers. Section 5.1 reports data taken with POLCAL phase one on the POLARBEAR-1 telescope from a deployment in March 2017, while Section 5.2 reports results from POLCAL phase two testing on the POLARBEAR-2b receiver in the laboratory in November 2019.

5.1 POLCAL Deployment on the POLARBEAR-1 Telescope

The POLCAL phase one calibrator was deployed to Chile for two and a half weeks in March 2017 for testing on the POLARBEAR-1 telescope. The primary goal of this deployment was to verify operating and analysis procedures on an existing cryogenic receiver and make note of improvements or changes to be made for a second, final calibration run on the POLARBEAR-1 telescope. Due to unresolved issues with the telescope control electronics and the imminent deployment of the first of the three Simons Array telescopes, only this first engineering test run deployment was performed for POLCAL calibration of the POLARBEAR-1 telescope. In this section we present the calibration results from this first deployment that verified the ability to determine reasonable detector polarization angles from a POLCAL calibration scan on a CMB experiment in the field.

5.1.1 POLCAL Observation Strategy

During POLCAL's two and a half week deployment, POLARBEAR-1 observed POLCAL calibrations scans on five days from a telescope-calibrator distance of about 400 meters. This distance is notably located in the near-field of the POLARBEAR-1 telescope and was chosen because observations with POLCAL located at the neighboring Tokyo Atacama Observatory (TAO) at a far-field distance of ~ 6 kilometers was not possible due to complications with the road leading to TAO. Two of the five days of observations were not considered in the final data analyses due to poor weather during calibration scans. Images of POLCAL on the Cerro Toco saddle pointed towards the POLARBEAR-1 telescope are shown in Figure 5.1.

POLCAL calibrations scans with POLARBEAR-1's CRHWP not spinning were performed identically to the procedure laid out in Section 4.1.3, with analyses following the same procedure as with the laboratory room-temperature diode characterization by fitting demodulated bolometer timestreams to Equation 4.2. It is important to note that any calibration scans performed

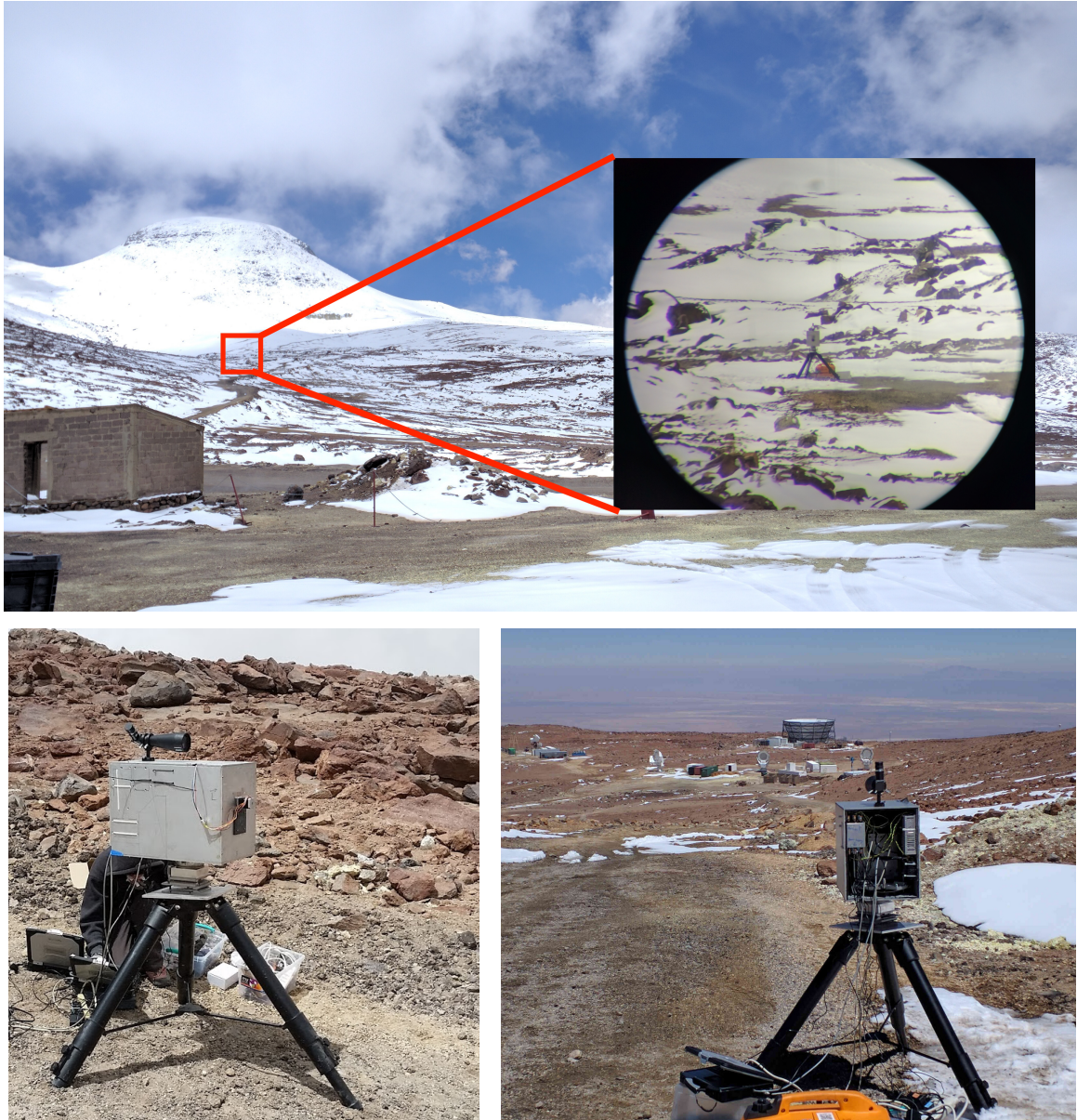


Figure 5.1: Images of the POLCAL calibrator on the Cerro Toco saddle during the POLARBEAR-1 engineering test run deployment.

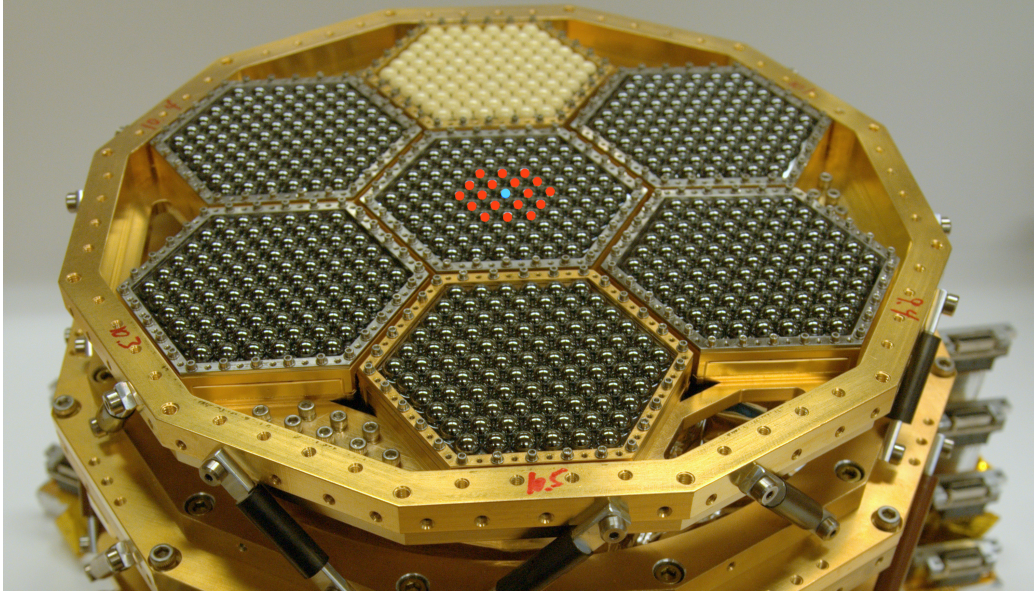


Figure 5.2: Photo of the POLARBEAR-1 focal plane with the center wafer’s central pixel highlighted in blue and surrounding 18 pixels marked in red. The beam size of POLCAL on the focal plane is such that each of the highlighted pixels saw non-zero chopped, polarized optical signal with signal-to-noise dropping with distance from the center pixel. Original image from [54].

with the CRHWP stationary can only determine relative detector angles as the CRHWP angle is only recorded while it is spinning. To get an absolute polarization calibration reference, several calibration scans were performed with the POLARBEAR-1 CRHWP spinning, with calibration procedure and analyses similar to that of calibration of the POLARBEAR-2a receiver which will be described in Section 5.2.

Before each calibration scan POLCAL was calibrated to the local gravitational vector as per the procedure described in Section 4.1.2. POLCAL was then pointed downwards a few degrees towards the POLARBEAR-1 telescope and plane D from Figure 4.3 was re-levelled to the gravitational vector with any angle offsets from pointing recorded and taken into account in the analyses. As the POLCAL beam on the POLARBEAR-1 focal plane is ~ 3 pixels in diameter, the goal for this deployment was to calibrate the center and surrounding pixels for each wafer. An image of an example POLARBEAR-1 wafer and the location of pixels that had a high signal-to-noise response from POLCAL calibration scans is shown in Figure 5.2.

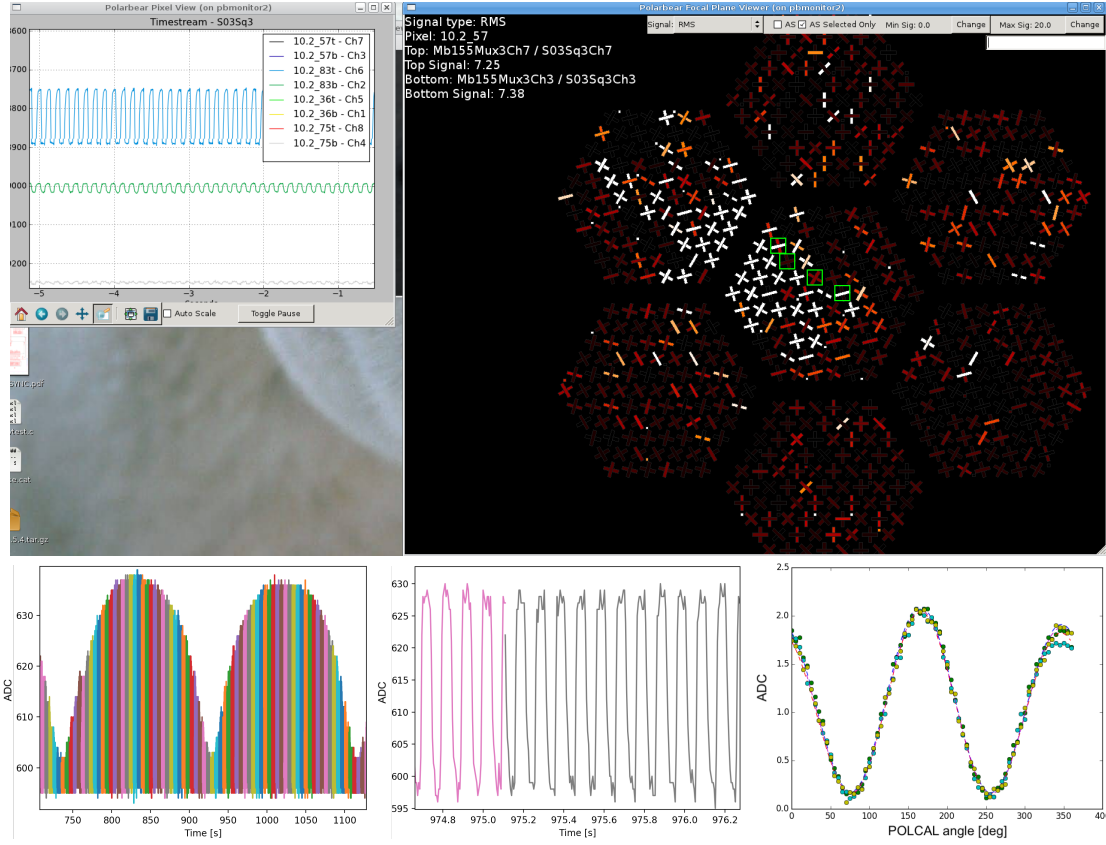


Figure 5.3: *Top:* Screen shot of the live focal plane viewer that shows the first observed chopped polarized POLCAL response in POLARBEAR-1 detector timestreams, with bolometers that see high optical power illuminated in white. *Bottom Left:* An example detector timestream that has been separated and color-coded according to each POLCAL calibration angle step throughout the scan. *Bottom Middle:* A zoom-in of ~ 2 seconds of the timestream shown in the left figure. *Bottom Right:* The demodulated timestream for three successive calibration scans (blue, yellow, and green) plotted according to corresponding POLCAL angle step.

5.1.2 Chopped Polarized Optical Signal and Demodulation Verification

One of the primary goals of the first engineering test run of POLCAL on the POLARBEAR-1 telescope was to verify that detectors on the telescope actually saw the chopped POLCAL signal and to show that the analysis procedure to determine detector polarization angles could be carried out. Figure 5.3 shows the POLCAL “first light” and a sample detector’s timestream during a POLCAL calibration scan, which confirmed several important engineering run goals. First, it was verified that raw detector timestreams were visually consistent with a polarized sinu-

soidal response as the POLCAL rotation stage angle was stepped between $0^\circ - 360^\circ$. Zooming in on these timestreams also confirmed that modulation from the physical chopper wheel was observed. Lastly, demodulating the chopped timestreams at each POLCAL angle revealed that the demodulated sinusoidal signal could be fit to Equation 4.2 to determine each individual detector's observed relative polarization angle.

5.1.3 POLCAL Derived Detector Angles and Comparisons to Tau A Calibration

Once the relative detector polarization angles from many POLCAL calibration scans are determined, the inverse-variance weighted average angles between all calibration scans are calculated for each detector. A natural way to check the self-consistency of the calibration is to calculate the orthogonality of derived top and bottom PSB pixel-pair angles $\Delta_{tb, meas}$ (expected to be 90°), analogous to the self-consistency check of the Tau A derived polarization angles shown in Figure 3.9. The results from the self-consistency check for $\Delta_{tb, meas}$ as measured with POLCAL on the POLARBEAR-1 telescope is shown in Figure 5.4, as is the comparison to the respective $\Delta_{tb, TauA}$ values as calculated from Tau A calibration detailed in Section 3.3. Between all performed calibration scans, POLCAL pointed at three separate wafers allowing for a total of 57 pixels to be calibrated assuming the center 19 pixels of each wafer has high signal-to-noise ratios. After cutting bolometers with poor signal-to-noise and obvious non-linearities, a total of 45 PSB-pixel pairs remained with a majority of the pixels residing on center wafer 10.2 as most calibration scans were performed pointed at this wafer. The average orthogonality for PSB pixel-pair angles from POLCAL polarization angle calibration is calculated to be $90.26^\circ \pm 1.90^\circ$ from a 1D Gaussian fit to the resulting histogram, in good agreement with the design value of 90° . The average difference between the POLCAL measured orthogonality values and their respective Tau A derived values (from Figure 3.9) is calculated to be $0.01^\circ \pm 1.26^\circ$ from another 1D Gaussian fit.

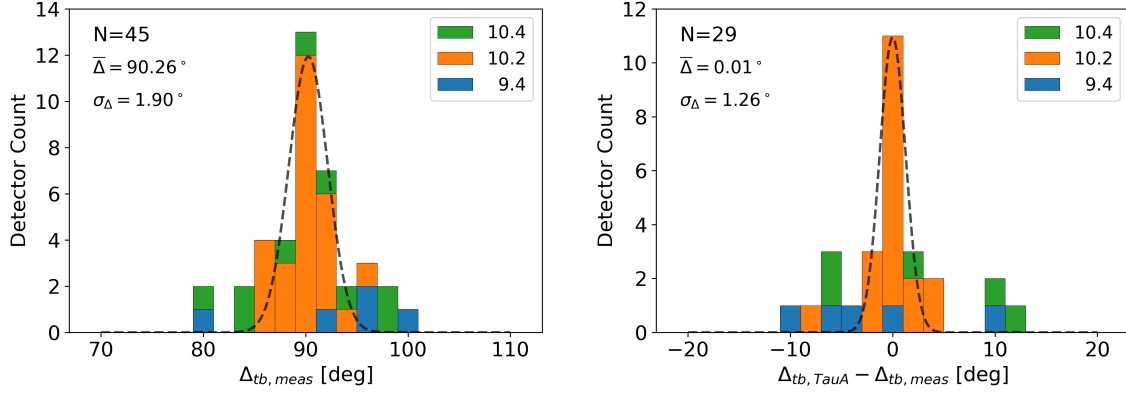


Figure 5.4: *Left:* The orthogonality $\Delta_{tb, meas}$ for 45 pixels across three wafers as measured with POLCAL on the POLARBEAR-1 telescope. The dashed black line is a 1D Gaussian fit to the data with fitted parameters shown in the top left. *Right:* The difference between the POLCAL derived orthogonality and the Tau A derived values. Not all pixels have a recorded Tau A orthogonality value, so only the 29 pixels that do are plotted here.

The results shown in Figure 5.4 confirms that POLCAL can effectively determine the polarization angles of detectors and yields similar results to calibration against observations of polarized celestial sources such as Tau A. However, the systematic error from this POLCAL deployment appears to be of the order ~ 1 degree. This is likely due to a number of unfortunate circumstances during this first deployment such as accidental saturation of bolometers and unintentional beam systematics involved with the physical chopper wheel and smaller exit aperture size. Both of these issues have been corrected in POLCAL phase two, but POLCAL was unfortunately not re-deployed on POLARBEAR-1 as intended due to de-commissioning of the telescope in favor of the Simons Array experiment.

5.2 POLCAL Demonstration on the POLARBEAR-2b Cryogenic Receiver

To further characterize POLCAL as a CMB experiment polarization angle calibration source and validate POLCAL operating procedure, calibration scans using POLCAL phase two

were performed and analyzed on the POLARBEAR-2b cryogenic receiver in the laboratory. Pictures of the test setup are shown in Figure 5.5. While these calibration scans were performed, three of the seven wafers on the focal plane were optically open to incoming radiation (while the other four were optically blocked for dark testing), each with varying thicknesses of MF-110 neutral density filters placed in front of them to prevent detector saturation in the laboratory setting. This implies that 3,252 of the 7,588 bolometers on the focal plane had the potential to be polarization calibrated because the POLCAL source illuminates the entire focal plane when the receiver is de-coupled from the telescope, as it was in the laboratory. The remainder of this section will present results of measurements of detector time constants, polarization angles, and “polarization wobble” (to be explained below) estimations from POLCAL calibration scans performed on the POLARBEAR-2b receiver.

5.2.1 Bolometer Time Constants

A TES bolometer requires some finite amount of time (referred to as the “bolometer time constant”) to respond to changes in optical power. The time constant τ is unique to each bolometer and can be calculated from several inherent characteristics of the bolometer, defined as

$$\tau = \frac{C}{G}(\mathcal{L} + 1)^{-1} \quad (5.1)$$

where C is the bolometer heat capacity, G is the bolometer-bath thermal link conductance, and $\mathcal{L}$ is the bolometer loop gain. The quantity $\tau_0 = C/G$ represents the “natural time constant” of a bolometer in the absence of electrothermal feedback. The loop gain $\mathcal{L}$ dictates the strength of the electrothermal feedback in a bolometer and is a ratio of the change in electrical bias power to the change in total power.

Data taken using POLCAL on the POLARBEAR-2b receiver makes use of a cryogenically cooled continuously rotating half-wave plate (CRHWP). If the bolometers responded to changes

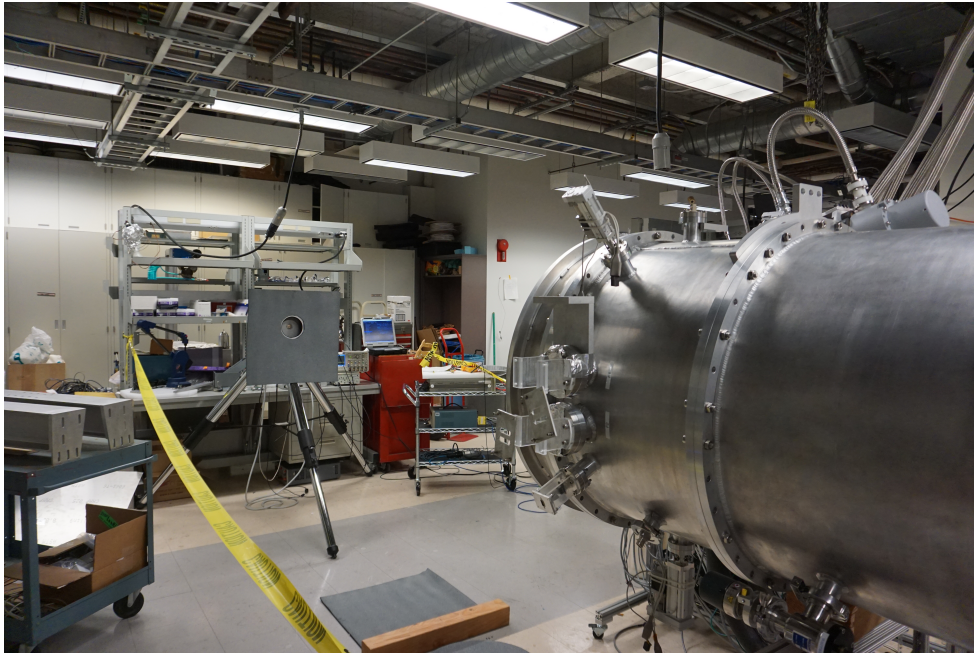
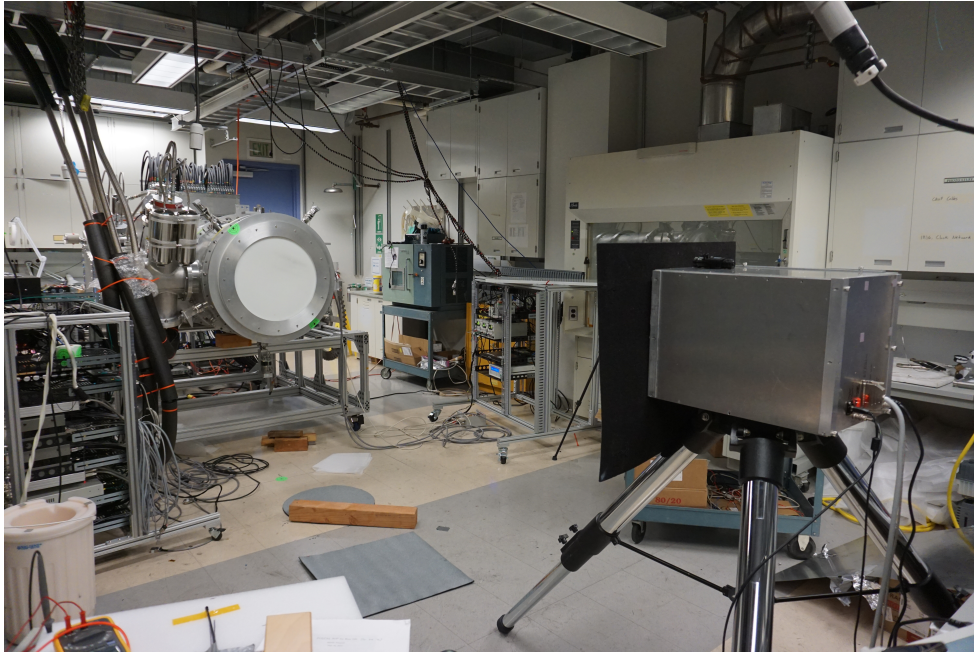


Figure 5.5: *Top:* Image of POLCAL pointed towards the POLARBEAR-2b receiver in the laboratory. *Bottom:* Another image of the same setup but from the opposite perspective.

in optical power instantaneously then we could simply demodulate the CRHWP signal with no further processing needed to obtain the optical power incident on detectors as a function of time. In reality, the bolometers have non-zero time constants which must first be deconvolved from the detector timestreams to get the appropriate optical power incident on detectors at any given time. As the CRHWP rotates at ~ 2.7 Hz (or ~ 1000 degrees per second), every millisecond of time constant unaccounted for will result in about a one degree error in determining the polarization angle of incoming polarized radiation. Therefore it is critical to characterize each bolometer's time constant before demodulating the CRHWP signal.

Bolometer time constants effectively act as a single-pole low pass filter in which the amplitude of a modulated polarized thermal source is deteriorated as the modulation frequency increases. Specifically, the amplitude as a function of modulation frequency is given by

$$A(f) = \frac{A_0}{\sqrt{1 + (2\pi f\tau)^2}} \quad (5.2)$$

where τ is the bolometer time constant, f is the modulation frequency, and A_0 is the maximum amplitude at low modulation frequency. The time constants can be measured directly by varying the modulation frequency f , measuring the amplitude of the modulated signal, and fitting the resulting curve to Equation 5.2 for τ . This procedure to find bolometer time constants was performed by Tucker Elleflot using POLCAL on the POLARBEAR-2b receiver for ~ 100 bolometers, the procedure and results of which are detailed in Section 5.3 of [35].

The PIN switch used in POLCAL modulates the signal to an effective square wave (as the switching speed of the PIN switch is of order a few nanoseconds), but the bolometer time constants have the effect of smoothing out this square wave as the PIN switch changes from open to closed and vice versa. A crude way to estimate bolometer time constants is to fit an exponential decay function to every PIN switch transition in the detector timestream while the CRHWP is stationary. This method was used to estimate the bolometer time constants in the

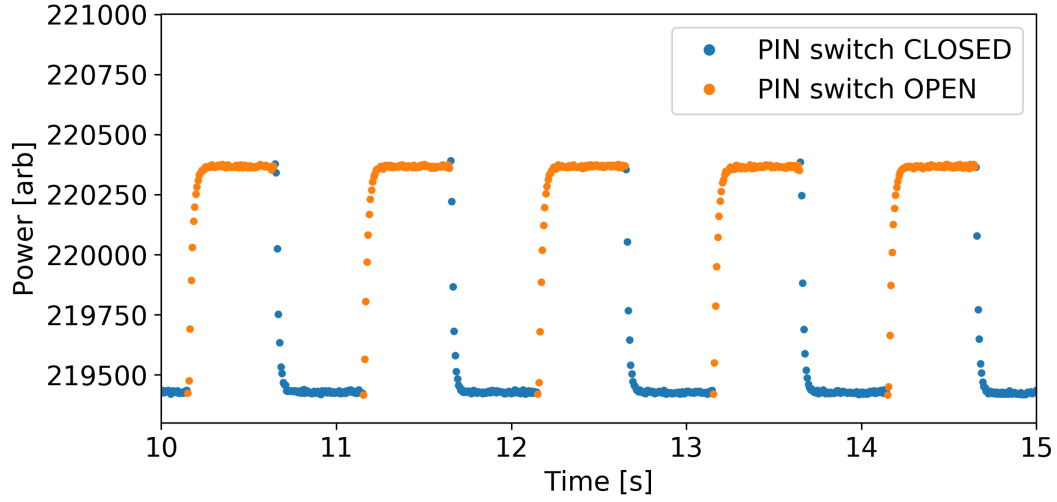


Figure 5.6: An example of a few seconds of the modulated POLCAL signal as seen by a single POLARBEAR-2b bolometer. POLCAL emits polarized radiation when the PIN switch is open (blue) and is blocked when the PIN switch is closed (orange). The modulation frequency depicted here is 1 Hz.

POLARBEAR-2b receiver beyond the ~ 100 values presented in [35] so that detector data taken with the CRHWP spinning could be deconvolved from their respective time constants to accurately determine detector polarization angles. The procedure for estimating these time constants with this method is detailed below.

Figure 5.6 shows a segment of the PIN switch-modulated POLCAL signal as seen by a POLARBEAR-2b detector during a POLCAL calibration scan with the stationary CRHWP. The transitions between the PIN switch being switched from open to closed and vice versa are separated and each transition is individually fit to the equation

$$S(t) = Ae^{-t/\tau} + C \quad (5.3)$$

where A is the amplitude in arbitrary power units, t is the detector timestamps, τ is the fitted bolometer time constant, and C is an arbitrary power offset. An example of two successive modulation step fits is shown in Figure 5.7. Once every transition has been fit for a bolometer

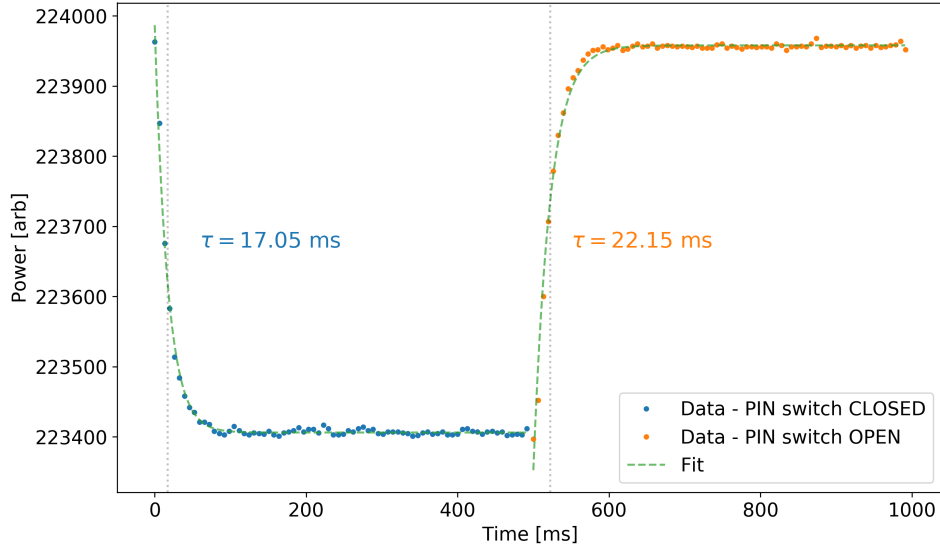


Figure 5.7: Two sample modulation transitions from Figure 5.6. The timestream switching from the PIN closed to PIN open state is depicted in blue while the timestream switching from the PIN open to the PIN closed state is depicted in orange. Each case is fit to the model in Equation 5.3 (dashed green line) with the time constants τ shown as dotted black lines for each transition. This fit is performed for each PIN switch transition throughout the calibration scan to estimate the time constant for every detector.

throughout the duration of a calibration scan, each fitted τ value is then inverse-variance-weighted averaged to generate a time constant τ for that bolometer. This procedure is then performed for every bolometer in a calibration scan.

Detector time constants were estimated for POLARBEAR-2b using this method for both the 90 GHz and 150 GHz bands for detectors in both the overbiased ($R_{frac} = 1$) and tuned ($R_{frac} = 0.75$) states, with results shown in Figure 5.8. A couple of interesting observations can be made from these results. First is that the results agree with the expectation that bolometers will have longer time constants in the overbias state than when tuned. The second is that the time constants for bolometers observing in the 90 GHz band are approximately double the values for bolometers observing in the 150 GHz band. This is expected behavior as the time constants are inversely proportional to their loop gain (as seen to Equation 5.1), and the loop gain of 90 GHz bolometers is roughly half that of the 150 GHz bolometers in the POLARBEAR-2b receiver [35].

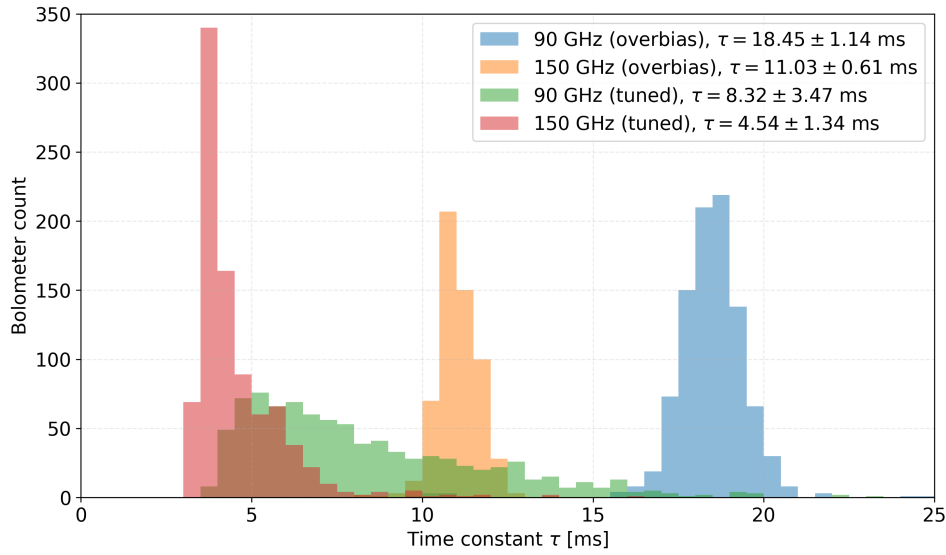


Figure 5.8: Estimated time constants for bolometers in the POLARBEAR-2b receiver as measured with POLCAL. 90 (150) GHz band bolometer time constants in the overbias state are shown in blue (orange), while 90 (150) GHz values with bolometers in the tuned state are shown in green (red). Respective median values for each histogram and their respective errors as calculated by a Gaussian fit are shown in the legend.

It may be that some of the tuned 90 GHz bolometers shown in Figure 5.8 were partially saturated by the bright POLCAL source causing the distribution of time constants to appear much broader than the other measurements. This is evidenced by the fact that most of the longer time constants in this distribution belong to detectors on the wafer with the least amount of optical attenuation in front of it.

It should be noted that the method for estimating time constants used here will be less accurate than using the fitting method as described by Equation 5.2 as the value of the time constants approach the sample spacing of data taken. This can be seen in Figure 5.6 where the sample spacing is ~ 6 milliseconds (corresponding to a ~ 152 Hz data sampling rate) and that bolometer time constants in the tuned state approach similar values.

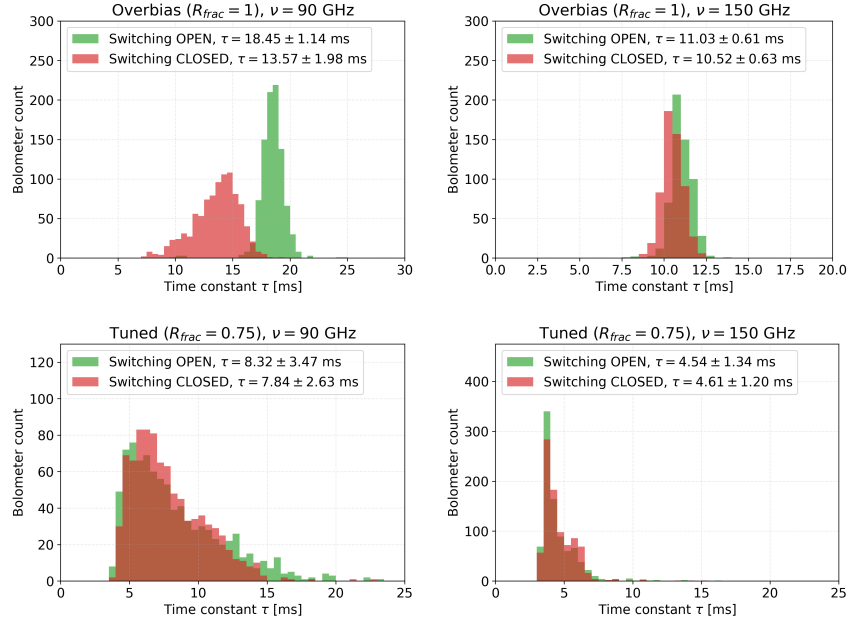


Figure 5.9: *Top row:* Bolometer time constants for the PIN switch switching open (green) and closed (red) in the overbias state at 90 GHz (left) and 150 GHz (right). *Bottom row:* Same as the above row but in the bolometer tuned state.

Time Constants Switching PIN Switch Open Versus Closed

Another interesting question is whether or not the time constants calculated via the process in Figure 5.7 agree when the PIN switch is transitioned from the open to closed state and vice versa. Ideally the values would agree, but effects such as bolometers saturating and going non-linear could affect agreement.

Histograms of the 90 GHz and 150 GHz bolometers in both the overbias and tuned states for the PIN switch opening versus closing is shown in Figure 5.9. For bolometers in the tuned state, calculated bolometer time constants for both switching open and closed agree within the fitted error for both the 90 GHz and 150 GHz bands. In the overbias state, however, there is slight tension between the time constants switching open and closed at 150 GHz and a large tension at 90 GHz. Bolometers in the overbiased state are biased above their superconducting transition temperature and have the potential to exhibit non-linear response as optical power is increased. This is the most likely candidate as to why there is discrepancy in the overbias

histograms. The POLCAL source is also much brighter at 90 GHz than it is at 150 GHz (due to the inefficient frequency doubler), which has the potential to drive the bolometer temperature even higher at 90 GHz, resulting in higher potential non-linearity and could explain why there is a larger discrepancy in the 90 GHz band in the overbias state.

5.2.2 Bolometer Polarization Angles

Once the bolometer time constants have been extracted, the polarization angle of individual detectors can be determined from calibrations scans performed using a CRHWP. This section details the analysis and results from POLCAL calibration scans performed on the POLARBEAR-2b receiver for both overbiased and tuned detectors.

Analytical Model With a Spinning CRHWP

In the absence of a CRHWP or other mechanisms for modulating incoming polarized radiation, the CMB experiment calibration procedure and analysis using POLCAL would be identical to that of what is detailed in Section 4.1.3 with a model described by Equation 4.2. Because the POLARBEAR-2b receiver employs the use of a CRHWP for continuous polarization modulation, a new analytical model and procedure must be developed. However, the data taking procedure is similar in that the detector timestreams are continuously recorded while POLCAL rotates to an angle, waits for some specified integration time, then rotates to the next angle until a full 360° scan has been performed.

With the CRHWP running, the polarized signal from POLCAL will be modulated at four times the CRHWP rotation frequency and is referred to as the $4f$ component of the measurement. Additionally, the POLCAL signal is modulated as a square wave by the PIN switch diode at a frequency much less than the CRHWP $4f$ frequency such that there are multiple rotations of the CRHWP per PIN switch modulation cycle. When the PIN switch is closed (POLCAL signal is emitted) the polarized POLCAL signal is CRHWP modulated along with any background

polarized radiation from the laboratory, while the PIN switch open state (POLCAL signal is blocked) allows for a separate measurement of just the modulated background radiation. By modulating the CRHWP and PIN switch in this way, the systematic of polarized background can be separated from the POLCAL signal to allow for a more accurate determination of the detector polarization angles.

The data processing procedure after performing a calibration scan with the CRHWP running is as follows. First, the detector timestreams are deconvolved from their respective time constants as measured in Section 5.2.1 and are split according to the POLCAL rotation angle, then split again according to whether the PIN switch is open or closed. As each PIN switch open or closed detector timestream will have observed several rotations of the CRHWP (assuming the frequency of the PIN switch modulation is much less than that of the CRHWP modulation), it is assumed that the detector response $S(\theta)$ follows a model given by a sum of sines and cosines at harmonics of the modulation frequency given by

$$\begin{aligned}
 S(\theta) = & A_{0f} \\
 & + A_{1f,c} \cos \theta + A_{1f,s} \sin \theta \\
 & + A_{2f,c} \cos 2\theta + A_{2f,s} \sin 2\theta \\
 & + A_{4f,c} \cos 4\theta + A_{4f,s} \sin 4\theta
 \end{aligned} \tag{5.4}$$

where $A_{Nf,s}$ and $A_{Nf,c}$ are the amplitude of each sine and cosine harmonic and θ is the angle of the CRHWP. If the angular frequency of the CRHWP is known then θ is a simply a linear function in time. The true detector timestream can be decomposed infinitely into harmonics higher than 4θ , but as the modulated polarized signal for a CRHWP only appears in the $4f$ term we only consider harmonics up to $4f$ for computational purposes.

Each separated detector timestream is demodulated according to Equation 5.4 to obtain the amount of signal present in each of the $1f$, $2f$, and $4f$ modes. An example POLARBEAR-2b

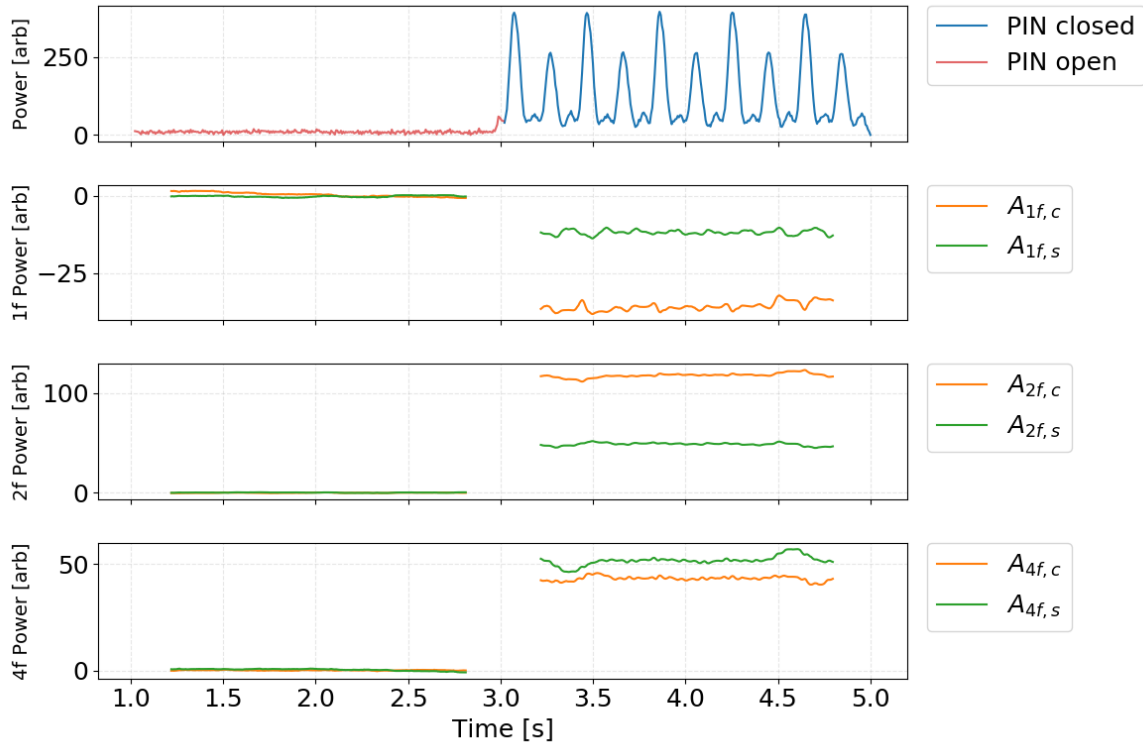


Figure 5.10: *First plot:* A sample POLARBEAR-2b detector timestream for one POLCAL PIN switch cycle with the CRHWP spinning. Detector signal with the PIN switch open is shown in red, while signal with the PIN switch closed is depicted in blue. Note that the signal timestream has been DC subtracted and sign-flipped such that an increase on the y-axis corresponds to increased optical power on the detector. *Second plot:* The $1f$ CRHWP demodulation coefficients $A_{1f,c}$ (orange) and $A_{1f,s}$ (green) from Equation 5.4 for the above detector timestream. *Third plot:* Same as above but for the $2f$ CRHWP demodulation coefficients. *Fourth plot:* Same as above but for the $4f$ CRHWP demodulation coefficients.

detector timestream with demodulated $1f$, $2f$, and $4f$ components for one POLCAL PIN switch cycle is shown in Figure 5.10. The $1f$ component is expected to be constant excepting any periodic signal that might come from imperfections in the CRHWP itself. Differential emission from the birefringent sapphire transmission axes is expected to show up as a periodic signal in the $2f$ component due to the lack of anti-reflective coating on the sapphire used in the testing setup. The $4f$ component is expected to contain any polarized radiation that originates beyond the sapphire optical element itself, which consists of the polarized POLCAL signal plus any stray polarized radiation from background.

Once both the PIN switch open and closed states have been CRHWP demodulated, the background $4f$ amplitude $A_{4f,x}^{open}$ is removed from the POLCAL amplitude $A_{4f,x}^{closed}$ by calculating

$$\begin{aligned} A'_{4f,c} &= \overline{A}_{4f,c}^{closed} - \overline{A}_{4f,c}^{open} \\ A'_{4f,s} &= \overline{A}_{4f,s}^{closed} - \overline{A}_{4f,s}^{open} \end{aligned} \quad (5.5)$$

where the $A'_{4f,x}$ represent the background removed POLCAL demodulated amplitudes, while $\overline{A}_{4f,x}^{open}$ and $\overline{A}_{4f,x}^{closed}$ are the average demodulated amplitudes of the PIN switch open and closed data at each POLCAL calibration angle (with x representing the cosine c and sine s components).

The phase of the $4f$ signal δ_{4f} at any given POLCAL calibration angle is then calculated with

$$\delta_{4f} = \frac{1}{2} \text{atan2} (A'_{4f,s}, A'_{4f,c}). \quad (5.6)$$

This phase δ_{4f} can be intuited as the phase angle offset between the current POLCAL polarization vector and the detector angle (assuming the CRHWP initial angle θ_0 aligns with the gravitational vector). Note that Equation 5.6 can also be used to calculate the phase angle for the $1f$ and $2f$ components using the respective demodulation amplitudes.

The phase δ_{4f} is calculated at each POLCAL angle throughout a full 360° calibration scan, as shown for a single bolometer in Figure 5.11. The slope of the line formed when plotting the $4f$ phase δ_{4f} against the POLCAL polarization angle ψ is expected to be unity as the phase should be exactly the offset between the POLCAL polarization angle and the detector angle. When performing a simple linear fit with free parameter ϕ of the form

$$\delta_{4f} = \psi + \phi \quad (5.7)$$

to the data as in Figure 5.11, the fitted y-intercept phase ϕ is exactly the offset angle between the initial POLCAL and detector polarization planes. If POLCAL has been properly calibrated to

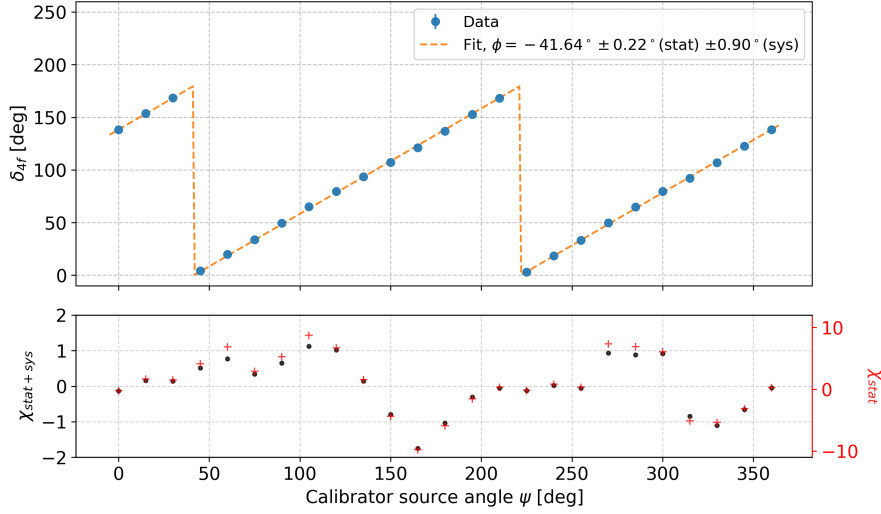


Figure 5.11: *Top:* The calculated $4f$ phase δ_{4f} plotted against POLCAL calibration angle (blue) and best fit model to Equation 5.7 (dashed orange line) for a sample detector in the POLARBEAR-2b receiver. The statistical error reported in the legend is derived from the fit angle error while the systematic error is estimated to be the value that makes the reduced chi-squared equal to one. *Bottom:* Weighted residual between the data and the model with $\chi = (S_{data} - S_{fit})/\sigma_{data}$ for both. Black points represent χ calculated using both statistical and systematic error, while red crosses only account for statistical error.

the local gravitational vector, this linear fit yields the absolute polarization angle of the detector. While the bolometer angle ϕ could be determined from a single POLCAL angle ψ and respective phase δ_{4f} , we solve for δ_{4f} at many POLCAL angles and fit the resulting line to Equation 5.7 to check for any potential systematic effects and estimate the resulting systematic uncertainty. Repeating the fit for ϕ for each detector in the calibration scan gives the polarization angles of detectors for the entire receiver.

Statistical and Systematic Errors

The statistical error $\Delta\phi_{stat}$ in the fitted detector angle ϕ is defined to be the error from the fit to Equation 5.7. The systematic error is more complicated to calculate due to several factors inherent to configuration of the POLARBEAR-2b receiver at the time data was taken. None of the optics in the receiver (lenses, CRHWP, etc.) were anti-reflection coated as it would be

when deployed, so errant reflections could affect results and are extremely difficult to quantify. Additionally, the CRHWP used in these analyses is an uncompleted three-stack sapphire design that only acts as a true half-wave plate for radiation exactly at 120 GHz. As POLCAL calibration scans were performed between 75-115 GHz and 150-170 GHz, this means that all polarization reaching the detector will be elliptical to varying degrees and could present systematic effects combined with non-idealities in the CRHWP sapphire¹. For the purposes of these analyses, the systematic error in detector angle $\Delta\phi_{stat}$ is defined to be the amount that the error bars in δ_{4f} must be increased to give a reduced chi-squared equal to one when fitting the data to Equation 5.7. The results in the following section indicate that the magnitude of these systematic errors are of the order of a few degrees.

Detector Polarization Angle Results

Bolometer angles in both the overbiased and tuned states across three wafers in the POLARBEAR-2b receiver as measured with POLCAL in the laboratory are reported in Figure 5.12 and Figure 5.13. The statistical and systematic errors for each respective measurement calculated with the methodology described in the previous section are also reported in these two figures. The three optical wafers are oriented on the focal plane such that Q and U pixels make a 0° and 45° angle with respect to the vertical axis of the receiver. As each Q and U pixel consists of perpendicular “top” and “bottom” bolometers, the only expected bolometer angles across the three optical wafers are 0° (Q_{top}), 45° (U_{top}), 90° (Q_{bottom}), and 135° (U_{bottom}). Figure 5.12 and Figure 5.13 demonstrate that these four angles are in fact the primary angles measured. It should be noted that the angles and errors reported here represent the inverse-variance weighted average values measured across six POLCAL frequencies (80, 95, 110, 152, 160, 170 GHz), causing the histogram peaks to appear broadened due to effects such as polarization wobble as described in Section 5.2.3 . The potentially large, unknown systematic error associated with the non-ideal

¹These effects will be minimized in the field as the deployed configuration of the receiver will have anti-reflection coated optics and a full three-stack sapphire CRHWP with high bandwidth half-wave plate modulation

optical elements in the receiver as described in the previous section are also a contributing factor to this apparent broadening.

As with POLARBEAR-1 pixels, the top and bottom bolometers on a pixel are expected to be orthogonal. The orthogonality of PSB pixel-pair angles across the six POLCAL frequencies was calculated according to the POLARBEAR-2b hardware map² as generated in ‘Run18b’ in the laboratory and are reported in Figure 5.14. Errors in the labelling of Q and U pixels or top and bottom bolometers in the hardware map can generate calculated orthogonality of 0° , 45° , and 135° depending on how a particular bolometer is mislabelled. The erroneous values caused by these hardware map errors are apparent in Figure 5.14 and show that up to 30%-50% of bolometers are potentially mislabelled. Generating an accurate hardware map for the multiplexed readout used in experiments like the POLARBEAR-2b receiver is an extremely difficult task that is not perfected until extensive characterization is performed in the field with both astrophysical and artificial calibrators, a task that hadn’t been thoroughly performed for the POLARBEAR-2b receiver in the laboratory at the time of POLCAL testing. However, polarization angle calibrators such as POLCAL can and will be used in conjunction with Tau A observations for the entire Simons Array in the future to help diagnose and correct potential hardware map errors.

5.2.3 Sinuous Antenna Polarization Wobble

The three POLARBEAR-2 receivers that make up the Simons Array consist of focal planes with thousands of TES bolometers coupled to multi-chroic, dual-polarization sinuous antennas (as discussed in Section 2.4.1). The sinuous antenna design is desirable for CMB observations as it allows for simultaneous measurement of two independent ultra-wide bandwidth frequency channels and is sensitive to two perpendicular linear polarizations for incoming radiation [32, 74].

²A “hardware map” refers to the mapping between the measured resonance frequencies on a multiplexed readout comb (POLARBEAR-2b multiplexes 40 detectors per SQUID comb) to their respective detector names, which provides a reference for detector properties such as top or bottom labelling, Q or U orientation, A- or B-sense distinction, physical location on the focal plane, 90 GHz or 150 GHz observing band, etc.

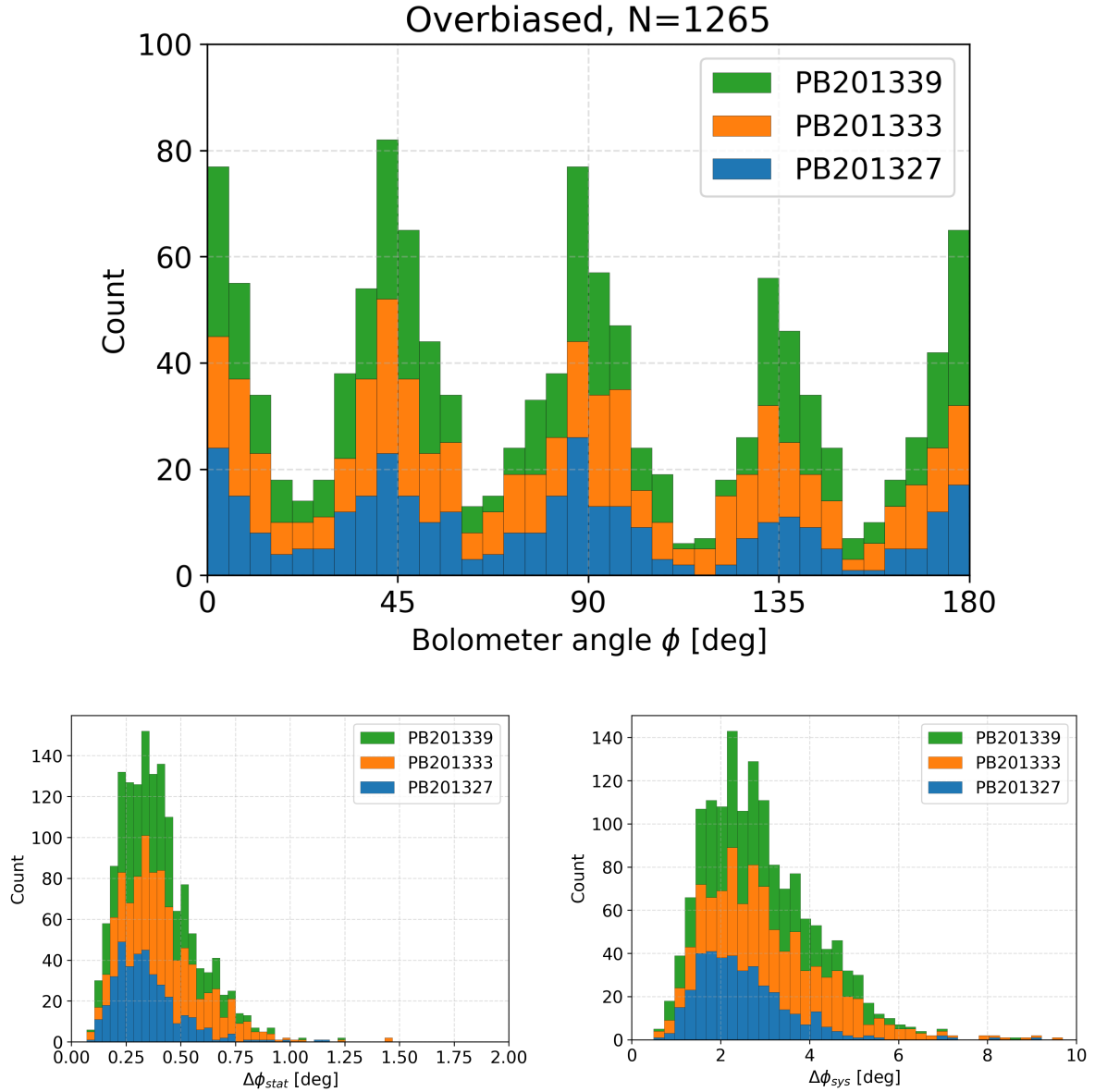


Figure 5.12: *Top:* Measured angles for 1265 overbiased bolometers across three wafers in the POLARBEAR-2b receiver. Offsets from the initial CRHWP position are taken into account such that the expected angles are $0^\circ/90^\circ$ (Q pixels) and $45^\circ/135^\circ$ (U pixels). Angles represent an average over observed POLCAL frequencies per bolometer. *Bottom:* Statistical and systematic errors associated with bolometer angle values from above plot.

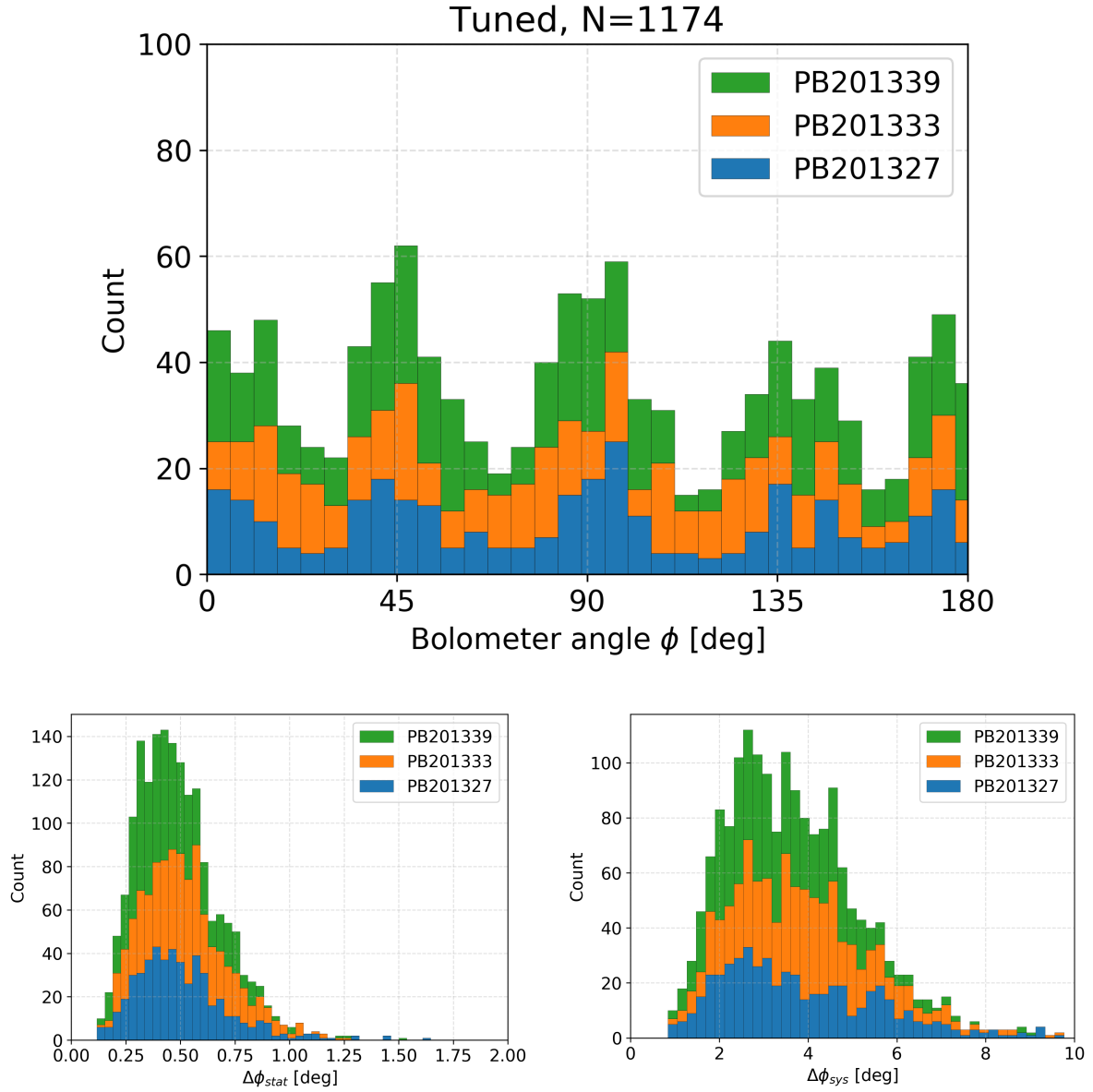


Figure 5.13: *Top:* Measured angles for 1174 tuned bolometers across three wafers in the POLARBEAR-2b receiver. Offsets from the initial CRHWP position are taken into account such that the expected angles are $0^\circ/90^\circ$ (Q pixels) and $45^\circ/135^\circ$ (U pixels). Angles represent an average over observed POLCAL frequencies per bolometer. *Bottom:* Statistical and systematic errors associated with bolometer angle values from above plot.

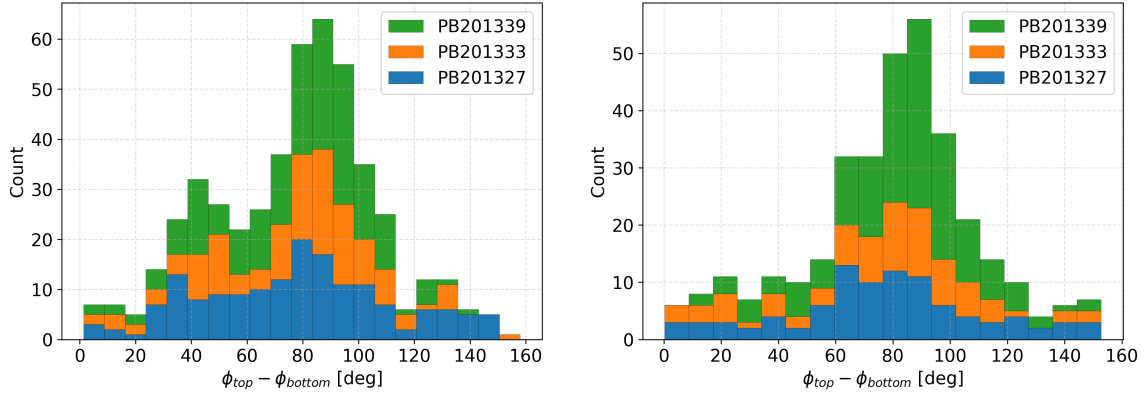


Figure 5.14: The orthogonality between top and bottom bolometer angles as defined by the POLARBEAR-2b hardware map (as of Run18b). Histograms include data from all observed POLCAL frequencies. Each orthogonality value is expected to be 90° , but peaks around 45° and 135° indicate potential hardware map mislabelled Q and U pixels.

While the sinuous antenna possesses many desirable properties for CMB observations, it is not without certain faults. In the context of measuring the polarization angle of incoming light, sinuous antennas exhibit an interesting behavior known as “polarization wobble.” That is, the polarization axis of a sinuous antenna oscillates as a function of frequency. This is obviously not ideal in the context of measuring the CMB polarization, especially across a wide range of frequencies within the bandwidth of the detector. The wobble for the sinuous antenna design used in the Simons Array receivers is expected to oscillate by up to ± 5 degrees across either frequency channel [34].

The relation between the polarization wobble $\Delta\phi$ and observed radiation frequency ν is expected to be log periodic and of the form [88]

$$\Delta\phi = A \sin(B \log(\nu) + \psi), \quad (5.8)$$

where A is the amplitude of the wobble, B is the wobble oscillation period, ν is the frequency in GHz, and ψ is a phase offset that includes terms such as the kinetic inductance of the niobium strip lines. The simulated polarization wobble for an example sinuous antenna is shown in Figure 5.15.

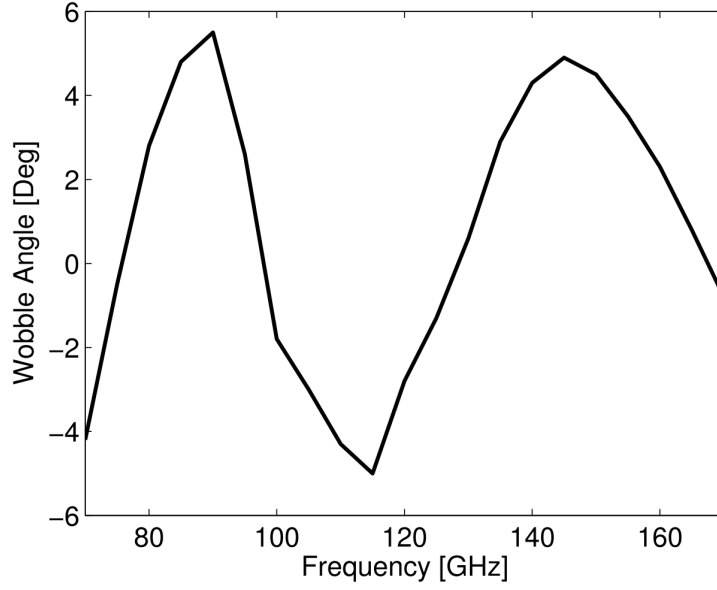


Figure 5.15: Simulated polarization wobble in a sinuous antenna between 70 GHz and 170 GHz. Image from [88].

To mitigate the effect that this wobble might have on measuring the polarization of the CMB, the Simons Array has elected to have neighboring pixels on the focal plane be mirror images of each other, called “A-sense” and “B-sense” pixels. A diagram of this type of pixel mapping is shown in Figure 5.16. If these pairs of pixels were to both observe radiation with some angle θ , then one would seem to measure the polarization angle of the radiation to be $\theta + \Delta\phi(\nu)$ while the other would measure $\theta - \Delta\phi(\nu)$, where $\Delta\phi(\nu)$ is the degree of polarization wobble at the radiation’s frequency ν . The polarization wobble cancelling procedure for the Simons Array experiment using neighboring pairs of Q and U pixels in both the A- and B-sense can be found in Chapter 5 of [88].

The polarization wobble for sinuous antennas can be directly measured using a polarized source with a well known polarization axis and narrow frequency bandwidth. The polarization calibrator POLCAL described in Chapter 4 is thus well suited to measure the effects of polarization wobble as the initial source polarization angle is extremely well known and the Gunn oscillator output bandwidth at any given frequency is effectively a delta function at that frequency.

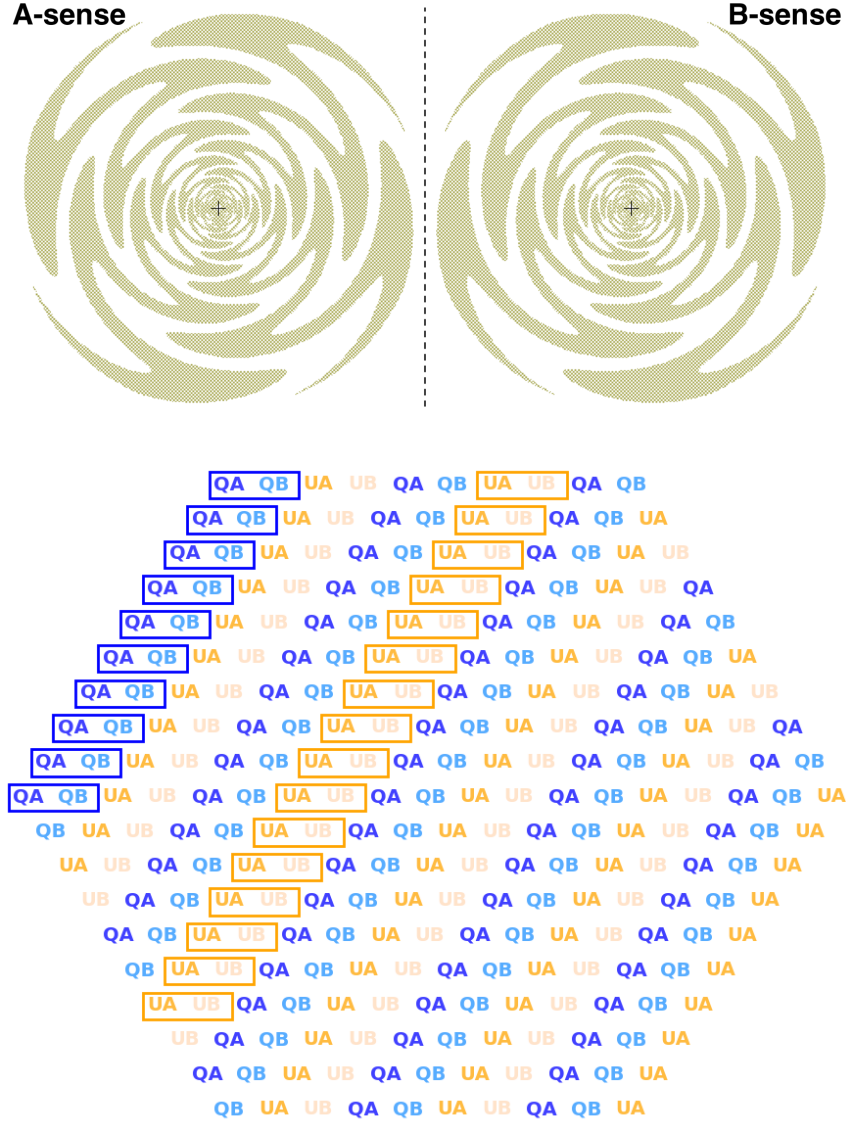


Figure 5.16: *Top:* An example A- (left) and B-sense (right) mirror-imaged sinuous antenna pixel pair. Image from [88]. *Bottom:* A schematic showing the location of four types of pixels on a single wafer. QA (blue) and QB (light blue) pixels are Q-oriented pixels in the A- and B-sense, while UA (orange) and UB (light orange) pixels are U-oriented pixels in the A- and B-sense. Examples of QA/QB mirror-imaged pixel pairs are highlighted with blue rectangles, while UA/UB pairs are highlighted with orange rectangles. The spatial nearness of these pairs allows for wobble cancellation following the procedure laid out in [88].

Performing a POLCAL calibration scan for an A- and B-sense pixel pair, both with expected pixel angle ϕ , will result in one of the two pixels appearing to be oriented at a polarization angle of $\phi + \Delta\phi(v)$ while the other will appear to be at angle $\phi - \Delta\phi(v)$. We can make an estimate of the polarization wobble for POLARBEAR-2b sinuous antenna coupled detectors by comparing the measured polarization angles of many A- and B-sense bolometer pairs at varying POLCAL output frequencies.

The histograms of POLARBEAR-2b detector polarization angles as measured by POLCAL at various frequencies shown in Figure 5.12 and Figure 5.13 contains both A- and B-sense pixel angles, potentially obfuscating any visual polarization wobble effects and broadening the angle histogram widths. To estimate the degree of polarization wobble as a function of frequency for the sinuous antennas in POLARBEAR-2b, histograms of the difference of measured polarization angles for each of the two bolometers on each A- and B-sense pixel pair ($\Delta\phi_{top} = \phi_{A_{top}} - \phi_{B_{top}}$, $\Delta\phi_{bot} = \phi_{A_{bot}} - \phi_{B_{bot}}$) are first constructed at each POLCAL frequency. A Gaussian curve is fit to each histogram, with the center of the Gaussian representing the polarization wobble value at each respective frequency.

The A/B pixel-pair differenced bolometer angle histograms generated for each POLCAL frequency with POLARBEAR-2b detectors both in the overbias and tuned states are shown in Figure 5.17 and Figure 5.18 respectively. Figure 5.19 compactly shows the polarization wobble calculations from these histograms in both the tuned and overbiased state for detectors versus frequency along with the resulting fit to Equation 5.8. Fitting the weighted average of the overbiased and tuned bolometer wobble measurements to the model in Equation 5.8, assuming $A = 4.9$ as per [88], yields values for the wobble oscillation period B and phase ψ yields of $B = 11.65 \pm 0.36$ and $\psi = 7.15 \pm 1.74$. These values are consistent with the theory presented in [88] assuming some inherent kinetic inductance in the niobium strip lines, which has the effect of phase shifting the polarization wobble curve due to variable wave speed in the strip lines from varying inductance.

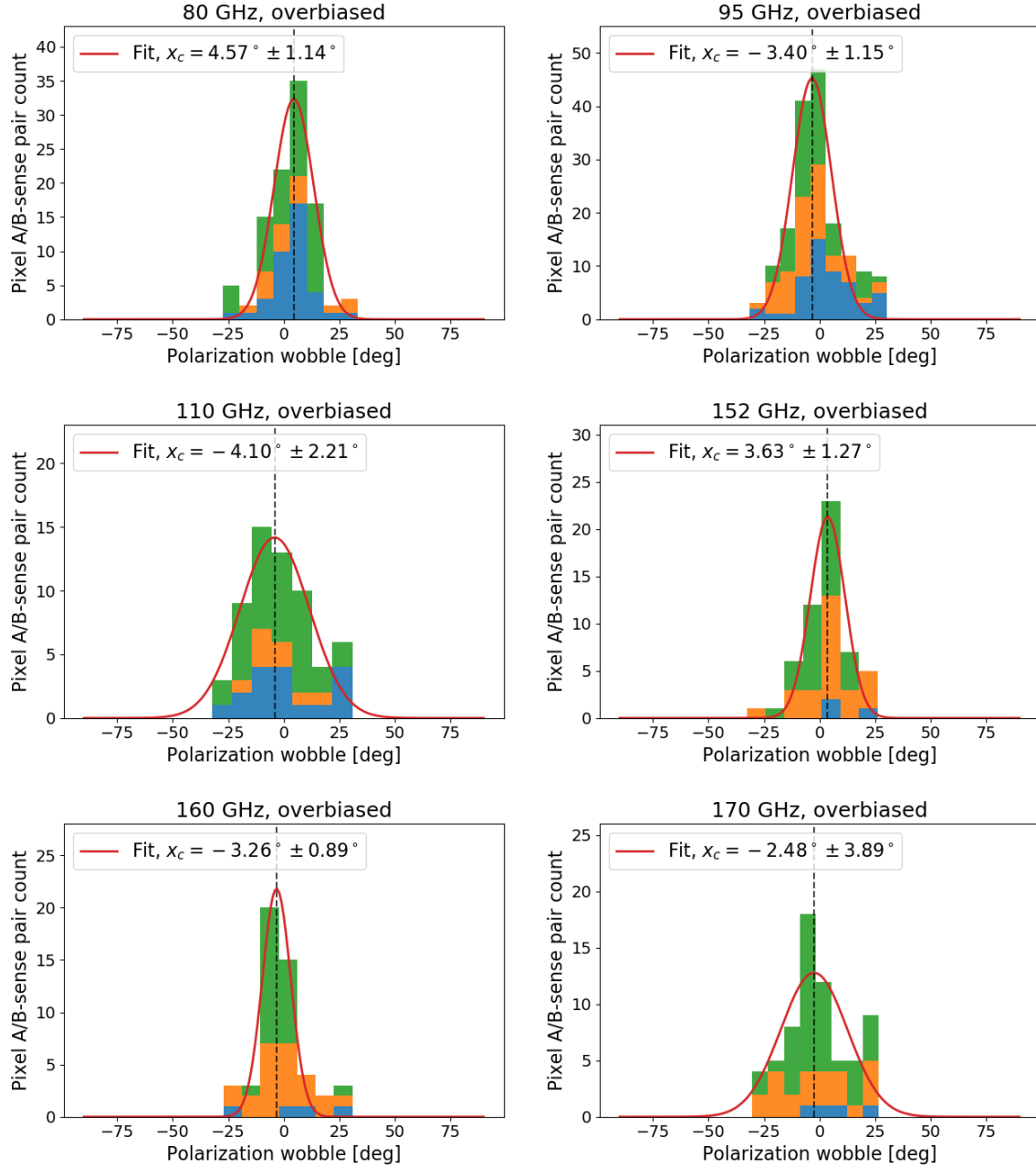


Figure 5.17: Histograms of the measured polarization angle difference between A- and B-sense bolometer pairs across three wafers in the POLARBEAR-2b receiver in the overbiased state. Wafers 13.39, 13.33, and 13.27 are represented by green, orange, and blue respectively. The red curve is a Gaussian fit to the data with the dotted black line depicting the fitted center value. Center fit values and respective errors are reported in the top left of each histogram.

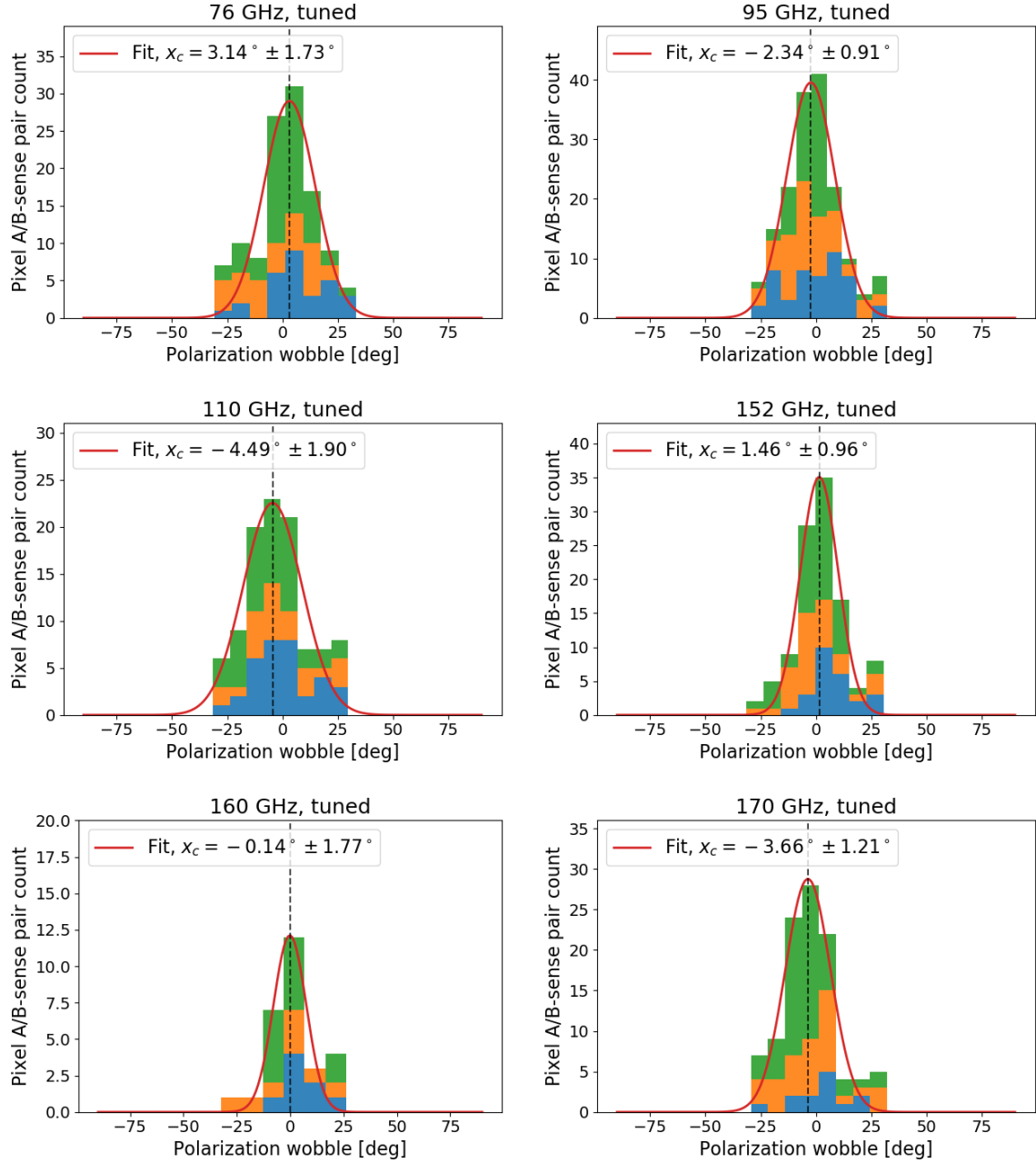


Figure 5.18: Histograms of the measured polarization angle difference between A- and B-sense bolometer pairs across three wafers in the POLARBEAR-2b receiver in the tuned state. Wafers 13.39, 13.33, and 13.27 are represented by green, orange, and blue respectively. The red curve is a Gaussian fit to the data with the dotted black line depicting the fitted center value. Center fit values and respective errors are reported in the top left of each histogram.

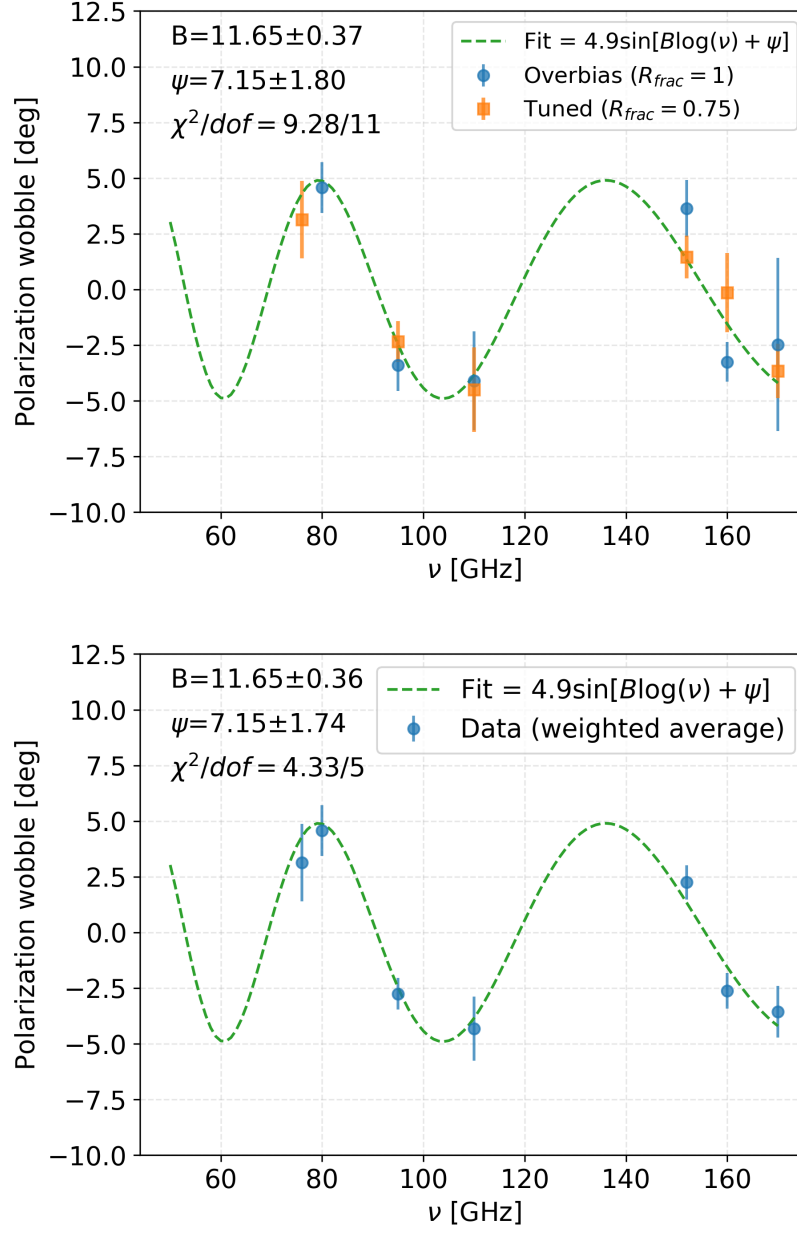


Figure 5.19: Measurements of the polarization wobble using the POLARBEAR-2b receiver as a function of POLCAL frequency. *Top:* Polarization wobble is plotted separately for data taken in the detector overbias (blue) and tuned (orange) regimes. The green dashed line represents the best fit from Equation 5.8 to the data. The fitted values for B and ψ are shown in the top left, along with the χ^2 per degree of freedom. *Bottom:* Same as the above plot but the fit is performed to the weighted average of the overbiased and tuned data (blue) at each frequency. In both plots, the parameter A from Equation 5.8 is assumed to be 4.9 [88].

5.3 Summary

This chapter presented results from testing of the absolute polarization calibrator described in Chapter 4 on the POLARBEAR-1 telescope and POLARBEAR-2b receiver. The operation and analysis procedures of the calibrator were validated on a field-operable CMB experiment during a 2017 deployment on the POLARBEAR-1 telescope. The calibrator’s capacity to measure pixel-pair angle differences were found to be compatible with Tau A observation derived values, validating the calibrator’s potential to measure the absolute polarization orientation of CMB detectors in the field. The process of estimating POLARBEAR-2b bolometer time constants to deconvolve from the CRHWP modulated detector timestreams was described. POLARBEAR-2b receiver detector angles as calculated with the calibrator were presented, as were estimates of the sinuous antenna polarization wobble from detector angles measured at varying calibrator source frequencies. Unavoidable systematic errors in both the POLARBEAR-1 and POLARBEAR-2b measurements resulted in polarization angle errors larger than the 0.1° target, however future deployment of the calibrator on the Simons Array is not expected to have the same systematic effects. The confirmation of operational and analysis procedures from POLARBEAR-1 and POLARBEAR-2b measurements combined with the precision presented in Chapter 4 shows that this polarization calibrator appears well suited to decrease uncertainties on CMB experiment polarization angles and enabling new searches for CPR from Lorentz and parity violating physics in our universe. Whether the increased precision on polarization calibration of CMB experiments from using this calibrator leads to a detection of CPR or simply places tighter constraints on this new physics, either scenario ultimately helps us paint an ever clearer picture of the universe that surrounds us.

Chapter 6

Conclusions

Since the discovery of the CMB by Penzias and Wilson in 1965, monumental strides in the field of cosmological theory and experimentation have been made. From the measurement of the blackbody power spectrum by the COBE-FIRAS instrument to the most recent measurements of the degree-scale B-mode power spectrum by POLARBEAR-1, the growing number of funded CMB experiments demonstrates the world's hunger for the knowledge of how our universe has evolved into what we observe today. The current generation of CMB experiments are currently able to claim measurements of the gravitational lensing B-mode power spectrum along with tighter upper limits on the primordial B-mode power spectrum as evidenced by Figure 1.5.

The fact that photon noise is the dominant source of noise in many modern CMB experiments means that the only way to increase sensitivity in CMB observations is to either observe for longer periods of time or to increase the number of detectors observing the CMB over more frequency bands. This has inspired large scale CMB experiments and inter-collaborative efforts to answer the universe's biggest questions. This is evidenced by the upcoming CMB Stage 4 experiment (CMB-S4) [1] which is a worldwide multi-collaboration effort to develop a series of telescopes in various sizes, observation bands, and designs with order $10^5 - 10^6$ detectors. The Simons Observatory experiment (SO) [6] is another upcoming experiment that is currently in the

building phase that unites the ACT and POLARBEAR/Simons Array collaborations in an effort to measure both the large and small angular scale B-modes through a series of large and small aperture telescopes.

With the ever increasing push for more sensitive measurements of the CMB polarization power spectra, there is a natural demand for increased calibration methods to lower all systematics affecting measurements of the tensor-to-scalar ratio r . As the bounds on r are pushed below $r = 0.01$, the need for improved polarization calibration naturally arises due to spurious B-modes generated by a detector misalignment. This increase in precise astronomical polarization calibration will enable the search for new Lorentz and parity violating physics as stricter upper limits on CMB E- and B-mode cross-correlations can be placed.

This dissertation has provided an overview of the theory of the CMB and the efforts being made to measure its polarization power spectra. A general overview of the design and science goals of the POLARBEAR-1 and Simons Array experiments was provided, along with the major scientific results published by the POLARBEAR-1 collaboration. The methodology behind polarization calibrating a CMB experiment to the polarized celestial source Tau A was discussed, and results from Tau A and Jupiter observations were presented for both the POLARBEAR-1 and POLARBEAR-2a telescopes. The design and laboratory testing of a novel ground-based absolute polarization calibrator was detailed along with results from calibration scans performed on the POLARBEAR-1 telescope and POLARBEAR-2b receiver. This calibrator has exciting potential for strict polarization calibration of the Simons Array and upcoming Simons Observatory experiments to enable the search for physics that departs from the standard model in the form of Lorentz and parity violating cosmic polarization rotation induced in the CMB polarization.

Bibliography

- [1] K. N. Abazajian, P. Adshead, Z. Ahmed, S. W. Allen, D. Alonso, K. S. Arnold, C. Baccigalupi, J. G. Bartlett, N. Battaglia, B. A. Benson, C. A. Bischoff, J. Borrill, V. Buza, E. Calabrese, R. Caldwell, J. E. Carlstrom, C. L. Chang, T. M. Crawford, F.-Y. Cyr-Racine, F. De Bernardis, T. de Haan, S. d. S. Alighieri, J. Dunkley, C. Dvorkin, J. Errard, G. Fabbian, S. Feeney, S. Ferraro, J. P. Filippini, R. Flauger, G. M. Fuller, V. Gluscevic, D. Green, D. Grin, E. Grohs, J. W. Henning, J. C. Hill, R. Hlozek, G. Holder, W. Holzappel, W. Hu, K. M. Huffmanberger, R. Keskitalo, L. Knox, A. Kosowsky, J. Kovac, E. D. Kovetz, C.-L. Kuo, A. Kusaka, M. L. Jeune, A. T. Lee, M. Lilley, M. Loverde, M. S. Madhavacheril, A. Mantz, D. J. E. Marsh, J. McMahon, P. D. Meerburg, J. Meyers, A. D. Miller, J. B. Munoz, H. N. Nguyen, M. D. Niemack, M. Peloso, J. Peloton, L. Pogosian, C. Pryke, M. Raveri, C. L. Reichardt, G. Rocha, A. Rotti, E. Schaan, M. M. Schmittfull, D. Scott, N. Sehgal, S. Shandera, B. D. Sherwin, T. L. Smith, L. Sorbo, G. D. Starkman, K. T. Story, A. van Engelen, J. D. Vieira, S. Watson, N. Whitehorn, and W. L. K. Wu. CMB-S4 Science Book, First Edition. *arXiv e-prints*, 2016.
- [2] K. N. Abazajian, K. Arnold, J. Austermann, B. A. Benson, C. Bischoff, J. Bock, J. R. Bond, J. Borrill, I. Buder, D. L. Burke, E. Calabrese, J. E. Carlstrom, C. S. Carvalho, C. L. Chang, H. C. Chiang, S. Church, A. Cooray, T. M. Crawford, B. P. Crill, K. S. Dawson, S. Das, M. J. Devlin, M. Dobbs, S. Dodelson, O. Doré, J. Dunkley, J. L. Feng, A. Fraisse, J. Gallicchio, S. B. Giddings, D. Green, N. W. Halverson, S. Hanany, D. Hanson, S. R. Hildebrandt, A. Hincks, R. Hlozek, G. Holder, W. L. Holzappel, K. Honscheid, G. Horowitz, W. Hu, J. Hubmayr, K. Irwin, M. Jackson, W. C. Jones, R. Kallosh, M. Kamionkowski, B. Keating, R. Keisler, W. Kinney, L. Knox, E. Komatsu, J. Kovac, C. L. Kuo, A. Kusaka, C. Lawrence, A. T. Lee, E. Leitch, A. Linde, E. Linder, P. Lubin, J. Maldacena, E. Martinec, J. McMahon, A. Miller, V. Mukhanov, L. Newburgh, M. D. Niemack, H. Nguyen, H. T. Nguyen, L. Page, C. Pryke, C. L. Reichardt, J. E. Ruhl, N. Sehgal, U. Seljak, L. Senatore, J. Sievers, E. Silverstein, A. Slosar, K. M. Smith, D. Spergel, S. T. Staggs, A. Stark, R. Stompor, A. G. Viereg, G. Wang, S. Watson, E. J. Wollack, W. L. Wu, K. W. Yoon, O. Zahn, and M. Zaldarriaga. Inflation physics from the cosmic microwave background and large scale structure. *Astroparticle Physics*, 63:55–65, 2015.
- [3] S. Adachi, M. A. O. A. Faúndez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone,

- K. Crowley, A. Cukierman, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. A Measurement of the Degree Scale CMB B-mode Angular Power Spectrum with POLARBEAR. *arXiv e-prints*, 10:38, 2019.
- [4] S. Adachi, M. A. O. A. Faúndez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, M. Dobbs, H. E. Bouhargani, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Galitzki, N. Goeckner-Wald, J. Groh, G. Hall, M. Hasegawa, M. Hazumi, H. Hirose, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, S. Kikuchi, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, C. L. Reichardt, Y. Segawa, P. Siritanasak, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, C. Tsai, C. Vergès, B. Westbrook, and Y. Zhou. A measurement of the CMB E-mode angular power spectrum at subdegree scales from 670 square degrees of POLARBEAR data. *arXiv e-prints*; *arXiv:2005.061*, may 2020.
- [5] R. Adam, P. A. Ade, N. Aghanim, Y. Akrami, M. I. Alves, F. Argüeso, M. Arnaud, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, S. Basak, P. Battaglia, E. Battaner, R. Battye, K. Benabed, A. Benoît, A. Benoit-Lévy, J. P. Bernard, M. Bersanelli, B. Bertin-court, P. Bielewicz, I. Bikmaev, J. J. Bock, H. Böhringer, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, M. Bucher, R. Burenin, C. Burigana, R. C. Butler, E. Calabrese, J. F. Cardoso, P. Carvalho, B. Casaponsa, G. Castex, A. Catalano, A. Challinor, A. Chamballu, R. R. Chary, H. C. Chiang, J. Chluba, G. Chon, P. R. Christensen, S. Church, M. Clemens, D. L. Clements, S. Colombi, L. P. Colombo, C. Combet, B. Comis, D. Contreras, F. Couchot, A. Coulais, B. P. Crill, M. Cruz, A. Curto, F. Cuttaia, L. Danese, R. D. Davies, R. J. Davis, P. De Bernardis, A. De Rosa, G. De Zotti, J. Delabrouille, J. M. Delouis, F. X. Désert, E. Di Valentino, C. Dickinson, J. M. Diego, K. Dolag, H. Dole, S. Donzelli, O. Doré, M. Douspis, A. Ducout, J. Dunkley, X. Dupac, G. Efstathiou, P. R. Eisenhardt, F. Elsner, T. A. Enßlin, H. K. Eriksen, E. Falgarone, Y. Fantaye, M. Farhang, S. Feeney, J. Fergusson, R. Fernandez-Cobos, F. Feroz, F. Finelli, E. Florido, O. Forni, M. Frailis, A. A. Fraisse, C. Franceschet, E. Franceschi, A. Frejsel, A. Frolov, S. Galeotta, S. Galli, K. Ganga, C. Gauthier, R. T. Génova-Santos, M. Gerbino, T. Ghosh, M. Giard, Y. Giraud-Héraud, E. Giusarma, E. Gjerløw, J. González-Nuevo, K. M. Górski, K. J. Grainge, S. Gratton, A. Gregorio, A. Gruppuso, J. E. Gudmundsson, J. Hamann, W. Handley, F. K. Hansen, D. Hanson, D. L. Harrison, A. Heavens, G. Helou, S. Henrot-Versillé, C. Hernández-Monteagudo, D. Herranz, S. R. Hildebrandt, E. Hivon, M. Hobson, W. A. Holmes, A. Hornstrup, W. Hovest, Z. Huang, K. M. Huffenberger, G. Hurier, S. Ilić, A. H. Jaffe, T. R. Jaffe, T. Jin, W. C. Jones,

M. Juvela, A. Karakci, E. Keihänen, R. Keskitalo, I. Khamitov, K. Kiiveri, J. Kim, T. S. Kisner, R. Kneissl, J. Knoche, L. Knox, N. Krachmalnicoff, M. Kunz, H. Kurki-Suonio, F. Lacasa, G. Lagache, A. Lähteenmäki, J. M. Lamarre, M. Langer, A. Lasenby, M. Lattanzi, C. R. Lawrence, M. Le Jeune, J. P. Leahy, E. Lellouch, R. Leonardi, J. León-Tavares, J. Lesgourgues, F. Levrier, A. Lewis, M. Liguori, P. B. Lilje, M. Lilley, M. Linden-Vørnle, V. Lindholm, H. Liu, M. López-Caniego, P. M. Lubin, Y. Z. Ma, J. F. Maciás-Pérez, G. Maggio, D. Maino, D. S. Mak, N. Mandolesi, A. Mangilli, A. Marchini, A. Marcos-Caballero, D. Marinucci, M. Maris, D. J. Marshall, P. G. Martin, M. Martinelli, E. Martínez-González, S. Masi, S. Matarrese, P. Mazzotta, J. D. Mcewen, P. Mcgehee, S. Mei, P. R. Meinhold, A. Melchiorri, J. B. Melin, L. Mendes, A. Mennella, M. Migliaccio, K. Mikkelsen, M. Millea, S. Mitra, M. A. Miville-Deschênes, D. Molinari, A. Moneti, L. Montier, R. Moreno, G. Morgante, D. Mortlock, A. Moss, S. Mottet, M. Münchmeyer, D. Munshi, J. A. Murphy, A. Narimani, P. Naselsky, A. Nastasi, F. Nati, P. Natoli, M. Negrello, C. B. Netterfield, H. U. Nørgaard-Nielsen, F. Noviello, D. Novikov, I. Novikov, M. Olamaie, N. Oppermann, E. Orlando, C. A. Oxborrow, F. Paci, L. Pagano, F. Pajot, R. Paladini, S. Pandolfi, D. Paoletti, B. Partridge, F. Pasian, G. Patanchon, T. J. Pearson, M. Peel, H. V. Peiris, V. M. Pelkonen, O. Perdureau, L. Perotto, Y. C. Perrott, F. Perrotta, V. Pettorino, F. Piacentini, M. Piat, E. Pierpaoli, D. Pietrobon, S. Plaszczynski, D. Pogosyan, E. Pointecouteau, G. Polenta, L. Popa, G. W. Pratt, G. Prézeau, S. Prunet, J. L. Puget, J. P. Rachen, B. Racine, W. T. Reach, R. Rebolo, M. Reinecke, M. Remazeilles, C. Renault, A. Renzi, I. Ristorcelli, G. Rocha, M. Roman, E. Romelli, C. Rosset, M. Rossetti, A. Rotti, G. Roudier, B. Rouillé D’orfeuil, M. Rowan-Robinson, J. A. Rubinó-Martín, B. Ruiz-Granados, C. Rumsey, B. Rusholme, N. Said, V. Salvatelli, L. Salvati, M. Sandri, H. S. Sanghera, D. Santos, R. D. Saunders, A. Sauvé, M. Savelainen, G. Savini, B. M. Schaefer, M. P. Schammel, D. Scott, M. D. Seiffert, P. Serra, E. P. Shellard, T. W. Shimwell, M. Shiraishi, K. Smith, T. Souradeep, L. D. Spencer, M. Spinelli, S. A. Stanford, D. Stern, V. Stolyarov, R. Stompor, A. W. Strong, R. Sudiwala, R. Sunyaev, P. Sutter, D. Sutton, A. S. Suur-Uski, J. F. Sygnet, J. A. Tauber, D. Tavagnacco, L. Terenzi, D. Texier, L. Toffolatti, M. Tomasi, M. Tornikoski, D. Tramonte, M. Tristram, A. Troja, T. Trombetti, M. Tucci, J. Tuovinen, M. Türlér, G. Umana, L. Valenziano, J. Valiviita, F. Van Tent, T. Vassallo, L. Vibert, M. Vidal, M. Viel, P. Vielva, F. Villa, L. A. Wade, B. Walter, B. D. Wandelt, R. Watson, I. K. Wehus, N. Welikala, J. Weller, M. White, S. D. White, A. Wilkinson, D. Yvon, A. Zacchei, J. P. Zibin, and A. Zonca. Planck 2015 results: I. Overview of products and scientific results. *Astronomy and Astrophysics*, 594:39, 2016.

- [6] P. Ade, J. Aguirre, Z. Ahmed, S. Aiola, A. Ali, D. Alonso, M. A. Alvarez, K. Arnold, P. Ashton, J. Austermann, H. Awan, C. Baccigalupi, T. Baildon, D. Barron, N. Battaglia, R. Battye, E. Baxter, A. Bazarko, J. A. Beall, R. Bean, D. Beck, S. Beckman, B. Beringue, F. Bianchini, S. Boada, D. Boettger, J. R. Bond, J. Borrill, M. L. Brown, S. M. Bruno, S. Bryan, E. Calabrese, V. Calafut, P. Calisse, J. Carron, A. Challinor, G. Chesmore, Y. Chinnone, J. Chluba, H. M. S. Cho, S. Choi, G. Coppi, N. F. Cothard, K. Coughlin, D. Crichton, K. D. Crowley, K. T. Crowley, A. Cukierman, J. M. D’Ewart, R. Dünner, T. De Haan, M. Devlin, S. Dicker, J. Didier, M. Dobbs, B. Dober, C. J. Duell, S. Duff, A. Duivenvoorden,

- J. Dunkley, J. Dusatko, J. Errard, G. Fabbian, S. Feeney, S. Ferraro, P. Fluxà, K. Freese, J. C. Frisch, A. Frolov, G. Fuller, B. Fuzia, N. Galitzki, P. A. Gallardo, J. T. G. Gherzi, J. Gao, E. Gawiser, M. Gerbino, V. Gluscevic, N. Goeckner-Wald, J. Golec, S. Gordon, M. Gralla, D. Green, A. Grigorian, J. Groh, C. Groppi, Y. Guan, J. E. Gudmundsson, D. Han, P. Hargrave, M. Hasegawa, M. Hasselfield, M. Hattori, V. Haynes, M. Hazumi, Y. He, E. Healy, S. W. Henderson, C. Hervias-Caimapo, C. A. Hill, J. C. Hill, G. Hilton, M. Hilton, A. D. Hincks, G. Hinshaw, R. Hložek, S. Ho, S. P. P. Ho, L. Howe, Z. Huang, J. Hubmayr, K. Huffenberger, J. P. Hughes, A. Ijjas, M. Ikape, K. Irwin, A. H. Jaffe, B. Jain, O. Jeong, D. Kaneko, E. D. Karpel, N. Katayama, B. Keating, S. S. Kernasovskiy, R. Keskitalo, T. Kisner, K. Kiuchi, J. Klein, K. Knowles, B. Koopman, A. Kosowsky, N. Krachmalnicoff, S. E. Kuenstner, C. L. Kuo, A. Kusaka, J. Lashner, A. Lee, E. Lee, D. Leon, J. S. Leung, A. Lewis, Y. Li, Z. Li, M. Limon, E. Linder, C. Lopez-Caraballo, T. Louis, L. Lowry, M. Lungu, M. Madhavacheril, D. Mak, F. Maldonado, H. Mani, B. Mates, F. Matsuda, L. Maurin, P. Mauskopf, A. May, N. McCallum, C. McKenney, J. McMahon, P. D. Meerburg, J. Meyers, A. Miller, M. Mirmelstein, K. Moodley, M. Munchmeyer, C. Munson, S. Naess, F. Nati, M. Navaroli, L. Newburgh, H. N. Nguyen, M. Niemack, H. Nishino, J. Orlowski-Scherer, L. Page, B. Partridge, J. Peloton, F. Perrotta, L. Piccirillo, G. Pisano, D. Poletti, R. Puddu, G. Puglisi, C. Raum, C. L. Reichardt, M. Remazeilles, Y. Rephaeli, D. Riechers, F. Rojas, A. Roy, S. Sadeh, Y. Sakurai, M. Salatino, M. S. Rao, E. Schaan, M. Schmittfull, N. Sehgal, J. Seibert, U. Seljak, B. Sherwin, M. Shimon, C. Sierra, J. Sievers, P. Sikhosana, M. Silva-Feaver, S. M. Simon, A. Sinclair, P. Siritanasak, K. Smith, S. R. Smith, D. Spergel, S. T. Staggs, G. Stein, J. R. Stevens, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, G. Teply, D. B. Thomas, B. Thorne, R. Thornton, H. Trac, C. Tsai, C. Tucker, J. Ullom, S. Vagnozzi, A. V. Engelen, J. V. Lanen, D. D. Winkle, E. M. Vavagiakis, C. Vergès, M. Vissers, K. Wagoner, S. Walker, J. Ward, B. Westbrook, N. Whitehorn, J. Williams, J. Williams, E. J. Wollack, Z. Xu, B. Yu, C. Yu, F. Zago, H. Zhang, and N. Zhu. The Simons Observatory: Science goals and forecasts. *Journal of Cosmology and Astroparticle Physics*, 2019(2), aug 2019.
- [7] P. A. Ade, N. Aghanim, M. I. Alves, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, H. Aussel, C. Baccigalupi, A. J. Banday, R. B. Barreiro, R. Barrena, M. Bartelmann, J. G. Bartlett, N. Bartolo, S. Basak, E. Battaner, R. Battye, K. Benabed, A. Benoît, A. Benoit-Lévy, J. P. Bernard, M. Bersanelli, B. Bertin-court, M. Bethermin, P. Bielewicz, I. Bikmaev, A. Blanchard, J. Bobin, J. J. Bock, H. Böhringer, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, H. Bourdin, J. W. Bowyer, M. Bridges, M. L. Brown, M. Bucher, R. Burenin, C. Burigana, R. C. Butler, E. Calabrese, B. Cappellini, J. F. Cardoso, R. Carr, P. Carvalho, M. Casale, G. Castex, A. Catalano, A. Challinor, A. Chamballu, R. R. Chary, X. Chen, H. C. Chiang, L. Y. Chiang, G. Chon, P. R. Christensen, E. Churazov, S. Church, M. Clemens, D. L. Clements, S. Colombi, L. P. Colombo, C. Combet, B. Comis, F. Couchot, A. Coulais, B. P. Crill, M. Cruz, A. Curto, F. Cuttaia, A. Da Silva, H. Dahle, L. Danese, R. D. Davies, R. J. Davis, P. De Bernardis, A. De Rosa, G. De Zotti, T. Déchelette, J. Delabrouille, J. M. Delouis, J. Démoclès, F. X. Désert, J. Dick, C. Dickinson, J. M. Diego, K. Dolag, H. Dole, S. Donzelli,

O. Doré, M. Douspis, A. Ducout, J. Dunkley, X. Dupac, G. Efstathiou, F. Elsner, T. A. Enßlin, H. K. Eriksen, O. Fabre, E. Falgarone, M. C. Falvella, Y. Fantaye, J. Fergusson, C. Filliard, F. Finelli, I. Flores-Cacho, S. Foley, O. Forni, P. Fosalba, M. Frailis, A. A. Fraisse, E. Franceschi, M. Freschi, S. Fromenteau, M. Frommert, T. C. Gaier, S. Galeotta, J. Gallegos, S. Galli, B. Gandolfo, K. Ganga, C. Gauthier, R. T. Génova-Santos, T. Ghosh, M. Giard, G. Giardino, M. Gilfanov, D. Girard, Y. Giraud-Héraud, E. Gjerløw, J. González-Nuevo, K. M. Górski, S. Gratton, A. Gregorio, A. Gruppuso, J. E. Gudmundsson, J. Haissinski, J. Hamann, F. K. Hansen, M. Hansen, D. Hanson, D. L. Harrison, A. Heavens, G. Helou, A. Hempel, S. Henrot-Versillé, C. Hernández-Monteagudo, D. Herranz, S. R. Hildebrandt, E. Hivon, S. Ho, M. Hobson, W. A. Holmes, A. Hornstrup, Z. Hou, W. Hovest, G. Huey, K. M. Huffenberger, G. Hurier, S. Ilić, A. H. Jaffe, T. R. Jaffe, J. Jasche, J. Jewell, W. C. Jones, M. Juvela, P. Kalberla, P. Kangaslahti, E. Keihänen, J. Kerp, R. Keskitalo, I. Khamitov, K. Kiiveri, J. Kim, T. S. Kisner, R. Kneissl, J. Knoche, L. Knox, M. Kunz, H. Kurki-Suonio, F. Lacasa, G. Lagache, A. Lähteenmäki, J. M. Lamarre, M. Langer, A. Lasenby, M. Lattanzi, R. J. Laureijs, A. Lavabre, C. R. Lawrence, M. Le Jeune, S. Leach, J. P. Leahy, R. Leonardi, J. León-Tavares, C. Leroy, J. Lesgourgues, A. Lewis, C. Li, A. Liddle, M. Liguori, P. B. Lilje, M. Linden-Vørnle, V. Lindholm, M. López-Caniego, S. Lowe, P. M. Lubin, J. F. Maciás-Pérez, C. J. Mactavish, B. Maffei, G. Maggio, D. Maino, N. Mandolesi, A. Mangilli, A. Marcos-Caballero, D. Marinucci, M. Maris, F. Marleau, D. J. Marshall, P. G. Martin, E. Martínez-González, S. Masi, M. Massardi, S. Matarrese, T. Matsumura, F. Matthai, L. Maurin, P. Mazzotta, A. McDonald, J. D. Mcewen, P. Mcgehee, S. Mei, P. R. Meinhold, A. Melchiorri, J. B. Melin, L. Mendes, E. Menegoni, A. Mennella, M. Migliaccio, K. Mikkelsen, M. Millea, R. Miniscalco, S. Mitra, M. A. Miville-Deschênes, D. Molinari, A. Moneti, L. Montier, G. Morgante, N. Morisset, D. Mortlock, A. Moss, D. Munshi, J. A. Murphy, P. Naselsky, F. Nati, P. Natoli, M. Negrello, N. P. Nesvadba, C. B. Netterfield, H. U. Nørgaard-Nielsen, C. North, F. Noviello, D. Novikov, I. Novikov, I. J. O'dwyer, F. Orieux, S. Osborne, C. O'sullivan, C. A. Oxborrow, F. Paci, L. Pagano, F. Pajot, R. Paladini, S. Pandolfi, D. Paoletti, B. Partridge, F. Pasian, G. Patanchon, P. Paykari, D. Pearson, T. J. Pearson, M. Peel, H. V. Peiris, O. Perdureau, L. Perotto, F. Perrotta, V. Pettorino, F. Piacentini, M. Piat, E. Pierpaoli, D. Pietrobon, S. Plaszczynski, P. Platania, D. Pogosyan, E. Pointecouteau, G. Polenta, N. Ponthieu, L. Popa, T. Poutanen, G. W. Pratt, G. Prézeau, S. Prunet, J. L. Puget, A. R. Pullen, J. P. Rachen, B. Racine, A. Rahlin, C. Räth, W. T. Reach, R. Rebolo, M. Reinecke, M. Remazeilles, C. Renault, A. Renzi, A. Riazuelo, S. Ricciardi, T. Riller, C. Ringeval, I. Ristorcelli, G. Robbers, G. Rocha, M. Roman, C. Rosset, M. Rossetti, G. Roudier, M. Rowan-Robinson, J. A. Rubinõ-Martín, B. Ruiz-Granados, B. Rusholme, E. Salerno, M. Sandri, L. Sanselme, D. Santos, M. Savelainen, G. Savini, B. M. Schaefer, F. Schiavon, D. Scott, M. D. Seiffert, P. Serra, E. P. Shellard, K. Smith, G. F. Smoot, T. Souradeep, L. D. Spencer, J. L. Starck, V. Stolyarov, R. Stompor, R. Sudiwala, R. Sunyaev, F. Sureau, P. Sutter, D. Sutton, A. S. Suur-Uski, J. F. Sygnet, J. Tauber, D. Tavagnacco, D. Taylor, L. Terenzi, D. Texier, L. Toffolatti, M. Tomasi, J. P. Torre, M. Tucci, M. Tucci, J. Tuovinen, M. Türler, M. Tuttlebee, G. Umana, L. Valenziano, J. Valiviita, B. Van Tent, J. Varis, L. Vibert, M. Viel, P. Vielva, F. Villa, N. Vittorio, L. A. Wade, B. D. Wandelt, C. Watson, R. Watson, I. K. Wehus, N. Welikala, J. Weller, M. White,

- S. D. White, A. Wilkinson, B. Winkel, J. Q. Xia, D. Yvon, A. Zacchei, J. P. Zibin, and A. Zonca. Planck 2013 results. I. Overview of products and scientific results. *Astronomy and Astrophysics*, 571(2):42, 2014.
- [8] P. A. Ade, Z. Ahmed, R. W. Aikin, K. D. Alexander, D. Barkats, S. J. Benton, C. A. Bischoff, J. J. Bock, R. Bowens-Rubin, J. A. Brevik, I. Buder, E. Bullock, V. Buza, J. Connors, J. Cornelison, B. P. Crill, M. Crumrine, M. Dierickx, L. Duband, C. Dvorkin, J. P. Filippini, S. Fliescher, J. Grayson, G. Hall, M. Halpern, S. Harrison, S. R. Hildebrandt, G. C. Hilton, H. Hui, K. D. Irwin, J. Kang, K. S. Karkare, E. Karpel, J. P. Kaufman, B. G. Keating, S. Kefeli, S. A. Kernasovskiy, J. M. Kovac, C. L. Kuo, N. A. Larsen, K. Lau, E. M. Leitch, M. Lueker, K. G. Megerian, L. Moncelsi, T. Namikawa, C. B. Netterfield, H. T. Nguyen, R. O’Brient, R. W. Ogburn, S. Palladino, C. Pryke, B. Racine, S. Richter, A. Schillaci, R. Schwarz, C. D. Sheehy, A. Soliman, T. St Germaine, Z. K. Staniszewski, B. Steinbach, R. V. Sudiwala, G. P. Teply, K. L. Thompson, J. E. Tolan, C. Tucker, A. D. Turner, C. Umiltà, A. G. Vieregg, A. Wandui, A. C. Weber, D. V. Wiebe, J. Willmert, C. L. Wong, W. L. Wu, H. Yang, K. W. Yoon, and C. Zhang. Constraints on Primordial Gravitational Waves Using Planck, WMAP, and New BICEP2/ Keck Observations through the 2015 Season. *Physical Review Letters*, 121(22), oct 2018.
- [9] P. A. Ade, R. W. Aikin, M. Amiri, D. Barkats, S. J. Benton, C. A. Bischoff, J. J. Bock, J. A. Brevik, I. Buder, E. Bullock, G. Davis, P. K. Day, C. D. Dowell, L. Duband, J. P. Filippini, S. Fliescher, S. R. Golwala, M. Halpern, M. Hasselfield, S. R. Hildebrandt, G. C. Hilton, K. D. Irwin, K. S. Karkare, J. P. Kaufman, B. G. Keating, S. A. Kernasovskiy, J. M. Kovac, C. L. Kuo, E. M. Leitch, N. Llombart, M. Lueker, C. B. Netterfield, H. T. Nguyen, R. O’Brient, R. W. Ogburn IV, A. Orlando, C. Pryke, C. D. Reintsema, S. Richter, R. Schwarz, C. D. Sheehy, Z. K. Staniszewski, K. T. Story, R. V. Sudiwala, G. P. Teply, J. E. Tolan, A. D. Turner, A. G. Vieregg, P. Wilson, C. L. Wong, and K. W. Yoon. BICEP2. II. Experiment and three-year data set. *The Astrophysical Journal*, 792(1), 2014.
- [10] P. A. Ade, Y. Akiba, A. E. Anthony, K. Arnold, M. Atlas, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, D. Flanagan, A. Gilbert, W. Grainger, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, J. Howard, P. Hyland, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, M. Navaroli, H. Nishino, A. Orlando, H. Paar, J. Peloton, D. Poletti, E. Quealy, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, I. Schanning, D. E. Schenck, B. D. Sherwin, A. Shimizu, C. Shimmin, M. Shimon, P. Siritanasak, G. Smecher, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, and O. Zahn. A measurement of the cosmic microwave background B-mode polarization power spectrum at sub-degree scales with POLARBEAR. *The Astrophysical Journal*, 794(2):171, may 2014.
- [11] P. A. R. Ade, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, F. Bianchini, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, K. Crowley, A. Cukierman,

- R. Dünner, M. Dobbs, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. C. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, M. L. Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, Y. Minami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, P. L. Richards, C. Ross, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori, D. Tanabe, G. P. Teply, T. Tomaru, C. Tucker, N. Whitehorn, and A. Zahn. A Measurement of the Cosmic Microwave Background B-mode Polarization Power Spectrum at Subdegree Scales from Two Years of POLARBEAR Data. *The Astrophysical Journal*, 848(2):121, 2017.
- [12] P. A. R. Ade, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, A. Gilbert, N. Goeckner-Wald, J. Groh, W. L. Holzapfel, Y. Hori, L. Howe, A. H. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, Y. Li, E. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. J. Myers, M. Navaroli, D. Poletti, G. Puglisi, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, D. E. Schenck, B. D. Sherwin, M. Shimon, I. Shirley, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, A. Suzuki, J.-I. Suzuki, B. Wilson, A. Yadav, A. Zahn, and O. Zahn. POLARBEAR constraints on cosmic birefringence and primordial magnetic fields. *Physical Review D*, 92(12):1550–7998, 2015.
- [13] N. Aghanim, Y. Akrami, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J. J. Bock, and J. R. Bond. Planck 2018 results. I. Overview and the cosmological legacy of Planck. *Astronomy & Astrophysics*, oct 2019.
- [14] S. d. S. Alighieri, F. Finelli, and M. Galaverni. LIMITS ON COSMOLOGICAL BIREFRINGENCE FROM THE ULTRAVIOLET POLARIZATION OF DISTANT RADIO GALAXIES. *The Astrophysical Journal*, 715(1):33–38, may 2010.
- [15] R. Antonucci. Unified Models for Active Galactic Nuclei and Quasars. *Annual Review of Astronomy and Astrophysics*, 31(1):473–521, sep 1993.
- [16] J. Aumont, L. Conversi, C. Thum, H. Wiesenmeyer, E. Falgarone, J. F. Macías-Pérez, F. Piacentini, E. Pointecouteau, N. Ponthieu, J. L. Puget, C. Rosset, J. A. Tauber, and M. Tristram. Measurement of the Crab nebula polarization at 90 GHz as a calibrator for CMB experiments. *Astronomy and Astrophysics*, 514:A70, may 2010.
- [17] J. Aumont, J. F. Macías-Pérez, A. Ritacco, N. Ponthieu, and A. Mangilli. Absolute calibration of the polarisation angle for future CMB B-mode experiments from current and future measurements of the Crab nebula. *Astronomy & Astrophysics*, 2018.

- [18] D. Barron. *Precision measurements of cosmic microwave background polarization to study cosmic inflation and large scale structure*. PhD thesis, The University of California, San Diego, 2015.
- [19] D. Barron, P. A. R. Ade, Y. Akiba, C. Aleman, K. Arnold, M. Atlas, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, M. Dobbs, T. Elleflot, J. Errard, G. Fabbian, C. Feng, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, N. Katayama, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. L. Jeune, A. T. Lee, E. M. Leitch, E. Linder, F. Matsuda, T. Matsumura, X. Meng, H. Morii, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, C. Raum, G. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. Rotermund, D. E. Schenck, B. D. Sherwin, I. Shirley, M. Sholl, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, J. Suzuki, S. Takada, S. Takakura, T. Tomaru, B. Wilson, A. Yadav, H. Yamaguchi, and O. Zahn. Development and characterization of the readout system for POLARBEAR-2. *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII*, 9153:915335, oct 2014.
- [20] D. Boettger. *CMB Polarization Measurements with the POLARBEAR Experiment*. PhD thesis, The University of California, San Diego, 2014.
- [21] M. L. Brown, P. Ade, J. Bock, M. Bowden, G. Cahill, P. G. Castro, S. Church, T. Culverhouse, R. B. Friedman, K. Ganga, W. K. Gear, S. Gupta, J. Hinderks, J. Kovac, A. E. Lange, E. Leitch, S. J. Melhuish, Y. Memari, J. A. Murphy, A. Orlando, C. O. Sullivan, L. Piccirillo, C. Pryke, N. Rajguru, B. Rusholme, R. Schwarz, A. N. Taylor, K. L. Thompson, A. H. Turner, E. Y. Wu, and M. Zemcov. Improved measurements of the temperature and polarization of the cosmic microwave background from quad. *Astrophysical Journal*, 705(1):978–999, 2009.
- [22] P. Cabella, P. Natoli, and J. Silk. Constraints on CPT violation from Wilkinson Microwave Anisotropy Probe three year polarization data: A wavelet analysis. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 76(12):123014, dec 2007.
- [23] J. E. Carlstrom, R. Plambeck, and D. D. Thornton. A Continuously Tunable 65-115 GHz Gunn Oscillator. *IEEE Transactions on Microwave Theory and Techniques*, 33(7):610 – 619, 1985.
- [24] S. M. Carroll. Quintessence and the rest of the world: Suppressing long-range interactions. *Physical Review Letters*, 81(15):3067–3070, 1998.
- [25] S. M. Carroll, G. B. Field, and R. Jackiw. Limits on a Lorentz-and parity-violating modification of electrodynamics. *Physical Review D*, 41:15, 1990.
- [26] A. T. Crites, J. W. Henning, P. A. Ade, K. A. Aird, J. E. Austermann, J. A. Beall, A. N. Bender, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. C. Chiang, H. M. Cho, R. Citron, T. M. Crawford, T. D. Haan, M. A. Dobbs, W. Everett, J. Gallicchio, J. Gao, E. M. George, A. Gilbert, N. W. Halverson, D. Hanson, N. Harrington, G. C. Hilton, G. P.

- Holder, W. L. Holzapfel, S. Hoover, Z. Hou, J. D. Hrubes, N. Huang, J. Hubmayr, K. D. Irwin, R. Keisler, L. Knox, A. T. Lee, E. M. Leitch, D. Li, C. Liang, D. Luong-Van, J. J. McMahon, J. Mehl, S. S. Meyer, L. Mocanu, T. E. Montroy, T. Natoli, J. P. Nibarger, V. Novosad, S. Padin, C. Pryke, C. L. Reichardt, J. E. Ruhl, B. R. Saliwanchik, J. T. Sayre, K. K. Schaffer, G. Smecher, A. A. Stark, K. T. Story, C. Tucker, K. Vanderlinde, J. D. Vieira, G. Wang, N. Whitehorn, V. Yefremenko, and O. Zahn. MEASUREMENTS OF E-MODE POLARIZATION AND TEMPERATURE-E-MODE CORRELATION IN THE COSMIC MICROWAVE BACKGROUND FROM 100 SQUARE DEGREES OF SPTPOL DATA. *Astrophysical Journal*, 805(1):36, 2015.
- [27] R. D. Davies, R. A. Watson, and C. M. Gutiérrez. Galactic synchrotron emission at high frequencies. *Monthly Notices of the Royal Astronomical Society*, 278(4):925–939, 1996.
- [28] P. de Bernardis, S. Masi, P. de Bernardis, S. Masi, P. de Bernardis, and S. Masi. Cosmic Microwave Background and Cosmic Polarization Rotation: An Experimentalist View. *International Journal of Modern Physics D*, 25(11):1640012, oct 2016.
- [29] S. Di Serego Alighieri. Cosmological birefringence: An astrophysical test of fundamental physics. Technical report, 2011.
- [30] S. Dodelson. *Modern Cosmology*. 2003.
- [31] C. Dragone. Offset Multireflector Antennas with Perfect Pattern Symmetry and Polarization Discrimination. *Bell System Technical Journal*, 57(7):2663–2684, sep 1978.
- [32] R. H. Duhamel. Dual Polarized Sinuous Antennas, feb 1987.
- [33] R. Durrer and A. Neronov. Cosmological Magnetic Fields: Their Generation, Evolution and Observation. *Astronomy and Astrophysics Review*, 21(1), mar 2013.
- [34] J. M. Edwards, R. O’Brien, A. T. Lee, and G. M. Rebeiz. Dual-polarized sinuous antennas on extended hemispherical silicon lenses. *IEEE Transactions on Antennas and Propagation*, 60(9):4082–4091, 2012.
- [35] T. Elleflot. *Measuring the Polarization of the Cosmic Microwave Background with POLARBEAR-1 and Developing the Next-Generation Experiment POLARBEAR-2*. PhD thesis, The University of California, San Diego, 2019.
- [36] J. Errard, P. A. Ade, Y. Akiba, K. Arnold, M. Atlas, C. Baccigalupi, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, J. Delabrouille, M. Dobbs, A. Ducout, T. Elleflot, G. Fabbian, C. Feng, S. Feeney, A. Gilbert, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, Y. Inoue, G. C. Jaehnig, A. H. Jaffe, O. Jeong, N. Katayama, J. Kaufman, B. Keating, Z. Kermish, R. Keskitalo, T. Kisner, M. Le Jeune, A. T. Lee, E. M. Leitch, D. Leon, E. Linder, F. Matsuda, T. Matsumura, N. J. Miller, M. J. Myers, M. Navaroli, H. Nishino, T. Okamura, H. Paar, J. Peloton, D. Poletti, G. Puglisi, G. Rebeiz, C. L. Reichardt, P. L. Richards,

- C. Ross, K. M. Rotermond, D. E. Schenck, B. D. Sherwin, P. Siritanasak, G. Smecher, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, A. Tikhomirov, T. Tomaru, N. Whitehorn, B. Wilson, A. Yadav, and O. Zahn. MODELING ATMOSPHERIC EMISSION for CMB GROUND-BASED OBSERVATIONS. *The Astrophysical Journal*, 809(1):63, aug 2015.
- [37] M. A. O. A. Fa’undez, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, H. E. Bouhargani, J. Carron, K. Cheung, Y. Chinone, T. Elleflot, J. Errard, G. Fabbian, C. Feng, T. Fujino, N. Goeckner-Wald, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, H. Hirose, O. Jeong, N. Katayama, B. Keating, S. Kikuchi, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, F. Matsuda, T. Matsumura, Y. Minami, M. Navaroli, H. Nishino, A. T. P. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, Y. Segawa, B. D. Sherwin, M. Silva-Feaver, P. Siritanasak, R. Stompor, A. Suzuki, O. Tajima, S. Takatori, D. Tanabe, G. P. Teply, and C. Tsai. Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum from Two Years of POLARBEAR Data. *arXiv e-prints*, nov 2019.
- [38] M. Galaverni, G. Gubitosi, F. Paci, and F. Finelli. Cosmological birefringence constraints from CMB and astrophysical polarization data. *Journal of Cosmology and Astroparticle Physics*, 2015(8):31, aug 2015.
- [39] V. Gluscevic, D. Hanson, M. Kamionkowski, and C. M. Hirata. First CMB constraints on direction-dependent cosmological birefringence from WMAP-7. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 86(10), 2012.
- [40] A. H. Guth. Inflationary universe: A possible solution to the horizon and flatness problems. *Physical Review D*, 23(2):347–356, 1981.
- [41] F. K. Hansen, S. Henrot-Versillé, D. Herranz, E. Hivon, Z. Huang, A. H. Jaffe, W. C. Jones, E. Keihänen, R. Keskitalo, K. Kiiveri, N. Krachmalnicoff, M. Kunz, H. Kurki-Suonio, J.-M. Lamarre, M. Langer, A. Lasenby, M. Lattanzi, C. R. Lawrence, M. Le Jeune, J. P. Leahy, F. Levrier, and M. Liguori. Planck intermediate results. XLIX. Parity-violation constraints from polarization data. *Astronomy & Astrophysics*, 54:41, 2016.
- [42] J. J. Hester. The Crab Nebula: An Astrophysical Chimera. *Annual Review of Astronomy and Astrophysics*, 46(1):127–155, sep 2008.
- [43] C. A. Hill, S. Beckman, Y. Chinone, N. Goeckner-Wald, M. Hazumi, B. Keating, A. Kusaka, A. T. Lee, F. Matsuda, R. Plambeck, A. Suzuki, and S. Takakura. Design and development of an ambient-temperature continuously-rotating achromatic half-wave plate for CMB polarization modulation on the POLARBEAR-2 experiment. *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 9914:99142U, 2016.
- [44] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolta, M. Halpern, R. S. Hill, N. Odegard, L. Page, K. M. Smith, J. L. Weiland, B. Gold, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, E. Wollack, and E. L. Wright. Nine-year

wilkinson microwave anisotropy probe (WMAP) observations: Cosmological parameter results. *Astrophysical Journal, Supplement Series*, 208(2), dec 2013.

- [45] L. Howe, K. Arnold, B. Keating, L. N. Lowry, C. Tsai, G. Coppi, A. May, G. P. Teply, N. Stebor, J. C. Groh, A. Lee, X. Guo, and L. Piccirillo. Design and characterization of the POLARBEAR-2b and POLARBEAR-2c cosmic microwave background cryogenic receivers. *SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, 10708:131, 2018.
- [46] Y. Inoue, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. A. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskital, T. Kisner, A. Kusaka, M. L. Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, K. Mizukami, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, Y. Segaw, B. D. Sherwin, I. Shirley, P. Siritanasak, N. Stebor, R. S. A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirol, T. Tomaru, N. Whitehorn, A. Zahn, and O. Zahn. POLARBEAR-2: an instrument for CMB polarization measurements. *SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 991411:1–8, 2016.
- [47] Y. Inoue, T. Hamada, M. Hasegawa, M. Hazumi, Y. Hori, A. Suzuki, T. Tomaru, T. Matsumura, T. Sakata, T. Minamoto, and T. Hirai. Two-layer anti-reflection coating with mullite and polyimide foam for large-diameter cryogenic infrared filters. *Applied Optics*, 55(34):D22, dec 2016.
- [48] G. C. Jaehnig. *Measuring cosmic microwave background polarization with POLARBEAR*. PhD thesis, The University of Colorado, 2018.
- [49] M. Kamionkowski, A. Kosowsky, and A. Stebbins. A probe of primordial gravity waves and vorticity. *Physical Review Letters*, 78(11):2058–2061, 1997.
- [50] D. Kaneko, S. Adachi, P. A. Ade, M. Aguilar Faúndez, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, D. Beck, S. Beckman, F. Bianchini, D. Boettger, J. Borrill, J. Carron, S. Chapman, K. Cheung, Y. Chinone, K. Crowley, A. Cukierman, M. Dobbs, R. Dünner, H. El-Bouhargani, T. Elleflot, J. Errard, G. Fabbian, S. M. Feeney, C. Feng, T. Fujino, N. Galitzki, A. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. W. Halverson, T. Hamada, M. Hasegawa, M. Hazumi, C. A. Hill, L. Howe, Y. Inoue, G. Jaehnig, O. Jeong, N. Katayama, B. Keating, R. Keskitalo, S. Kikuchi, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. N. Lowry, A. Mangu, F. Matsuda, Y. Minami, M. Navaroli, H. Nishino, J. Peloton, A. T. Pham, D. Poletti, G. Puglisi, C. L. Reichardt, C. Ross, Y. Segawa, M. Silva-Feaver, P. Siritanasak, N. Stebor, R. Stompor, A. Suzuki, O. Tajima, S. Takakura, S. Takatori,

- D. Tanabe, G. P. Teply, T. Tomaru, C. Tsai, C. Verges, B. Westbrook, and Y. Zhou. Deployment of POLARBEAR-2A. *Journal of Low Temperature Physics*, 199(3):1137–1147, may 2020.
- [51] J. P. Kaufman, B. G. Keating, and B. R. Johnson. Precision tests of parity violation over cosmological distances. *Monthly Notices of the Royal Astronomical Society*, 455(2):1–12, 2015.
- [52] J. P. Kaufman, N. J. Miller, M. Shimon, D. Barkats, C. Bischoff, I. Buder, B. G. Keating, J. M. Kovac, P. A. Ade, R. Aikin, J. O. Battle, E. M. Bierman, J. J. Bock, H. C. Chiang, C. D. Dowell, L. Duband, J. Filippini, E. F. Hivon, W. L. Holzapfel, V. V. Hristov, W. C. Jones, S. S. Kernasovskiy, C. L. Kuo, E. M. Leitch, P. V. Mason, T. Matsumura, H. T. Nguyen, N. Ponthieu, C. Pryke, S. Richter, G. Rocha, C. Sheehy, M. Su, Y. D. Takahashi, J. E. Tolan, and K. W. Yoon. Self-calibration of BICEP1 three-year data and constraints on astrophysical polarization rotation. *Physical Review D*, 89(6), 2014.
- [53] B. G. Keating, M. Shimon, and A. P. S. Yadav. Self-calibration of cosmic microwave background polarization experiments. *The Astrophysical Journal Letters*, 762(2), 2013.
- [54] Z. D. Kermish, P. Ade, A. Anthony, K. Arnold, D. Barron, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, M. A. Dobbs, J. Errard, G. Fabbian, D. Flanigan, G. Fuller, A. Ghribi, W. Grainger, N. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, W. L. Holzapfel, J. Howard, P. Hyland, A. Jaffe, B. Keating, T. Kisner, A. T. Lee, M. Le Jeune, E. Linder, M. Lungu, F. Matsuda, T. Matsumura, X. Meng, N. J. Miller, H. Morii, S. Moyerman, M. J. Myers, H. Nishino, H. Paar, E. Quealy, C. L. Reichardt, P. L. Richards, C. Ross, A. Shimizu, M. Shimon, C. Shimmin, M. Sholl, P. Siritanasak, H. Spieler, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, T. Tomaru, C. Tucker, and O. Zahn. The POLARBEAR experiment. In *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI*, volume 8452, page 84521C. SPIE, oct 2012.
- [55] J. Kim. How to make a clean separation between CMB E- and B-modes with proper foreground masking. *Astronomy and Astrophysics*, 531:32, 2011.
- [56] E. Komatsu, J. Dunkley, M. R. Nolta, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. Limon, L. Page, D. N. Spergel, M. Halpern, R. S. Hill, A. Kogut, S. S. Meyer, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation. *The Astrophysical Journal Supplement, Volume 180, Issue 2, pp. 330-376 (2009).*, 180:330–376, mar 2008.
- [57] E. Komatsu, K. M. Smith, J. Dunkley, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. R. Nolta, L. Page, D. N. Spergel, M. Halpern, R. S. Hill, A. Kogut, M. Limon, S. S. Meyer, N. Odegard, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright. Seven-year wilkinson microwave anisotropy probe (WMAP) observations: Cosmological interpretation. *Astrophysical Journal, Supplement Series*, 192(2):18, feb 2011.

- [58] A. Kusaka, J. Appel, T. Essinger-Hileman, J. A. Beall, L. E. Campusano, H.-M. M. Cho, S. K. Choi, K. Crowley, J. W. Fowler, P. Gallardo, M. Hasselfield, G. Hilton, S.-P. P. P. Ho, K. Irwin, N. Jarosik, M. D. Niemack, G. W. Nixon, M. Snolta, L. A. Page, G. A. Palma, L. Parker, S. Raghunathan, C. D. Reintsema, J. Sievers, S. M. Simon, S. T. Staggs, K. Visnjic, K.-W. W. Yoon, M. Nolta, L. A. Page, G. A. Palma, L. Parker, S. Raghunathan, C. D. Reintsema, J. Sievers, S. M. Simon, S. T. Staggs, K. Visnjic, and K.-W. W. Yoon. Results from the Atacama B-mode Search (ABS) experiment. *Journal of Cosmology and Astroparticle Physics*, 2018(9), jan 2018.
- [59] A. Lewis. CMB anisotropies from primordial inhomogeneous magnetic fields. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 70(4), 2004.
- [60] A. Lewis, A. Challinor, A. Lewis, and A. Challinor. CAMB: Code for Anisotropies in the Microwave Background. *Astrophysics Source Code Library*, page ascl:1102.026, 2011.
- [61] S. Y. Li, J. Q. Xia, M. Li, H. Li, and X. Zhang. Testing CPT symmetry with current and future CMB measurements. *The Astrophysical Journal*, 799(2):211, jan 2015.
- [62] Y.-P. Li, Y. Liu, S.-Y. Li, H. Li, and X. Zhang. Tibet’s Ali: A New Window to Detect the CMB Polarization. *arXiv e-prints*, sep 2017.
- [63] A. Lue, L. Wang, and M. Kamionkowski. Cosmological signature of new parity-violating interactions. *Physical Review Letters*, 83(8):1506–1509, 1999.
- [64] J. F. Macías-Pérez, F. Mayet, J. Aumont, and F. X. Désert. Global spectral energy distribution of the crab nebula in the prospect of the planck satellite polarization calibration. *The Astrophysical Journal*, 711(1):417–423, 2010.
- [65] S. Masi, P. A. R. Ade, J. J. Bock, J. R. Bond, J. Borrill, A. Boscaleri, P. Cabella, C. R. Contaldi, B. P. Crill, P. de Bernardis, G. De Gasperis, A. de Oliveira-Costa, G. De Troia, G. Di Stefano, P. Ehlers, E. Hivon, V. Hristov, A. Iacoangeli, A. H. Jaffe, W. C. Jones, T. S. Kisner, A. E. Lange, C. J. MacTavish, C. Marini Bettolo, P. Mason, P. D. Mauskopf, T. E. Montroy, F. Nati, L. Nati, P. Natoli, C. B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, G. Polenta, S. Prunet, S. Ricciardi, G. Romeo, J. E. Ruhl, P. Santini, M. Tegmark, E. Torbet, M. Veneziani, and N. Vittorio. Instrument, method, brightness, and polarization maps from the 2003 flight of BOOMERanG. *Astronomy and Astrophysics*, 458(3):687–716, 2006.
- [66] J. C. Mather, E. S. Cheng, D. A. Cottingham, J. Eplee, R. E., D. J. Fixsen, T. Hewagama, R. B. Isaacman, K. A. Jensen, S. S. Meyer, P. D. Noerdlinger, S. M. Read, L. P. Rosen, R. A. Shafer, E. L. Wright, C. L. Bennett, N. W. Boggess, M. G. Hauser, T. Kelsall, J. Moseley, S. H., R. F. Silverberg, G. F. Smoot, R. Weiss, and D. T. Wilkinson. Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument. *The Astrophysical Journal*, 420:439, jan 1994.
- [67] F. Matsuda. *Cosmic Microwave Background Polarization Science and Optical Design of the Polarbear and Simons Array Experiments*. PhD thesis, UC San Diego, 2017.

- [68] F. Matsuda, L. Lowry, A. Suzuki, M. Aguilar Fáunderz, K. Arnold, D. Barron, F. Bianchini, K. Cheung, Y. Chinone, T. Elleflot, G. Fabbian, N. Goeckner-Wald, M. Hasegawa, D. Kaneko, N. Katayama, B. Keating, A. T. Lee, M. Navaroli, H. Nishino, H. Paar, G. Puglisi, P. L. Richards, J. Seibert, P. Siritanasak, O. Tajima, S. Takatori, C. Tsai, and B. Westbrook. The POLARBEAR Fourier transform spectrometer calibrator and spectroscopic characterization of the POLARBEAR instrument. *Review of Scientific Instruments*, 90(11), 2019.
- [69] C. P. McKay, E. I. Friedmann, B. Gómez-Silva, L. Cáceres-Villanueva, D. T. Andersen, and R. Landheim. Temperature and moisture conditions for life in the extreme arid region of the atacama desert: Four years of observations including the El Niño of 1997-1998. *Astrobiology*, 3(2):393–406, jun 2003.
- [70] N. J. Miller, M. Shimon, and B. G. Keating. CMB polarization systematics due to beam asymmetry: Impact on cosmological birefringence. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 79(10):103002, may 2009.
- [71] S. Naess, M. Hasselfield, J. McMahon, M. D. Niemack, G. E. Addison, P. A. Ade, R. Allison, M. Amiri, N. Battaglia, J. A. Beall, F. De Bernardis, J. R. Bond, J. Britton, E. Calabrese, H. M. Cho, K. Coughlin, D. Crichton, S. Das, R. Datta, M. J. Devlin, S. R. Dicker, J. Dunkley, R. Dünner, J. W. Fowler, A. E. Fox, P. Gallardo, E. Grace, M. Gralla, A. Hajian, M. Halpern, S. Henderson, J. C. Hill, G. C. Hilton, M. Hilton, A. D. Hincks, R. Hlozek, P. Ho, J. Hubmayr, K. M. Huffenberger, J. P. Hughes, L. Infante, K. Irwin, R. Jackson, S. M. Kasanda, J. Klein, B. Koopman, A. Kosowsky, D. Li, T. Louis, M. Lungu, M. Madhavacheril, T. A. Marriage, L. Maurin, F. Menanteau, K. Moodley, C. Munson, L. Newburgh, J. Nibarger, M. R. Nolta, L. A. Page, C. Pappas, B. Partridge, F. Rojas, B. L. Schmitt, N. Sehgal, B. D. Sherwin, J. Sievers, S. Simon, D. N. Spergel, S. T. Staggs, E. R. Switzer, R. Thornton, H. Trac, C. Tucker, M. Uehara, A. V. Engelen, J. T. Ward, and E. J. Wollack. The Atacama cosmology telescope: CMB polarization at $200 < l < 9000$. *Journal of Cosmology and Astroparticle Physics*, 2014(10):007–007, oct 2014.
- [72] F. Nati, M. J. Devlin, M. Gerbino, B. R. Johnson, B. Keating, L. Pagano, and G. Teply. POLOCALC: a Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background. *Journal of Astronomical Instrumentation*, 06(02):1740008, jun 2017.
- [73] W. T. Ni. Equivalence principles and electromagnetism. *Physical Review Letters*, 38(7):301–304, feb 1977.
- [74] R. O’Brien, J. Edwards, K. Arnold, G. Engargiola, W. Holzapfel, A. T. Lee, M. Myers, E. Quealy, G. Rebeiz, P. Richards, H. Spieler, and H. Tran. Sinuous antennas for cosmic microwave background polarimetry. In W. D. Duncan, W. S. Holland, S. Withington, and J. Zmuidzinas, editors, *Millimeter and Submillimeter Detectors and Instrumentation for Astronomy IV*, volume 7020, page 70201H. SPIE, aug 2008.
- [75] L. Pagano, P. De Bernardis, G. De Troia, G. Gubitosi, S. Masi, A. Melchiorri, P. Natoli, F. Piacentini, and G. Polenta. CMB polarization systematics, cosmological birefringence,

and the gravitational waves background. *Physical Review D - Particles, Fields, Gravitation and Cosmology*, 80(4):043522, aug 2009.

- [76] S. Paine. The am atmospheric model (v11.0). Technical report, sep 2004.
- [77] A. A. Penzias and R. W. Wilson. A Measurement of Excess Antenna Temperature at 4080 Mc/s. *The Astrophysical Journal*, 142:419, jul 1965.
- [78] M. J. Persky. Review of black surfaces for space-borne infrared systems. *Review of Scientific Instruments*, 70(5):2193–2217, 1999.
- [79] D. Poletti, G. Fabbian, M. Le Jeune, J. Peloton, K. Arnold, C. Baccigalupi, D. Barron, S. Beckman, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, A. Ducout, T. Elleflot, J. Errard, S. Feeney, N. Goeckner-Wald, J. Groh, G. Hall, M. Hasegawa, M. Hazumi, C. Hill, L. Howe, Y. Inoue, A. H. Jaffe, O. Jeong, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, A. Kusaka, A. T. Lee, D. Leon, E. Linder, L. Lowry, F. Matsuda, M. Navaroli, H. Paar, G. Puglisi, C. L. Reichardt, C. Ross, P. Siritanasak, N. Stebor, B. Steinbach, R. Stompor, A. Suzuki, O. Tajima, G. Teply, and N. Whitehorn. Making maps of cosmic microwave background polarization for B-mode studies: The POLARBEAR example. *Astronomy and Astrophysics*, 600:1–26, 2017.
- [80] A. Ritacco, J. F. M. Pérez, N. Ponthieu, R. Adam, P. Ade, P. André, J. Aumont, A. Beelen, A. Benoît, A. Bideaud, N. Billot, O. Bourrion, A. Bracco, M. Calvo, A. Catalano, G. Coiffard, B. Comis, A. D’Addabbo, M. De Petris, F. X. Désert, S. Doyle, J. Goupy, C. Kramer, G. Lagache, S. Leclercq, J. F. Lestrade, P. Mauskopf, F. Mayet, A. Maury, A. Monfardini, F. Pajot, E. Pascale, L. Perotto, G. Pisano, M. R. Iglesias, V. Revéret, L. Rodriguez, C. Romero, H. Roussel, F. Ruppin, K. Schuster, A. Sievers, G. Siringo, C. Thum, S. Trique-neaux, C. Tucker, H. Wiesemeyer, and R. Zylka. NIKA 150 GHz polarization observations of the Crab nebula and its spectral energy distribution. *Astronomy & Astrophysics*, apr 2018.
- [81] D. Rosen, A. Suzuki, B. Keating, W. Krantz, A. T. Lee, E. Quealy, P. L. Richards, P. Siritanasak, and W. Walker. Epoxy-based broadband antireflection coating for millimeter-wave optics. *Applied Optics*, 52(33):8102–8105, nov 2013.
- [82] D. Samtleben, S. Staggs, and B. Winstein. The Cosmic Microwave Background for Pedestrians: A Review for Particle and Nuclear Physicists. *Annual Review of Nuclear and Particle Science*, 57(1):245–283, 2007.
- [83] L. I. Schiff. On Experimental Tests of the General Theory of Relativity. *American Journal of Physics*, 28(4):340–343, apr 1960.
- [84] P. Siritanasak, C. Aleman, K. Arnold, A. Cukierman, M. Hazumi, K. Kazemzadeh, B. Keating, T. Matsumura, A. T. Lee, C. Lee, E. Quealy, D. Rosen, N. Stebor, and A. Suzuki. The Broadband Anti-reflection Coated Extended Hemispherical Silicon Lenses for Polarbear-2 Experiment. *Journal of Low Temperature Physics*, 184(3-4):553–558, aug 2016.

- [85] G. Smecher, F. Aubin, E. Bissonnette, M. Dobbs, P. Hyland, and K. MacDermid. A biasing and demodulation system for kilopixel TES bolometer arrays. *IEEE Transactions on Instrumentation and Measurement*, 61(1):251–260, jan 2012.
- [86] G. F. Smoot, C. L. Bennett, A. Kogut, E. L. Wright, J. Aymon, N. W. Boggess, E. S. Cheng, G. de Amici, S. Gulkis, M. G. Hauser, G. Hinshaw, P. D. Jackson, M. Janssen, E. Kaita, T. Kelsall, P. Keegstra, C. Lineweaver, K. Loewenstein, P. Lubin, J. Mather, S. S. Meyer, S. H. Moseley, T. Murdock, L. Rokke, R. F. Silverberg, L. Tenorio, R. Weiss, and D. T. Wilkinson. Structure in the COBE differential microwave radiometer first-year maps. *The Astrophysical Journal*, 396:L1, sep 1992.
- [87] N. Stebor, P. Ade, Y. Akiba, C. Aleman, K. Arnold, C. Baccigalupi, B. Barch, D. Barron, S. Beckman, A. Bender, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, T. de Haan, M. Dobbs, A. Ducout, R. Dunner, T. Elleflot, J. Errard, G. Fabbian, S. Feeney, C. Feng, T. Fujino, G. Fuller, A. J. Gilbert, N. Goeckner-Wald, J. Groh, G. Hall, N. Halverson, T. Hamada, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, W. L. Holzapfel, Y. Hori, L. Howe, Y. Inoue, F. Irie, G. Jaehnig, A. Jaffe, O. Jeong, N. Katayama, J. P. Kaufman, K. Kazemzadeh, B. G. Keating, Z. Kermish, R. Keskitalo, T. Kisner, A. Kusaka, M. Le Jeune, A. T. Lee, D. Leon, E. V. Linder, L. Lowry, F. Matsuda, T. Matsumura, N. Miller, J. Montgomery, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. R. Raum, G. M. Rebeiz, C. L. Reichardt, P. L. Richards, C. Ross, K. M. Rotermund, Y. Segawa, B. D. Sherwin, I. Shirley, P. Siritanasak, L. Steinmetz, R. Stompor, A. Suzuki, O. Tajima, S. Takada, S. Takatori, G. P. Teply, A. Tikhomirov, T. Tomaru, B. Westbrook, N. Whitehorn, A. Zahn, and O. Zahn. The Simons Array CMB polarization experiment. In W. S. Holland and J. Zmuidzinas, editors, *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, volume 9914, page 99141H. SPIE, jul 2016.
- [88] A. Suzuki. *Multichroic Bolometric Detector Architecture for Cosmic Microwave Background Polarimetry Experiments*. PhD thesis, The University of California, Berkeley, 2013.
- [89] S. Takakura, M. Aguilar, Y. Akiba, K. Arnold, C. Baccigalupi, D. Barron, S. Beckman, D. Boettger, J. Borrill, S. Chapman, Y. Chinone, A. Cukierman, A. Ducout, T. Elleflot, J. Errard, G. Fabbian, T. Fujino, N. Galitzki, N. Goeckner-Wald, N. W. Halverson, M. Hasegawa, K. Hattori, M. Hazumi, C. Hill, L. Howe, Y. Inoue, A. H. Jaffe, O. Jeong, D. Kaneko, N. Katayama, B. Keating, R. Keskitalo, T. Kisner, N. Krachmalnicoff, A. Kusaka, A. T. Lee, D. Leon, L. Lowry, F. Matsuda, T. Matsumura, M. Navaroli, H. Nishino, H. Paar, J. Peloton, D. Poletti, G. Puglisi, C. L. Reichardt, C. Ross, P. Siritanasak, A. Suzuki, O. Tajima, S. Takatori, and G. Teply. Performance of a continuously rotating half-wave plate on the POLARBEAR telescope. *Journal of Cosmology and Astroparticle Physics*, 2017(5):21, 2017.
- [90] S. Takakura, F. T. Matsuda, K. Arnold, D. Boettger, Y. Chinone, M. Hazumi, B. Keating, A. Kusaka, and A. T. Lee. Cross-polarization systematics due to Mizuguchi-Dragone condition breaking by a continuously rotating half-wave plate at prime focus in the Huan Tran telescope. In J. Zmuidzinas and J.-R. Gao, editors, *Millimeter, Submillimeter, and*

Far-Infrared Detectors and Instrumentation for Astronomy IX, volume 10708, page 144. SPIE, jul 2018.

- [91] G. P. Teply. *Measurement of the Polarization of the Cosmic Microwave Background with the Bicep2 and Keck Array Telescopes*. PhD thesis, California Institute of Technology, 2015.
- [92] The Planck Collaboration. Planck 2015 results. XXVI. The Second Planck Catalogue of Compact Sources. *Astronomy & Astrophysics*, 594:A26, 2016.
- [93] J. F. Wardle, R. A. Perley, and M. H. Cohen. Observational evidence against birefringence over cosmological distances. *Physical Review Letters*, 79(10):1801–1804, sep 1997.
- [94] J. L. Weiland, N. Odegard, R. S. Hill, E. Wollack, G. Hinshaw, M. R. Greason, N. Jarosik, L. Page, C. L. Bennett, J. Dunkley, B. Gold, M. Halpern, A. Kogut, E. Komatsu, D. Larson, M. Limon, S. S. Meyer, M. R. Nolta, K. M. Smith, D. N. Spergel, G. S. Tucker, and E. L. Wright. Seven-year wilkinson microwave anisotropy probe (WMAP) observations: Planets and celestial calibration sources. *Astrophysical Journal, Supplement Series*, 192(2):19, 2011.
- [95] L. M. Widrow. Origin of galactic and extragalactic magnetic fields, jul 2002.
- [96] E. Y. Wu, P. Ade, J. Bock, M. Bowden, M. L. Brown, G. Cahill, P. G. Castro, S. Church, T. Culverhouse, R. B. Friedman, K. Ganga, W. K. Gear, S. Gupta, J. Hinderks, J. Kovac, A. E. Lange, E. Leitch, S. J. Melhuish, Y. Memari, J. A. Murphy, A. Orlando, L. Piccirillo, C. Pryke, N. Rajguru, B. Rusholme, R. Schwarz, C. O’Sullivan, A. N. Taylor, K. L. Thompson, A. H. Turner, and M. Zemcov. Parity violation constraints using cosmic microwave background polarization spectra from 2006 and 2007 observations by the QUaD polarimeter. *Physical Review Letters*, 102(16):161302, apr 2009.
- [97] W. L. K. Wu, L. M. Mocanu, P. A. R. Ade, A. J. Anderson, J. E. Austermann, J. S. Avva, J. A. Beall, A. N. Bender, B. A. Benson, F. Bianchini, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. C. Chiang, R. Citron, C. C. Moran, T. M. Crawford, A. T. Crites, T. De Haan, M. A. Dobbs, W. Everett, J. Gallicchio, E. M. George, A. Gilbert, N. Gupta, N. W. Halverson, N. Harrington, J. W. Henning, G. C. Hilton, G. P. Holder, W. L. Holzapfel, Z. Hou, J. D. Hrubes, N. Huang, J. Hubmayr, K. D. Irwin, L. Knox, A. T. Lee, D. Li, A. Lowitz, A. Manzotti, J. J. McMahon, S. S. Meyer, M. Millea, J. Montgomery, A. Nadolski, T. Natoli, J. P. Nibarger, G. I. Noble, V. Novosad, Y. Omori, S. Padin, S. Patil, C. Pryke, C. L. Reichardt, J. E. Ruhl, B. R. Saliwanchik, J. T. Sayre, K. K. Schaffer, C. Sievers, G. Simard, G. Smecher, A. A. Stark, K. T. Story, C. Tucker, K. Vanderlinde, T. Veach, J. D. Vieira, G. Wang, N. Whitehorn, V. Yefremenko, C. Corbett Moran, T. M. Crawford, A. T. Crites, T. De Haan, M. A. Dobbs, W. Everett, J. Gallicchio, E. M. George, A. Gilbert, N. Gupta, N. W. Halverson, N. Harrington, J. W. Henning, G. C. Hilton, G. P. Holder, W. L. Holzapfel, Z. Hou, J. D. Hrubes, N. Huang, J. Hubmayr, K. D. Irwin, L. Knox, A. T. Lee, D. Li, A. Lowitz, A. Manzotti, J. J. McMahon, S. S. Meyer, K. K. Schaffer, C. Sievers, G. Simard, G. Smecher, A. A. Stark, K. T. Story, C. Tucker, K. Vanderlinde, T. Veach,

- J. D. Vieira, G. Wang, N. Whitehorn, and V. Yefremenko. A Measurement of the Cosmic Microwave Background Lensing Potential and Power Spectrum from 500 square deg of SPTpol Temperature and Polarization Data. *arXiv e-prints*, 23:21, 2019.
- [98] J.-Q. Q. Xia, H. Li, and X. Zhang. Probing CPT violation with CMB polarization measurements. *Physics Letters B*, 687(2-3):129–132, apr 2010.