A Rotating Polarized Source:
Instrument Development for Precision Calibration of
Cosmic Microwave Background Polarimeters at the
South Pole

A Thesis Presented
by

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to

The Department of Astronomy
and
The Department of Earth and Planetary Sciences

in partial fulfillment of the requirements
for a joint degree
of Bachelor of Arts

April 2012
Harvard University
Acknowledgements

There are a lot of people who deserve thanks for their help on this project, but my thesis advisors, John Kovac and Abigail Vieregg, deserve special thanks for their continual support and patience throughout this project. The amount that I have learned from both of them throughout this process has been astronomical, and I cannot thank them enough for their time and dedication. The other members of John’s lab, Colin Bischoff, Chin Lin Wong and Michael Gordon also deserve thanks for their help with many aspects of this project. Thank you to the best machinist ever, Steve Sansone, for all of his help on this undertaking. Thank you to Jeff Vieregg for his help during the final push to finish the RPS in time for deployment to the South Pole. And thank you to Irene Coyle and Peg Herlihy for their help getting purchase orders and the like sorted out for the many components acquired for this project.

My fellow Astro and EPS thesis writers also deserve thanks, for helping me keep my sanity intact throughout the many challenges of thesis writing. Thank you to my EPS advisor Sarah Stewart for her support, and thank you to Chenoweth Moffatt for always being the voice of reason. Lastly, I need to thank all of my friends and family for putting up with me and my constant canceling and rescheduling of plans over the past several months. I could not have done this without their support.
Abstract

The detection of degree-scale B-mode polarization in the Cosmic Microwave Background (CMB) would be a confirmation of the Inflationary model of the universe, and would allow for the determination of the energy scale of the universe at early times. BICEP2 and the Keck Array are two experiments located at the South Pole designed to constrain the amplitude of B-mode polarization in the CMB. B-modes are inherently faint making the sensitivity of such experiments of utmost importance. Optimal sensitivity can be ensured through meticulous instrument characterization which reduces systematic contamination of CMB observations. Two possible sources of systematic contamination derive from uncertainties in the cross polar response, $\epsilon$, and polarization response angle, $\psi$, of the detectors in BICEP2 and the Keck Array. A rotating polarized microwave source was developed to determine $\epsilon$ and $\psi$ with a high level of precision. A 140 to 160 GHz broadband noise source was polarized using a free-standing wire grid polarizer, and the apparatus was rotated using a 1 arcsec resolution rotary stage. This source assembly was enclosed within an aluminum honeycomb box, lined with microwave absorber, to protect the assembly from the harsh Antarctic environment, and to reduce excess radiation emitted by the noise source from contaminating the desired polarized signal. Upon completion of the rotating polarized source (RPS), the instrument was tested and determined to have $\leq 0.01^\circ$ positional repeatability, and $\leq 0.03\%$ cross-polar response, well within the design goals of the instrument ($0.1^\circ$ positional repeatability and $0.5\%$ cross-polar response). Following this characterization, the RPS was deployed to the Amundsen-Scott South Pole Station, Antarctica during the 2011-2012 austral summer, where it was used for the characterization of the BICEP2 detectors. Preliminary results of the BICEP2 detector characterization are presented here. In subsequent seasons, the RPS will be used for the Keck Array, and such a device could prove useful for other polarization experiments.
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Chapter 1

Introduction

The origins of the universe has been a topic of intrigue for centuries, but current experiments are probing the early universe with unprecedented sensitivity. The Cosmic Microwave Background (CMB) offers an unique avenue for probing the state of the universe during its infancy.

The CMB was discovered in 1964 by Robert Wilson and Arno Penzias using the 20 ft horn antenna at Bell Labs in Holmdel, New Jersey (Penzias and Wilson, 1965). The discovery was made unintentionally, while Wilson and Penzias were making an effort to fully characterize their instrument. The two radio astronomers continually measured a 3 K excess in the noise temperature of their instrument, and investigated every possibility to explain this temperature excess, from seasonal variation to loss incurred at riveted joints to unpleasant materials left in the antenna by a family of pigeons (Wilson, 1979). Despite their best efforts, they could not attribute the 3 K excess to any sort of systematic effect. The explanation of this oddity came when observation met theory. Robert Dicke and his colleagues at Princeton had theorized that if the universe started in a hot Big Bang, then a relic of such an event would exist in the form of an isotropic and homogeneous background radiation in the universe, an idea that was first theorized by George Gamow and collaborators several decades earlier (Dicke et al., 1965). This relic of the Big Bang was
precisely what Wilson and Penzias discovered. The discovery was confirmed by other groups, and the blackbody spectrum of the background radiation was determined (Wilson, 1979).

The key to the discovery of the CMB was precise instrument characterization, and thus subsequent studies of the CMB have also required a high degree of precision. As studies of the CMB have progressed since the 1960’s, a great deal of effort has gone into characterizing the CMB and identifying its unique properties, which has required a need for even higher degrees of precision (Kovac and Barkats, 2007). Current studies of the CMB are focused on the search for B-mode polarization, a feature of the CMB that would lend strong support to the Inflationary model of the universe and even distinguish between various Inflationary models (Dodelson et al., 2009). The amplitude of B-mode polarization is unknown, but current constraints call for more sensitive instrumentation than previous experiments. This thesis is a presentation of the entire process of detector characterization for two CMB polarization experiments, BICEP2 and the Keck Array, from instrumentation development to data collection and analysis.

1.1 The Cosmological Model

The standard cosmological model states that the universe began in a hot dense state that expanded and cooled over time. This hot dense state prevented the formation of atoms, because the average energy of photons, in the photon-baryon plasma, was higher than the ionization energy of a given atom ($E_i = 13.6$ eV for H)(Carroll and Ostlie, 2007). Any atom that formed was subsequently dissociated by an incident photon as depicted by the reaction equation
Throughout this period of ionization, photons scattered off free electrons by Thomson Scattering, a form of elastic scattering that results in a transfer of energy and momentum between the photon and electron (Ryden, 2003).

As the universe expanded, the photon-baryon fluid cooled and the average energy of photons decreased. When this energy dropped below the ionization energy of hydrogen, the first atoms formed, reducing the number of free electrons, and thereby reducing the occurrence of Thomson Scattering (Ryden, 2003). The CMB is the surface of these last scattered photons. When atoms began to form, photons began to travel free in the universe, transitioning the universe to its current transparent state (Carroll and Ostlie, 2007).

One problem with the standard cosmological model is known as the horizon problem. The size of each causally connected region at the surface of last scattering corresponds to $\sim 1^\circ$ on the sky today, however the CMB is relatively uniform in all directions despite this causal disconnect, which cannot be explained by the standard model of cosmology (Ryden, 2003). The Inflationary model solves this problem. Inflation is a period of exponential expansion that occurred during the early universe, resulting in seemingly causally disconnected regions today to be casually connected at some time before Inflation (Carroll and Ostlie, 2007). This exponential expansion would have resulted in gravitational waves in the early universe, and the effect of these waves on the photon-baryon fluid would be imprinted in the surface of last scattering (Dodelson et al., 2009).
1.2 CMB Polarization

Thomson Scattering, a prevalent process during the early universe, occurs when electromagnetic radiation incident on a free electron cause the electron to oscillate in line with the electric field, which results in electromagnetic dipole radiation that radiates perpendicular to the motion of the electron and is polarized in the same direction of the electron’s motion (Carroll and Ostlie, 2007). If the incident radiation on an electron is uniform, then no net polarization will occur. However, in the presence of a quadrupole moment, Thomson scattering will result is net polarization (Carroll and Ostlie, 2007).

Over dense regions in the early universe can give rise to a quadrupole moment, which leads to a pattern of linear polarization known as E-mode polarization in the CMB. Gravitational waves can also cause a quadrupole moment, but the resultant pattern of polarization in that case, is known as B-mode polarization and unlike E-modes has a handedness to its pattern.

Figure 1.1: Characteristic Pattern of E-mode and B-mode Polarization (Dodelson et al., 2009)- The CMB can be decomposed into two polarization patterns. E-mode polarization occurs due to density perturbations in the photon-baryon plasma of the early universe. E-modes have a gradient pattern with no curl component. B-mode polarization occurs in the presence of gravitational waves in the early universe. B-modes have a distinct curl pattern. A 45° rotation of E-modes results in B-mode polarization.
CMB polarization can be decomposed into E-mode polarization and B-mode polarization. E-modes are curl-free, gradient patterns in the CMB, where as B-modes have a handedness, a curl component, as depicted in Figure 1.1. It is important to note, that a 45° rotation of the E-mode pattern translates the pattern into a B-mode. E-mode polarization was discovered in the CMB by the DASI experiment in 2002 (Kovac et al., 2002). E-mode signal is 1% that of the temperature anisotropies of the CMB, which can be seen in the CMB power spectrum shown in Figure 1.2 (Chiang et al., 2010). We can see from this spectrum that an inverse relationship exists between the E-mode polarization and temperature anisotropies, which is expected since the same physical state gave rise to both effects, namely, density perturbations.

The existence of B-mode polarization would imply the presence of gravitational waves in the photon-baryon fluid, which would be conformational evidence of the Inflationary model of the universe. Furthermore, the amplitude of B-mode polarization is directly related to the amplitude of these inflationary gravitational waves, which is directly related to the energy scale of the universe at early times. The amplitude of B-mode polarization is reported as the ratio, r, such that

\[ r = \frac{T}{S} \]

where T is the power of tensor perturbations resulting from gravitational waves, and S is the power of scalar perturbations resulting from density perturbations. No detection of B-mode polarization has been made, but Figure 1.2 shows the constraints placed on r, by several recent experiments, including BICEP1, the predecessor to BICEP2 and the Keck Array, which constrained the amplitude to \( r < 0.72 \) at 95% confidence (Chiang et al., 2010). Currently, the best constrain is from the WMAP experiment with \( r < 0.36 \) at 95% con-
Figure 1.2: CMB Power Spectrum (Chiang et al., 2010)- The power spectrum of the CMB for TE, EE and BB cross-correlations. E-mode polarization is about 1% the amplitude of the temperature anisotropies. B-mode polarization has not yet been detected, so only constraints on the amplitude are shown. A theoretical plot of B-modes at the $r = 0.1$ level are shown. The two peaks in the theoretical B-mode spectrum correspond to B-modes due to inflationary gravity waves and B-modes due to gravitational lensing. B-modes due to gravitational waves are predicted to peak on degree angular scales, which is the scale that BICEP2 and the Keck Array are observing.
1.3. **COSMOLOGICAL BIREFRINGENCE**

Confidence level, using indirect methods (Larson et al., 2011). Experiments, such as BICEP2 and the Keck Array are underway to constrain B-mode amplitude down to a value of $r = 0.01$, which corresponds to the energy scale of Inflation that would be consistent with energy scales expected under the Grand Unified Theory (GUT). This $r$-value also corresponds to the lensing confusion limit (Dodelson et al., 2009). Gravitational lensing can cause E-mode signal to be translated, such that a portion of the signal appears as a false B-mode pattern. The expected amplitude of these false B-modes is expected to be just beneath the $r = 0.01$ level on degree angular scales.

In addition to lensing effects, there are other possible sources of false B-mode patterns. Since B-modes are just a 45° rotation of E-modes, a miscalibration of the detectors observing the CMB could cause an apparent rotation to be observed (Takahashi et al., 2010). This rotation of E-modes into B-modes is particularly concerning because even a small leakage of E-modes could largely contaminate the real B-mode signal since the amplitude of E-modes is so much greater than that of B-modes (refer back to Figure 1.2). E-mode leakage due to systematic effects, such as imperfections in the detectors, can be accounted for by determining the actual polarization response angle of each detector (Takahashi et al., 2010).

### 1.3 Cosmological Birefringence

In addition to systematic effects, Cosmological Birefringence (CB) could also be a source of E-mode leakage into B-mode patterns. CB is an idea that the orientation of the polarization of light is rotated when traveling over cosmological distances (Alighieri, 2010). If CB is a real physical effect, then E-mode polarization patterns would get rotated, such that the new polarization pattern
would have a curl component to it, and thus a fraction of the E-mode signal would be mistaken for B-modes. This E-mode to B-mode leakage is a way to test the idea of Cosmological Birefringence. CB is a frequency independent effect that would be a violation of Charge-Parity-Time Reversal symmetry, Lorentz Invariance, and the Einstein Equivalence Principle (Alighieri, 2010). It would mean the universe has a handedness, because it preferentially rotates polarization in one direction and not in the other. The effect of CB is small and thus difficult to test in a laboratory setting, but the CMB offers a unique way to test for CB (Alighieri, 2010). If such an effect is not present and the universe is parity conserving, then the cross correlation of temperature and B-mode CMB maps, as well as E-mode with B-mode maps, should be null (Wu et al., 2009). The parity-violating effect would only be seen in TB or EB maps, assuming CB is an isotropic effect, but some theories behind CB suggest it could be anisotropic across the sky (Alighieri, 2010).

Several different approaches have been taken to testing CB including analysis of the polarization of radio galaxies and quasars, with CMB polarization being the newest approach (Alighieri, 2010). Past CMB polarization experiments have tested for this effect, but no convincing evidence for CB has surfaced. Combining data from WMAP, BOOMERanG, BICEP and QUaD, the current constraint on CB is $-1.34^\circ < \Delta \alpha < 0.82^\circ$ at 95% confidence level, where $\Delta \alpha$ is the angle of rotation of the plane of polarization due to CB (Xia, 2012). In order to improve upon current results, errors due to systematics in the measurement need to be reduced, so that systematic effects do not dominate measurements. Improved precision in establishing the polarization response orientation, $\psi$, of detectors is one way of improving CB measurements. The more precisely we know the polarization orientation of the incident photons, the more precisely CB can be constrained.
1.4 BICEP2 and The Keck Array

Two experiments currently working to constrain B-mode polarization are BICEP2 and the Keck Array. The predecessor to these experiments was BICEP1, a single refracting telescope with 49 pairs of bolometers. Results from BICEP1 constrain the B-mode polarization amplitude to $r < 0.72$ at 95% confidence level (Chiang et al., 2010). The goal of BICEP2 and Keck Array are to improve upon this measurement with improved sensitivity.

BICEP2 is a small aperture, 25cm, on-axis, cryogenically cooled refracting telescope. The design is meant to make the characterization and minimization of systematics optimal. The optics of the telescope consist of anti-reflection
coated lenses and infrared blocking filters, which are optimized for the 150 GHz observing frequency of BICEP2 (Ogburn et al., 2010). The focal plane consists of 512 antenna-coupled TES bolometers with both Al and Ti transitions (Brevik et al., 2010).

The Keck Array is a collection of five CMB polarimeters, each based on the BICEP2 polarimeter design. Each contains 512 antenna-coupled TES bolometric detectors that are cryogenically cooled to 250 mK, using a Cryomech PT140 two-stage pulse tube cooler (Sheehy et al., 2010). The first stage maintains $T < 50$ K, while the second stage maintains 3.5 K. This was a change from the BICEP2 design as it is a more compact design and thus allowed for the maximum number of cryostats to be placed into the existing mount, and eliminated the need for liquid cryogens (Sheehy et al., 2010). The Keck Array operates at an observing frequency of 150 GHz, but will eventually be upgraded to operate at 100 and 220 GHz as well, in order to distinguish frequency-dependent Galactic foregrounds from the frequency-independent primordial B-mode signatures (Sheehy et al., 2010).

In order for BICEP2 and the Keck Array to improve upon the BICEP1 results, an improvement in sensitivity is necessary. To ensure this improvement in sensitivity, systematic contamination must be reduced which can be accomplished through precise calibration of the TES bolometers, specifically, the polarization efficiency, $\epsilon$, and orientation response angle, $\psi$, of each detector. For BICEP1 this was achieved using a dielectric sheet calibrator for determining $\psi$, and a polarized broadband noise source was used for determining $\epsilon$ as well as confirming the measurements of $\psi$ (Takahashi et al., 2010). The polarized broadband noise source calibrator was effective for BICEP1, but due to the need of the telescope to be rotated to test various polarization angles, it resulted in complicated calibration data. Furthermore, due to the geometry
1.4. BICEP2 AND THE KECK ARRAY

Figure 1.4: Installation of the 5th Keck cryostat (Photo Credit: J. M. Kovac)-
During the 2011-2012 austral summer, two more cryostats were added to the
Keck Array, bringing the total number to five. The design of the cryostat
was altered from that of BICEP2, to maximize the number of receivers that
would fit in the existing mount. This image shows the installation of the final
cryostat, which was a tight fit.

BICEP2 and the Keck Array’s improved sensitivity compared to BICEP1,
translates into a lower noise level, which demands even better characterize of
the telescope to ensure that errors are dominated by systematic contamination.
Therefore a new calibrator will be used for BICEP2 and the Keck Array.
Chapter 2 discusses the development of this new calibration instrument.
1.5 The South Pole

BICEP1, BICEP2 and the Keck Array, as well as many other CMB experiments, have been located at the South Pole. The location offers unique advantages that are not available at any other site on Earth. The Earth’s atmosphere, being rich in water vapor, proves to be a difficult obstacle when it comes to the observation of the CMB. This is because microwave radiation corresponds to energies that are associated with the vibrational and rotational energy levels of water molecules. Therefore a CMB photon incident upon a water molecule will be absorbed (Ryden, 2003). There are two ways around such a problem: (1) get above the atmosphere, or, (2) observe from a location with a minimal amount of water vapor in the atmosphere. Since there are many economical disadvantages to the first option, choosing observing sites with low humidity is an ideal alternative.

The South Pole is one such location. It is classified as a desert, and thus has low humidity throughout the entire year. In addition its high elevation (2800 m) and even higher pressure altitude (3200 m), correspond to less atmosphere though which to observe, thus reducing atmospheric attenuation of the signal. The low temperatures at the South Pole, with a yearly average of -49°C, reduces the level of ground pickup from the Earth, though this affect is small since this deviation is not drastically different from the average temperature of the Earth when compared to the temperature of the sky. The atmosphere is also extremely stable due to low temperatures, small temperature variation, and katabatic flow as the dominant wind pattern in the region. The dominance of katabatic flow is due to the South Pole’s location atop the Antarctic Plateau (Kovac and Barkats, 2007). All of these factors make the South Pole one of the best location for observations at the observing frequencies of BICEP2 (150 GHz) and the Keck Array (100 GHz, 150 GHz, 220 GHz),
1.5. THE SOUTH POLE

Figure 1.5: Microwave Transmission at the South Pole (Kovac and Barkats, 2007) - The atmospheric transmission window available at the South Pole, makes it the best possible location on Earth to observe at microwave frequency. The transmission spectrum of Atacama, Chile, another common observing location is also shown for comparison. Although the transmission window at Atacama is good compared to most locations, such as Hanoi, Vietnam depicted here, it does not quite reach the same level of transmission as the South Pole, demonstrating that the conditions at the South Pole are ideal for CMB observations.

as can be seen from Figure 1.5. As depicted in Figure (?), even compared to the common observing location at Atacama desert, the South Pole has the best transmission spectrum for observations of the CMB, making the South Pole the ideal location for CMB polarization experiments.

In addition to the climate benefits of the South Pole, there are also logistical benefits. For instance, an infrastructure was already in place to support experiments such as BICEP2 and the Keck Array. Furthermore, the South Pole provides an observing field that is available 24 hours a day during winter months, with no Sun contamination.

Although the South Pole does prove to be a useful location for experiments described above, it provides challenges for the development of instrumentation
CHAPTER 1. INTRODUCTION

Figure 1.6: The South Pole \textit{(Photo Credit: J. M. Kovac)} - The South Pole during the 2011-2012 austral summer. The South Pole offers many advantages for CMB observations that are not available at any other location on Earth, which includes high elevation, low humidity, stable weather conditions, observing fields available 24-hours a day, logistical support, among other things.

to be utilized in such a harsh environment. The low temperatures of the South Pole, were an important considering in the design of the rotating polarized source (RPS).
Chapter 2

Instrument Design

In order for BICEP2 and the Keck Array to meet their sensitivity goals they must be properly calibrated. To carry out such a calibration an instrument must be developed that can determine the polarization orientation angle, $\psi$, and the cross-polar response, $\epsilon$, for each of the bolometric detectors. Without such a calibration, false B-mode patterns would appear in the data due to the leakage of E-modes caused by an apparent rotation of polarization. For BICEP2 and the Keck Array to meet their sensitivity goals, this systematic contamination cannot dominate the uncertainties in CMB maps. As previously mentioned, the sensitivity goal of the experiments is to reach a level of $r = 0.01$. The leakage of E-modes into false B-modes is given by

$$B_{\text{false}} = E \sin(2\Delta\psi)$$  \hspace{1cm} (2.1)

where $B_{\text{false}}$ is the amplitude of false B-modes due to leakage, $E$ is the amplitude of E-mode polarization at a given multipole, and $\Delta\psi$ is the uncertainty in the polarization orientation angles of the bolometers (Takahashi et al., 2010). Both BICEP2 and the Keck Array are designed to observe features at degree angular scales, which corresponds to a multipole of $l \sim 100$. The E-mode
amplitude at this multipole has been measured to be $\sim 1 \, \mu\text{K}$. The amplitude for B-modes at the level of $r = 0.01$ is $0.025 \, \mu\text{K}$ (Chiang et al., 2010). Therefore to meet the sensitivity goals of the experiments, $B_{\text{false}}$ must be less than $0.025 \, \mu\text{K}$, which corresponds to $\Delta\psi = 0.7^\circ$, given by Equation 2.1.

This value of $\Delta\psi = 0.7^\circ$ partially motivated the design specifications for the Rotating Polarized Source (RPS), the calibration instrument. A value of $\Delta\psi = 0.1^\circ$ was chosen for the design specifications, because of a secondary science goal of BICEP2 and the Keck Array, namely, testing for Cosmological Birefringence (CB), as discussed in Section 1.3. BICEP1 data was used to constrain the rotation of the plane of polarization, $\Delta\alpha$ (the angle of polarization rotation due to CB), down to a level of $0.99^\circ$ (Xia, 2012). With the 10-fold increase in sensitivity from BICEP1 to BICEP2 and the Keck Array, these current experiments should be capable of constraining $\Delta\alpha$ to a level of $0.099^\circ$, thus the a design goal of $0.1^\circ$ was chosen.

The precision for measuring the cross-polar response, $\epsilon$, was selected to be $\leq 0.5\%$, because the intrinsic cross-polar response in the detectors needs to be measured, and this measurement should not be limited by systematics, and a goal of $\leq 0.5\%$ is well below the expected cross-polar responses for the detectors.

The RPS works by emitting radiation with linear polarization of a known orientation angle toward the receiver (i.e. BICEP2 or the Keck Array) and data is collected with the receiver. The procedure can be repeated at many different orientation angles known to a precision of $\leq 0.1^\circ$ allowing the detector response to be plotted as function of polarization angle. The RPS, as depicted in Figure 2.1 consists of a chopped broadband noise source emitting radiation at 140 to 160 GHz (Section 2.1), a rotary stage with 1 arcsec resolution (Section 2.2), a free-standing wire grid polarizer with an expected cross-polar
response at 150 GHz of 0.1% (Section 2.3), a tiltmeter (Section 2.4), a mechanical support system (Section 2.5), and a heated enclosure (Section 2.5).

Figure 2.1: Schematic of RPS- The RPS is a device that emits 140-160 GHz radiation with a high degree of linear polarization. The angle of the polarization can be rotated through a full 360°. The radiation is produced from a broadband noise source that is composed of a sequence of multipliers and amplifiers. The noise emitted from the components of the source is shielded by an inner box encasing the broadband noise source. The signal from the source is polarized using a free-standing wire grid, that is held in place by an aluminum wire grid holder. The source, inner box, wire grid, and wire grid holder are rotated using a rotation stage, which allows for the RPS to adjust the angle of polarization of the emitted signal.
2.1 The Broadband Noise Source

The Keck Array will eventually have three observing frequencies of 100 GHz, 150 GHz and 220 GHz, and the ultimate goal is to use the RPS at all three frequencies, however since the Keck Array’s current operating frequency is 150 GHz, and the operating frequency of BICEP2 is 150 GHz, an RPS that operates at 150 GHz was the focus for this undertaking. The Keck Array will be upgraded to 100 GHz and 220 GHz in future observing seasons, at which time alterations will be made to the RPS to operate at other frequencies. With the design laid out in the following sections, the necessary alterations for changes in operating frequency should be minimal.

A broadband noise source that emits 140 to 160 GHz radiation was used for the RPS because the spectrum of the CMB at these frequencies is relatively flat, and we want to be simulating a spectrum similar to the CMB. The source, as shown in Figure 2.2, consists of a 50 Ω SMA terminator, two Spacek Labs SG156-40-17 amplifiers, an HP/AGILENT 33190B TTL Driver and HP/AGILENT 33144A SPST PIN Switch, a Spacek Labs A7713-6XW sextupler, two Aerowave 10-2220 dial variable attenuators, a Virginia Diodes WR6X2b-04 doubler, a Pacific Millimeter 14020 bandpass filter, and a Custom Microwave RCHO6R horn antenna.

This source is depicted in the electrical diagram in Figure 2.3. The 50 Ω resistor emits a blackbody spectrum. The signal is then boosted by the two Spacek Labs SG156-40-17 amplifiers (+30dB each), which are optimized for amplification of 12.5 to 18.34 GHz, after which the signal is chopped at 1 kHz using a PIN diode switch designed for 0.1 to 18 GHz. The signal then passes through the Spacek Labs sextupler, which is composed of a doubler, then an amplifier, then a tripler and then another amplifier. The input frequency of the sextupler is 10.83 GHz to 14.67 GHz, with an input power level of 15 dBm.
2.1. THE BROADBAND NOISE SOURCE

Figure 2.2: The 140-160 GHz Broadband Noise Source. The series of amplifiers and multipliers that make up the source, allow it to achieve the desired frequency range with high power. This design allows for easy manipulation of the multiplier series to produce other frequency ranges as well, such as the future Keck Array observing frequencies (100 GHz and 220 GHz). The horn antenna and bandpass filter are not pictured here.

The output of the sextupler is at the frequency range of 65 to 88 GHz with a 5 dBm power level. The signal then passes through two Aerowave 10-2220 variable attenuators with attenuation ability greater than 30 dB, which are optimized for use with 75 to 110 GHz radiation. Finally, the signal is doubled again by a Virginia Diodes NR6X2b-04 doubler, increasing the frequency to 130-176 GHz. The signal then passes through the Pacific Millimeter bandpass filter for 140-160 GHz, allowing only those frequencies to be emitted out of the horn antenna.

Since the microwave components in the broadband noise source transmit signal using standard rectangular waveguide, the radiation emitted from the source is linearly polarized.

Each of the microwave components in the source will radiate some amount of unwanted noise, and to prevent this noise from contaminating the signal emitted from the horn antenna, steps must be taken to shield the components.
Figure 2.3: Electrical Diagram of the 140-160 GHz Broadband Noise Source-A blackbody spectrum is produced at the 50 Ω resistor. The 12.5-18.34 GHz band of the spectrum is then amplified by two +40 dB amplifiers. The signal is then chopped using a PIN Switch and TTL Driver. The frequency of the radiation is then doubled and amplified, and then tripled and amplified again in the sextupler. The signal coming out of the sextupler will be 65 to 88 GHz. The signal then passes through two variable attenuators, after which it is doubled one more time to produce around 130 to 176 GHz radiation. The radiation finally passes through a 140-160 GHz bandpass filter and is emitted out the horn antenna.
2.1. THE BROADBAND NOISE SOURCE

This design of the broadband noise source, as a series of multipliers and amplifiers, allows for easy manipulation of the series to achieve an array of frequencies, including 100 GHz and 220 GHz, the future observing frequencies of the Keck Array.

The radiation emitted from the source has a particular beam pattern that dictated aspects of the design of the RPS. The beam pattern of the Custom Microwave RCHO6R horn antenna at 140 GHz is shown in Figure 2.4. For future alterations to the RPS to accommodate other frequency ranges, a different horn antenna would be used.

![Radiation Pattern @ 140 GHz](image)

**Figure 2.4:** Beam Pattern of the Horn Antenna (CMi, 2009)- The radiation pattern for the RCHO6R horn antenna. The plot shows beam power as a function of angle from the beam center. This beam pattern was used to determine the appropriate distance to mount the wire grid polarizer from the antenna. The RPS was designed such that the edges of the wire grid aperture received a signal between -25 and -35 dB from the horn antenna.
2.2 Rotary Stage

A rotation stage is used to rotate the broadband noise source in the RPS. The stage needed to be relatively lightweight and compact, as the weight of the entire instrument was a concern since it is used atop a 50 ft tall mast at the South Pole. The heaviest device to ever sit atop the mast weighed 40 lbs, thus the RPS’s maximum allowable weight is 40 lbs, though the lighter the better. The stage needed to be robust enough to support the weight of the broadband noise source, the wire grid polarizer and the support system for both components. It also needed to be easily mounted in a vertical position, such that rotation axis would be parallel to the ground. The central aperture of the stage must be large enough to accommodate a standard WR-6 waveguide flange, plus the support system for the broadband noise source. Furthermore, the stage needed to have resolution much better than 0.1°, in order for the RPS to have a $\Delta \psi \leq 0.1^\circ$.

One major consideration for the stage was the possibility of having an encoder, which would reliably report the positions of the stage at any given time. Both types of encoders were considered: absolute and quadrature (or incremental). Absolute encoders are designed such that immediately after being powered on, through the use of a mechanical system, the device knows its absolute position. Quadrature encoders, on the other hand, utilize either a square wave or sine wave signal to determine the encoder’s position, which requires a homing sequence after being powered on in order to determine its position.

The rotational freedom of the stage was also a concern because the stage needed to rotate a full $360^\circ$, but not continue to rotate multiple times in the same direction, such that the wires powering the broadband noise source would become wrapped and eventually pulled out of place. Limit switches built into
2.2. ROTARY STAGE

This stage met all of the desired characteristics for a rotary stage, except the absence of an encoder. However, it was decided that an encoder was not necessary for the RPS, and so the Thorlabs stage was chosen for its desirable qualities and reasonable price.

Limit switches are mechanical devices that when tripped stop the motion of the stage. They can be unidirectional or bidirectional, the former referring to a switch that is only tripped when the switch is past in a particular direction, the latter is a switch that is tripped regardless of the direction of motion.

Finally, the last consideration for the stage was the temperature operating range. Although the stage operates inside the heated enclosure of the RPS, the temperature of the heated enclosure may drop to as low as -20°C, under certain environmental conditions such as high winds during the summer months.

The rotation stage selected for the instrument was the Thorlabs NR360S with a Stepper Motor Actuator shown in Figure 2.5. The stage is controlled by the Thorlabs BSC101 Benchtop Stepper Motor Controller, which is a single channel controller with an ActiveX software interface. The resolution of the Thorlabs NR360S stage is 1 arcsec or 0.00028°. The horizontal load capacity
of the stage is 50 kg, and can rotate at a maximum speed of 20°/sec. The stage has a compact design with a clear aperture of diameter \( d = 50 \text{ mm} \). The stage utilizes a worm drive stepper motor that can be controlled both manually or with a controller. The operating temperature range of the stage is \(-20° \text{ C} \) to \( 40° \text{ C} \). The NR360S has a built in unidirectional limit switch, which, when used in conjunction with the ActiveX software, allows for the stage to run a homing sequence in order to determine its position upon being powered on, despite the absence of an encoder.

Table 2.1: Rotary Stage Selection

<table>
<thead>
<tr>
<th>Rotary Stage</th>
<th>Selected?</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport URS150BPP</td>
<td>No</td>
<td>Large, Heavy, and Expensive</td>
</tr>
<tr>
<td>Thorlabs NR360S</td>
<td>Yes</td>
<td>Compact, Lightweight, and Inexpensive</td>
</tr>
<tr>
<td>Aerotech AGR 50</td>
<td>No</td>
<td>Expensive</td>
</tr>
<tr>
<td>Aerotech AGR 75</td>
<td>No</td>
<td>Large, Heavy, and Expensive</td>
</tr>
<tr>
<td>Griffin Motion RTS-DD</td>
<td>No</td>
<td>Small</td>
</tr>
<tr>
<td>CVI Melles Griot AMR</td>
<td>No</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

Six rotary stages were considered for this application (summarized in Table 2.1): Newport URS150BPP Precision Rotation Stage, Thorlabs NR360S 360° Continuous Rotation Stage with Stepper Motor Actuator, Aerotech AGR 50 or 75 Worm Driven Rotary Stage, Griffin Motion RTS-DD Rotary Stage, and CVI Melles Griot AMR-Motorized 360° Rotation Stage. The Griffin Motion Stage was not selected because of its small central aperture measuring only 30 mm in diameter, and because it cannot easily be mounted in a vertical position as needed for the RPS. The Newport Stage and the Aerotech AGR 75 were not selected because of their large size and high cost. The CVI Melles Griot Stage was eliminated from consideration because it was virtually the same stage as the Thorlabs model, but several hundred dollars more expen-
sive. The remaining options were the Thorlabs Stage and the Aerotech AGR 50 Stage. Both stages are comparable in size, resolution and load capacity. The major difference was that the Aerotech AGR 50 included a build-in square wave incremental encoder, while the Thorlabs stage did not have any sort of an encoder option. The Aerotech stage was far more expensive because of its encoding capabilities, thus it was decided that for the RPS, an encoder was not necessary, so the Thorlabs stage was selected.

2.3 Wire Grid Polarizer

A wire grid polarizer is made from small conducting wires being tautly attached across a circular aperture onto a frame. Under the condition that the wavelength of incident radiation is much greater than the diameter of the wires, radiation incident upon the wire grid behaves differently depending on the polarization of the radiation. The polarization component parallel to the wires will have a very high reflection coefficient such that the conducting wires act essentially like a mirror. In contrast the component of polarized radiation orthogonal to the wires has a reflection coefficient near zero, and the wave passes virtually unaffected (Larsen, 1962). Thus, by emitting unpolarized radiation onto the wire grid, the components of the electromagnetic wave that are perpendicular to the wire are transmitted, while the components parallel to the wire grid are reflected. The result is linearly polarized radiation being transmitted through the grid. Wire grid polarizers allow for a high degree of polarization and thus are appropriate for our application.

The performance of a wire grid polarizer at a particular wavelength is dependent upon the diameter and spacing of the wires, thus different diameters, d, and spacing, S, optimize the performance of the grid for different wave-
lengths, since $S \ll \lambda$ (Houde et al., 2001). The effectiveness of a wire grid polarizer at a particular wavelength can be characterized by the reflection and transmission of light of a particular polarization. The reflection coefficient of light polarized parallel to the wires, $R_p$, is given by

$$R_p = \frac{1 + \left(\frac{2S}{\lambda}\right)^2\ln\left(\frac{S}{\pi d}\right)^2}{1 - \left(\frac{2S}{\lambda}\right)^2\ln\left(\frac{S}{\pi d}\right)^2}$$

(2.2)

where $S$ is the wire spacing, $d$ is the wire diameter and $\lambda$ is the wavelength (Lesurf, 1990). From this the transmission coefficient $T_p$ can also be determined as $T_p = 1 - R_p$. Similarly, the reflection coefficient for light polarized normal to the wires, $R_n$, is given by

$$R_n = \frac{(\pi^2 d^2)^2}{(2\lambda S)^2[1 + (\pi^2 d^2)/(2\lambda S)^2]}$$

(2.3)

as above, the transmission coefficient can be determined by $T_n = 1 - R_n$ (Lesurf, 1990).

For the RPS, a wire grid polarizer is needed that is optimized for the three observing frequencies of the Keck Array (100, 150 and 220 GHz). In addition, the aperture of the wire grid must be large, such that the central beam of the horn antenna from which the radiation is emitted does not illuminate the entire wire grid out to the frame. This is due to the boundary conditions that would occur if the aperture were fully illuminated. The effects that would arise at the boundary would result in leakage of unwanted polarizations into our signal. The effective aperture of the grid, however, will be dependent on the distance between the horn antenna and the wire grid. This consideration is discussed more thoroughly in Section 2.5.

The actual material from which the wire grid was made was also taken into account when choosing a wire grid. Ideally the frame and the wires would
have a similar coefficient of thermal expansion (CTE), such that when the grid is exposed to South Pole temperatures, the frame and wires do not contract at drastically different rates, causing the wires to stretch and develop slack in them. Tungsten is a good choice for the wires as its coefficient of thermal expansion is 4.5 \(\mu m/(m\cdot K)\), and thus will undergo a relatively mild thermal contraction. For frame material, Invar would be ideal as its CTE is only 1.2 \(\mu m/(m\cdot K)\), but unfortunately, Invar does not appear to be a widely used in standard wire grid construction. The shape of the frame of the grid also has various implications. A square frame would be convenient for the calibration of the RPS as it gives a reference surface to which the orientation of the wires can be compared. Unfortunately, square framed wire grids are more costly to construct and are less robust than circular frames, because of differential stress on frame due to the high amount of tension in the wires.

Table 2.2: Wire Grid Polarizer Selection

<table>
<thead>
<tr>
<th>Wire Grid</th>
<th>Selected?</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microtech G80X15L</td>
<td>Yes</td>
<td>Well-Matched for Application</td>
</tr>
<tr>
<td>Millitech GFS00K20020SN</td>
<td>No</td>
<td>No Free-Standing Wires</td>
</tr>
<tr>
<td>Space GS57207sp</td>
<td>No</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

Three wire grid polarizers were considered for the instrument (summarized in Table 2.2): Microtech Instruments G80 X 15-L, Millitech GFS-00-K20020SN, and the Specac GS57207sp. The Millitech wire grid was not chosen because it was not a free-standing wire grid polarizer. The wire grid consisted of a Kapton board with gold-plated, copper wires lain across it. It was unclear how the Kapton board would affect transmission and reflection, and thus it seemed prudent to use a free-standing wire grid polarizer, rather than a circuit-board style wire grid. The Specac wire grid met all of the design requirements and was specifically designed to operate at cold temperatures, but due to high
price and a long lead time, the Mircotech wire grid was chosen, since it too met all of the design requirements.

The Microtech G80 X 15-L wire grid polarizer has an aperture diameter of 88 mm, an outer diameter (OD) of 98 mm, with 15 \( \mu \text{m} \) diameter tungsten wires spaced 80 \( \mu \text{m} \) apart. Table 2.3 shows the expected performance for the G80 X 15-L wire grid polarizer for each of the three observing frequencies of Keck, calculated with Equation 2.2 and 2.3.

<table>
<thead>
<tr>
<th>( \nu ) (GHz)</th>
<th>( \lambda ) (mm)</th>
<th>( R_p ) (%)</th>
<th>( T_p ) (%)</th>
<th>( R_n ) (%)</th>
<th>( T_n ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3</td>
<td>99.9</td>
<td>0.1</td>
<td>0.002</td>
<td>99.998</td>
</tr>
<tr>
<td>150</td>
<td>2</td>
<td>99.8</td>
<td>0.2</td>
<td>0.005</td>
<td>99.995</td>
</tr>
<tr>
<td>220</td>
<td>1.36</td>
<td>99.6</td>
<td>0.4</td>
<td>0.01</td>
<td>99.990</td>
</tr>
</tbody>
</table>

As can be seen from Table 2.3, the wire grid is most effective at the 100 GHz observing frequency with 99.9\% of cross-polar radiation being reflected and only 0.1\% being transmitted. A high degree of precision is also achieved at 150 GHz and 220 GHz and both fall within our desired specifications, though for even higher precision at those frequencies, it would be possible to change out the wire grid if needed. However, these values are assuming un-polarized radiation incident upon the wire grid, but as previously mentioned, the radiation being emitted from the broadband noise source is linearly polarized. Therefore if the polarization orientation of the emitted radiation is aligned perpendicular to the wires of the wire grid polarizer, then even higher degrees of polarization can be achieved than are reported in Table 2.3.
2.4. TILTMETER

In order to accurately know the orientation of the polarized light emitted from the RPS, the orientation of the entire apparatus with respect to gravity must be known. A tiltmeter was incorporated into the RPS so that the device could be determined to be level with a high degree of precision, reducing any sort of systematic effect that could affect the operation of the RPS. The tiltmeter that was acquired is an Applied Geomechanics 801-S/L Tuff Tilt Uniaxial Tiltmeter (see Figure 2.6), which utilizes a electrolytic tilt transducer as its orientation sensing element. Internal electrodes are covered or uncovered by the conductive fluid as the transducer tilts. Changes in electrical resistance occurs when AC excitation passes through the transducer, which is measured with a voltage divider network. The signal is then amplified, rectified and filtered to produce a DC signal proportional to the measured angular rotation. This tiltmeter has an angular range of ±3° with a resolution of 0.0006° and
repeatability of 0.001°. Its temperature operating range is -25° to 70°, which lies above our minimum heated enclosure temperature of -20°C. The tiltmeter will be bolted to the same rigid plate as the rotation stage, making the orientation reading of the tiltmeter virtually the same as the orientation of the rotation stage, though the difference between the two was determined by a calibration technique and taken into account during data collection.

2.5 Mechanical Design

The broadband noise source, rotation stage, wire grid, and tiltmeter were all selected in order to meet particular specifications of the overall instrument, but in order to get these four parts to work as a single cohesive unit, mechanical design was necessary that would bring the four parts into a single instrument. The design was, of course, dictated by the dimensions and bolt patterns of each of the four major parts. A diagram of the entire RPS is presented in Figure 2.1. As can be seen from this diagram, the mechanical design consists of a broadband noise source and wire grid support system; a stage standoff; an aluminum base plate; an inner, radiation shielding box; and an outer, heated box.

The support system for the broadband noise source and wire grid polarizer were developed based on the location of mounting holes on the rotation stage. Only 4 such holes exist on the moving portion of the stage, thus to open up options for the support system, a mounting plate was built that would firmly attach to the stage via the 4 mounting holes. The inner diameter (ID) of the mounting plate was cut to 0.8 in, because this allows standard WR-6 waveguide flanges, with outer diameter (OD) = 0.75 in, to pass through the mounting plate. The OD of the mounting plate is 5 in. The mounting plate
was drilled with 3 different bolt patterns: (1) a bolt pattern corresponding to the 4 mounting holes on the rotary stage, (2) a bolt pattern matching the flange of the wire grid holder, and (3) a bolt pattern matching the broadband noise source support system.

The wire grid polarizer, has no mounting holes, and the prospect of drilling holes in such a fragile component was not a realistic option, thus, a holder for the wire grid was designed. The holder is a cylinder with ID=90 mm (3.5 in), OD=115 mm (4.5 in) and with an inlet cut in the top of the cylinder with ID=98 mm and a depth of 5.8 mm, the same dimensions as the wire grid polarizer (Figure 2.7). Holes were drilled in the front of the cylinder that allowed screws and nylon washers to be placed around the circumference of the cylinder to hold the wire grid in place. For the back end of the cylinder, a flange was created from 0.25 in aluminum with ID=3.5 in and OD=5 in, which made for easy attachment to the mounting plate. The bolt pattern of the flange consists of 5 equally spaced clearance holes, plus two alignment pins that were press-fit into the flange. The alignment pins reduce the slack between the mounting plate and flange, which reduces mechanical contributions on the precision to which the polarization orientation can be known.

The actual length of the wire grid holder was determined by the beam pattern of the horn antenna. The contributions from the beam near the frame of the wire grid should be small, because that will reduce the amount of cross-polar leakage in signal. The power at the edge of wire grid aperture should be less than -25 dB, but greater than -35 dB. Figure 2.4 gives the azimuth angle that corresponds to such specification, which corresponds to a beam size of 20°, likewise a power of -35 dB gives a beam size of 40°. The beam size and the diameter of the wire grid aperture (88 mm) was used to determine an appropriate length for the wire grid holder. Simple trigonometry gives the
desired length, by

\[
\tan(\theta) = \frac{r}{d}
\]

where \( \theta \) is half the beam angle, \( r \) is the radius of the wire grid aperture, and \( d \) is the distance from the horn to the wire grid. For a beam size of 20° the ideal distance between the horn antenna and the wire grid would be \( d = 4.8 \) in. Likewise, a beam size of 40° gives a distance, \( d = 2.1 \) in. Any distance between 2.1 in and 4.8 in would work for the purposes of the RPS. A cylinder length of 4 in was chosen, which corresponds to a distance of 3 in between the horn and wire grid. This distance will reduce effects of cross polar leakage, and puts the horn and grid far enough from each other to avoid any strange reflections between the two. To further reduce the presence of unwanted reflections in the cylinder, the inner surface of the cylinder was blackened. This entailed, covering the surface in Eccosorb HR-10 microwave absorber, and then impregnated the absorber with Styecast 2850 Black mixed with 4% (by mass) carbon black. This microwave absorber will also absorb some of the sidelobes of the horn antenna beam, as seen in Figure 2.4. The front side of the mounting plate that faces in toward the wire grid holder, was also blackened for the same purpose and in the same manner. In order to reduce the weight of the wire grid holder, excess aluminum along the length of the cylinder was machined away.

The design of the broadband noise source support system was dictated by the geometry of the source itself and the limitations imposed by the ID of the rotation stage. The basic idea behind the design was that of a U-channel, however since the entire source is wider than the ID of the rotation stage, the U-channel only supports one-leg of the source. The U-channel begins at the mounting plate (where bolt patterns were drilled to accommodate the mounting
2.5. MECHANICAL DESIGN

Figure 2.7: The Wire Grid in its Holder (left) - The wire grid holder, with detachable flange and wire grid in place. The nylon washers used to hold the grid in place are not pictured. Wire Grid Holder in situ (right) - The wire grid holder attached to the rest of the inner assembly of the RPS, prior to the blackening of the mounting plate.

of the U-channel) and continues backward, through the aperture of the rotation stage. Upon clearing the stage, the design deviates from a typical U-channel, as the bottom support plate extends out to support the components of the source outside the diameter of the stage aperture. The support plate and U-channel both continue back the length of the source, though the inner wall of the U-channel ends early in order to accommodate the turn that is made in the geometry of the source. This particular design was selected because it reduces the amount of stress that would be applied along the length of the source support plate, due to the weight of the broadband noise source. The
entire U-channel and support plate are made of 0.25 in aluminum to help prevent flexing of the support system, which would change the orientation of the source with respect to the rest of the RPS. The support system, as well as some of the aforementioned RPS components are shown in Figure 2.8.

Figure 2.8: The Source Assembly- The assembled inner portion of the instrument. The rotation stage with source attached by U-channel support system and the wire grid holder in place, with blackened inner surface. The rotation stage support standoff is also in place.

As previously mentioned in Section 2.1, the broadband noise source required radiation shielding to prevent noise from the microwave components from contaminating the polarized signal. An aluminum box, lined with HR-10 microwave absorber serves this function. The inner box was constructed out of two 0.05 in aluminum sheets, that were cut and bent into shape, such that the two sheets created four walls surrounding the source, as seen in Figure 2.9.
2.5. MECHANICAL DESIGN

The sheets were riveted together and bolted to the broadband source support system. The top of the box was then hinged to one of the sides of the box and latched closed on the other side. This hinged top allows for quick and easy access to the microwave components of the source for quick changes, such as adjustments to the variable attenuators.

![The Inner Box/Source Radiation Shielding](image)

Figure 2.9: The Inner Box/Source Radiation Shielding- The inner box, prior to lid attachment, and adherence of HR-10 Microwave Absorber. This box acts as a radiation shield, preventing noise emitted from the microwave components to interfere with the polarized signal being emitted from the RPS.

The tiltmeter and rotary stage both must be rigidly bolted to the same reference, so that the orientation given by the tiltmeter applies to the orientation of the stage with only a small error in orientation between them. To accomplish this, an aluminum base plate was constructed out of a 5/8 in thick sheet of aluminum. For the reduction of the total weight of the RPS, the alu-
minimum sheet was cut only large enough to accommodate the source standoff, tiltmeter and strip heater (8 in X 8 in). This platform is also the portion of the apparatus that rigidly connects to the mast at the South Pole, thus this aluminum base plate was drilled with a bolt pattern that matches that of the mast’s bolt pattern.

The radius of rotation of the inner box is larger than that of the rotary stage, thus in order to allow the inner box full rotation, the rotary stage was raised up above the aluminum base plate, which was accomplished by a standoff structure shown in Figure 2.10.

![Diagram of base plate and rotary stage standoff](image)

**Figure 2.10:** Base Plate and Rotary Stage Standoff-The standoff was necessary to allow full rotation of the source, innerbox and wire grid holder, because the dimensions of these components were larger than that of the stage itself. The base plate was necessary to give a rigid surface on which the tiltmeter and standoff could be securely mounted.

The heated enclosure was designed around the inner assembly of the RPS, shown in Figure 2.8. The enclosure was designed to thermally isolate the inner
assembly from the mast, which aids in the temperature control of the enclosure. This isolation was achieved using a 1/4 in thick sheet of G10 fiberglass, that was placed beneath the aluminum base plate, and above the bottom of the enclosure, a bolt pattern matching that of the base plate was drilled into the fiberglass. The sides of the enclosure were made from aluminum honeycomb sheets, which keeps the enclosure lightweight, but still robust. The bottom of the enclosure was constructed out of 1/2 in honeycomb and drilled with a bolt pattern that matched the aluminum base plate and South Pole mast. The sides and lid of the enclosure was constructed from 1/4 in honeycomb. The sides and bottom of the box were adhered together using compound cut aluminum angles riveted to the aluminum honeycomb. The lid of the enclosure, was attached using two hinges and secured into place with a latch, allowing for easy access to the inner assembly. The overall dimensions of this enclosure are 13 in X 12 in X 20.5 in. A 5 in diameter hole, concentric with the source’s axis of rotation, was cut from the front side of the enclosure. The opposite side of the enclosure was fitted with two D15 electrical feedthroughs. Each interior side of the enclosure was covered with HD-10 Eccosorb Microwave Absorber, adhered with silicon adhesive. The absorber at the front of the box was cut with a 4 in diameter hole, aligned to be concentric with axis of rotation of the source, and the absorber on the opposite side was cut to accommodate the electrical feedthroughs. Inside the enclosure an AD590 thermometer was used to measure the temperature of the RPS. A DC Voltage Flexible Silicone-Rubber Heat Strip, was adhered to the aluminum base plate and acts as the major heat source for the RPS. The goal was to keep the temperature inside of the enclosure above -20° C at any given time, since -20° is the minimum operating temperature of the rotation stage. The completed RPS with the inner assembly inside the heated enclosure is shown in Figure 2.11.
CHAPTER 2. INSTRUMENT DESIGN

Figure 2.11: Completed RPS- The RPS successfully met and exceeded all design requirements. It was deployed to the South Pole during the 2011-2012 austral summer, and will be returned to the South Pole every austral summer for future use. While not being used at the South Pole, the RPS will be used for testing at Harvard.

2.6 Software Development

The rotary stage is controlled using a BSC101 controller, which can be interfaced with an APT program. The standard program allows for basic control of the rotary stage, but a more advance control system is needed for the RPS in order to limit the rotational range of the stage. A LabView program was written that controls the motion of the stage. The program includes a homing sequence, allowing the stage to determine its position with respect to the limit switch in the stage. The program also limits the movement of the stage, by only allowing two 360° rotations of the stage in one direction. After the rota-
tion stage travels two rotations in one direction, the program requires that any further rotation be in the opposite direction. This limit on rotation reduces the risk of wiring in the RPS becoming twisted and being pulled out of the broadband source while the source is powered, which would likely damage the microwave components.
Chapter 3

Instrument Testing

Throughout the construction process and after the instrument was completed, tests were conducted to ensure the complete functionality of the rotating polarized source. These tests ensured that the instrument would properly function under operating conditions at the South Pole, and that the instrument met the design goals for precision.

3.1 Rotary Stage Testing

The Thorlabs NR360S Rotary Stage that was selected for this instrument, was rated to be used with only a 3 ft long cable, however, during operation of the RPS at the South Pole, the rotary stage would need to be powered by at least a 50 ft cable. To ensure that the stage could fully function using a cable significantly longer than 3 ft, a 100 ft cable was connectorized and used to connect the stage to the controller. The stage was then rotated with a load larger than that of the broadband noise source, wire grid and mechanical support structures. The performance of the stage appeared unaffected by the increased cable length, rotation commenced with no skipped steps and the speed of rotation was comparable to use with a 3 ft cable under the same load.
As part of the stage testing, the software control was also tested. The LabView program was designed to limit the motion of the stage to two full rotations, however we discovered that this limitation was applied to whatever positions the stage was in when it was powered on. Therefore, it could potentially move two full rotations, be powered off and then powered back on and moved another two full rotations in the same direction, resulting in a total movement of four rotations from its original position. Because the rotary stage lacks an encoder there was no way to create a program that could limit the rotation of the stage in all cases. Since over-rotation could lead to the cable powering the microwave components of the source being torn out of place, which would potentially damage the fragile microwave components, a simple mechanical fail safe was design that would cause power to the stage to be halted prior to an over-rotation occurring, thereby preventing any potential damage to the microwave components from over-rotation.

### 3.2 Broadband Noise Source Testing

In order to optimize the power output of the broadband noise source, we ran several tests with different configurations of the source. The setup of these tests were as follows: the broadband noise source was placed 9.5 in away from a horn antenna and detector diode connected to a Lock-in Amplifier (The 9.5 in was measured from the front of the source horn antenna to the front of the detector antenna). The TTL input from the broadband noise source was also connected to the Lock-in Amplifier, which allows us to set the chopping frequency of the source, which was set to 1 kHz. The position of the source was adjusted, while keeping the 9.5 inch distance constant, until the Lock-in
Amplifier was reading the maximum power output of the source for a distance of 9.5 in, corresponding to proper alignment of the horn antenna of the source and the horn antenna of the detector. Both of the source’s variable attenuators were opened completely, maximizing the power output of the source.

Our first test with this set up was to take an amplitude measurement with the source’s bandpass filter absent and then again with the filter in place. Doing this test we discovered a factor of 20 decrease in signal between the two source arrangements. Since the bandpass filter only allows frequencies between 140 to 160 GHz to be emitted, our factor of 20 decrease implies that the vast majority of the signal being produced by the source is outside of our desired frequency range. Upon completion of this test, we discovered that the filter was slightly misaligned and thus could be contributing to signal loss. Therefore the filter was realigned and the test was repeated. Our new results still gave us a signal decrease, but only a factor of 5 decrease. Although this result was more comforting than our initial result, the source was still not performing at the desired level. Since the source was outputting a far amount of power, just not in the desired frequency range, it was concluded that one of the multipliers was malfunctioning, and not outputting an appropriate frequency.

Since the problem appeared to be that the signal being produced by the source was not in the desired wavelength range, we looked to the sextupler as the possible source of the problem, as much of the frequency multiplication happens in this portion of the source. Thus, we changed out the sextupler for the Spacek Labs A7713-6XW sextupler. Using the same setup as described above (9.5 in distance, 1 kHz chopping frequency), we tested the source with the two sextuplers. With the original sextupler, the signal peaked at 83\(\mu\)V. With the A7713-6XW sextupler, the signal peaked at 1700 \(\mu\)V, a factor of 20 increase in power output. This change in sextupler was made permanent since
3.3. TEMPERATURE TESTING

it greatly improved the performance of the source. The likely cause of this difference is that one of the multipliers in the original sextupler was damaged, and thus not performing to specifications.

3.3 Temperature Testing

Temperature is an important consideration in the operation of the instrument. There are three reasons behind such a consideration: (1) to ensure that components of the instrument remained with the manufacturer’s recommended operating temperature (i.e. the temperature of the stage should not fall below -20°C, the temperature of the tiltmeter should not fall below -25°C), (2) to ensure that the microwave components comprising the broadband noise source would not overheat, and (3) since the precision of the tiltmeter is dependent on temperature, limiting temperature variations is an important concern.

The silicon-rubber heat strips that were selected for use inside the environmental enclosure were tested, by placing them on the aluminum baseplate of the instrument, applying a voltage, and measuring the temperature of various components of the RPS with a thermocouple. From this test, it was determined what size strip heater was necessary for heating the RPS while at the South Pole.

Overheating of the microwave components in the source was a concern, as the performance of the components would be impaired if overheating occurred. To ensure that the active components of the broadband noise source did not overheat, the heat sinking of the source was tested. First, each component that needs heat sinking was securely attached to its heat sink with heat sink grease placed on the contact surfaces of the parts. Next, the source was powered on and the temperature of the microwave component was measured, as was the
temperature of the heat sink. If heat was not properly transferring to the heat sink (i.e. if the temperatures of the microwave component and heat sink were not similar), then a different heat sink was used. This was done for all of the active components of the source, and thus it was determined that each one was properly heat sunk.

3.4 Polarization Testing

The polarization test and positional repeatability test were done using the same setup as described above. The inner assembly of the RPS (i.e. the rotation stage, wire grid with holder, and broadband noise source with enclosure) was powered on, with the TTL input of the source’s PIN switch going to the Lock-In Amplifier, and the wire grid was placed in its holder such that the polarization signal coming out of the waveguide was perpendicular to the wires of the wire grid, which allowed the maximum signal to pass through the grid. A horn antenna and detector diode were setup across from the RPS and connected to the Lock-In Amplifier. Another wire grid polarizer was placed in front of the horn and detector, and was aligned such that polarization allowed through the wire grid corresponding to the same polarization defined by the rectangular waveguide of the horn, effectively making the detector polarization sensitive. Eccosorb HR-10 microwave absorber was placed behind the detector and surrounding the detector’s wire grid polarizer. A small piece of absorber was also placed around the path defined between the wire grid and detector.

The polarization test was done by adjusting the position of the RPS until a maximum signal was being detected by the detector diode, to ensure proper alignment between the horns. Once proper alignment was established, the data collection could begin. The source was moved to a given angle, once
3.4. POLARIZATION TESTING

The inner assembly of the RPS was positioned a set distance away from a detector diode with horn antenna placed behind a wire grid polarizer. The region surrounding the detector’s wire grid was covered with microwave absorber to reduce cross-polar leakage. Both the inner assembly of the RPS and the detector diode were connected to a Lock-In Amplifier that was used to collect data from the positional repeatability test and polarization test.

Figure 3.1: Setup of Microwave Testing: The inner assembly of the RPS was positioned a set distance away from a detector diode with horn antenna placed behind a wire grid polarizer. The region surrounding the detector’s wire grid was covered with microwave absorber to reduce cross-polar leakage. Both the inner assembly of the RPS and the detector diode were connected to a Lock-In Amplifier that was used to collect data from the positional repeatability test and polarization test.
there the amplitude was recorded from the Lock-In and the source was moved to a new angle and this procedure was repeated until the source had traveled a full $360^\circ$. The steps taken between angles varied depending on how close to a maximum or minimum value the angle was. This procedure was carried out on two different occasions, the first time was done with a non-powered rotation stage, thus the stage was turned by hand. For this run, only one amplitude value was recorded for each angle. The second run was done with the stage powered on and rotated via the controller. For this run, four data points were taken at each angle, in order to be able to characterize the scatter in the measurement.

Figure 3.2 shows the data collected from the second data collection run, with the stage powered. The results are as expected with a sinusoidal behavior, where peaks correspond to the orientation of the wire grid on the RPS matching that of the detector and the troughs correspond when the wires on the two grids are exactly perpendicular to each other. There are some important features to note in the graph. The error bars are smaller than the points themselves and thus can barely be seen in the plot. The errors represent the scatter in the signal at each point, which as can be seen, was minimal. Another important feature is that the second peak reaches a higher maximum than the first peak. This feature was not present in the data of the first run. We considered the possibility that for the first run, the source was saturating the detector at its peaks and thus would not be able to distinguish the discrepancy apparent in the second data set. This explanation, however was ruled out, because if saturation had occurred then the peak would not have appeared rounded as it did, but would have be flat. Another possible explanation is a misalignment between the axis of rotation of the rotation stage and the position of the horn antenna. Such a misalignment could cause the source’s horn
3.4. POLARIZATION TESTING

Polarization Testing Data - The data shown is from the second data collection run. The amplitude of the signal is plotted as a function of source angle. An estimate of the cross-polar response can be gleaned from this data by comparing the amplitude of the signal at the peaks to the troughs. It is difficult to get a reliable signal amplitude near the minima, because the signal is so close to the noise floor of the measurement. Nonetheless, this data gave an estimate of cross-polar response of 0.03%.

![Microwave Testing](image)

Figure 3.2: Microwave Testing Data - The data shown is from the second data collection run. The amplitude of the signal is plotted as a function of source angle. An estimate of the cross-polar response can be gleaned from this data by comparing the amplitude of the signal at the peaks to the troughs. It is difficult to get a reliable signal amplitude near the minima, because the signal is so close to the noise floor of the measurement. Nonetheless, this data gave an estimate of cross-polar response of 0.03%.

to become out of alignment with the detector horn as the source rotates, thus resulting in a loss in the detected signal. This discrepancy can be remedied by either making adjustments to the source to improve the alignment of the horn and the rotation axis, or if the behavior is properly modeled it can be taken into account when analyzing RPS data.

From the data collected in Figure 3.2 we can determine the cross-polar response of the RPS. This can be done by looking at the peaks and troughs of the curve. The troughs correspond to when no signal should be reaching the detector, because the polarization that the detector is sensitive to is orthogonal to the polarization being emitted from the RPS. Theoretically then, no signal should be detected, but since the troughs are not at zero, some cross-
polarization is being emitted from the RPS and detected by the diode, though some of the nonzero behavior at the troughs could be attributed to the noise level of system. By comparing the peaks to the troughs we can see that this cross-polar response is only 0.03%, which is well within our design goal of 0.5% cross-polar response.

3.5 Positional Repeatability Testing

The setup for this test was identical to that described in the previous section and depicted in Figure 3.1. After examining the data collected in the polarization test, two angles were chosen that fall near points of maximum slope on the graph. The points chosen were $30^\circ$ and $310^\circ$. The stage was powered on and homed, and then was moved to $30^\circ$, where two data points were taken. The stage was then moved to $310^\circ$ where two more data points were taken. The stage was then re-homed and the same procedure was repeated. This was done four times. From this data we determined the largest signal amplitude discrepancy between the points, and then converted that discrepancy into an angle discrepancy, using a linear approximation at $30^\circ$ and $310^\circ$. From this it was concluded that the positional repeatability is good to $\leq 0.01^\circ$. This is only an upper limit because it does not take into account the drift in the system that occurred over the course of the measurements, thus, the positional repeatability is likely even better than $0.01^\circ$. 
Chapter 4

South Pole Deployment

Upon completion of the Rotating Polarization Source, it was deployed to the Amundsen-Scott South Pole Station during the 2011-2012 austral summer, for use with BICEP2 and the Keck Array. It was used, as designed, for BICEP2, however was used only as a bright source for beam mapping with the Keck Array. The RPS will be used in subsequent seasons for determining the cross-polar response and polarization response angles of the detectors of the Keck Array.

4.1 Source Calibration

In order for the RPS to provide meaningful measurements of the polarization response angle and cross-polar response, the orientation of the wires in the wire grid, with respect to a reference surface, must be known. The flat machined surface of the rotation stage was used as this reference surface, thus it was determined which orientation angle of the rotation stage corresponded to the wires in the grid being horizontal with respect to that surface. The calibration procedure for determining the angle was as follows: The rotation stage, wire grid holder and wire grid were removed from the rest of the instrument. The
parts were placed on a mill (allowing for translation of the rotary stage in the x and y direction) and a machinists' pocket microscope was rigidly attached to the mill and used to observe the wires making up the wire grid. The stage was rotated until the wires were approximately parallel to the cross hair of the scope. The mill was used to translate the stage in the y-direction until the cross-hair was overlying one of the wires. Next the stage was translated in the x-direction. If any deviation between the cross hair and the wire was observed, then the stage would be rotated to account for the deviation. This process was iterated until the stage could be translated in the x-direction without any noticeable deviation between the wire and cross-hair. When this point was reached the angle on the rotation stage was recorded.

The calibration angle was determined to be $76.50^\circ$, which corresponds to the wires begin horizontal with respect to the base plate of the RPS. The setup used for this calibration is shown in Figure 4.1. This calibration was performed at the South Pole, rather than in the lab in Cambridge, because the calibration should be repeated every time the wire grid is put in place in the RPS. Due to the fragile nature of the wire grid, it was not shipped to the South Pole in situ, thus the calibration was conducted when the RPS was reassembled at the South Pole.

### 4.2 Setup

In addition to the wire grid calibration, a tiltmeter calibration was conducted to determine what reading of the tiltmeter corresponded to the rotation stage and source being level. A bubble level was placed on the machined, flat surface of the stage, and the orientation of the RPS was adjusted until the bubble in the level was centered, when this position was reached the reading on the
4.2. SETUP

The polarization orientation angle of the RPS was calibrated by using the machined surface of the rotary stage as a reference surface, and then observing the wires in the grid through a handheld microscope. The stage was translated using a mill in the x and y directions, and the wires were rotated via the stage until one of the wires lined up with the cross-hair of the microscope, once this alignment was confirmed, the position of the stage was recorded, and this value refers to the position of the source at which the wires are horizontal. This value was determined to be 76.50°.

A tiltmeter was recorded and this value was used for determining when the orientation of the source, while in use, is level. This calibration procedure was done multiple times with the bubble level in different positions to ensure that an accurate value was gleaned. This technique allowed for the level orientation of the source to be known to a precision of 0.02°.

After the RPS was fully calibrated, it was mounted to the mast at the MAPO building (the same building that houses the Keck Array), which is
The source was mounted to the mast near the MAPO building for use with BICEP2. The RPS was bolted to the mounting plate of the mast, and then cables were run from the RPS to the ground where the RPS was controlled during data collection runs.

shown in Figure 4.2. During data runs with the RPS, it should be placed in the far-field of BICEP2. The far-field, $d_f$, is defined as

$$d_f = \frac{2D^2}{\lambda}$$  \hspace{1cm} (4.1)

where $D$ is the aperture of the receiver ($D = 264$ mm for BICEP2 (Aikin et al., 2010)), and $\lambda$ is the wavelength of the radiation ($\lambda = 2$ mm for 150 GHz). This gives a value of $d_f = 70$ m, since the distance between the MAPO building (where the RPS is mounted) and DSL building (where BICEP2 is housed) is 200 m, this places the RPS well within the far-field of BICEP2. At
4.2. SETUP

this distance, the signal from the RPS will appear as a point source to the BICEP2 receiver, which allows the optical performance of the receiver to be characterized.

Figure 4.3: RPS in Preparation for Data Collection *(Photo Credit: A. G. Vieregg)*- Once the RPS was mounted to the mast, it was raised into position. Three guy-wires were used to stabilize the RPS into a level position. The stability of the absolute orientation of the RPS during data collection runs was very dependent on environmental factors, such as the wind.

After the RPS was mounted to the mast, it was raised up into position as shown in Figure 4.3, but in order to properly position the RPS such that it is level, three guy-wires were used to stabilize the RPS and turnbuckles were used to adjust the orientation of the RPS. The components of the RPS (i.e. broadband noise source, rotation stage, tiltmeter, etc), were electrically connected and controlled by at the base of the mast. The readings from the tiltmeter were displayed on a voltmeter and the guy-wires were adjusted until the reading was within 30 mV of the target orientation (the level orientation
determined in the tiltmeter calibration), which corresponds to a precision of 0.02°. Once this orientation was reached the RPS was ready for use.

In order for BICEP2 to observe the source, a flat mirror, made from a sheet of aluminum honeycomb, was mounted above the receiver at a 40° angle, such that the detector beams are directed toward the source. In this condition, BICEP2 is under high optical loading as the telescope is pointed at the horizon rather than the cold sky. In addition, the brightness of the source imposes higher optical loading than the telescope would experience when observing the CMB. In this state, the detectors must operate on a different transition point and bias voltage than would be used for observations of the sky. In the case of high optical loading, the Al-transition is used, instead of the Ti-transition which is used during normal CMB observation (Brevik et al., 2010).

4.3 Data Collection

The setup for data collection is shown in Figure 4.4. The RPS had 24 scheduled runs between January 26, 2012 and February 6, 2012. Of these runs, 7 yielded useful data, while the others were aborted for various reasons, such as attenuating the source signal due to saturation of the detectors. Table 4.1 shows the successful data collection runs and corresponding focal plane coverage. Data were taken over 360° of source orientations using 15° steps, resulting in 25 source orientation angles taken. It took 6 hours to cover each row of the focal plane, with each of the steps taking 6 minutes to complete. BICEP2 and the flat mirror were moved such that the source scans the focal plane of the receiver. These raster scans are conducted until each detector in the focal plane has been mapped.
4.3. DATA COLLECTION

Table 4.1: RPS Schedule of Successful Runs

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>Duration (hr)</th>
<th>Rows Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>01/20/12</td>
<td>10.1</td>
<td>1-3</td>
</tr>
<tr>
<td>12</td>
<td>02/01/12</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>02/02/12</td>
<td>3.0</td>
<td>2-3</td>
</tr>
<tr>
<td>19</td>
<td>02/03/12</td>
<td>7.6</td>
<td>2-4</td>
</tr>
<tr>
<td>20</td>
<td>02/03/12</td>
<td>6.4</td>
<td>2</td>
</tr>
<tr>
<td>21</td>
<td>02/03-05/12</td>
<td>51.9</td>
<td>1-16</td>
</tr>
<tr>
<td>24</td>
<td>02/06/12</td>
<td>17.4</td>
<td>1-16</td>
</tr>
</tbody>
</table>

Figure 4.4: RPS, in use, at the South Pole (Photo Credit: J. M. Kovac)- While the RPS was in use, the device was mounted atop the mast at the MAPO building, while BICEP2 in the DSL building observed the device using a flat mirror.
Chapter 5

Analysis and Results

Data were taken for each row of detectors at two different deck angles of the telescope, $dk = 0^\circ$ and $dk = 90^\circ$. However, two rows of detectors at each deck angle was missed, due to an error in the source observing schedule. An example of the maps created from the raster scans conducted at the South Pole, is shown in Figure 5.1, which shows one row of detectors (both A/B detector pairs) at each of the source polarization angles. Notice, that the response from the A and B detectors are $90^\circ$ opposite each other. Two-dimensional Gaussian curves were fit to each detector response at each source polarization angle. This fitting procedure was carried out by R.W. Ogburn. The following data analysis draws on these Gaussian fits.

For each detector, the amplitude of the Gaussian was plotted as a function of source angle for each of the detector pairs, which can be seen in Figure 5.3. Theoretically, we would expect this data to follow a sinusoidal pattern with a period of $180^\circ$. This is because the source was rotated a full $360^\circ$, meaning that the wires of the grid polarizer, were vertical two times and horizontal two times throughout the data taking process, which corresponds to two maxima and two minima in the detector signal. Maxima corresponding to when the
5.1. MODELING

The expected behavior of the data collected should resemble that of a cosine curve with a period of $180^\circ$ with some offset. Thus the data were fit to a model that took this behavior into account, specifically...
\[ M_0(\theta) = A \cos(2(\theta - \psi)) + B \]  \hspace{1cm} (5.1)

where \( A \) is the amplitude, \( B \) is the offset, \( \theta \) is a given source angle, and \( \psi \) is the polarization response angle. These fitting parameters can be used to determine the two values needed, polarization angle, \( \psi \) and cross-polar response, \( \epsilon \). The polarization angle, \( \psi \), is one of the fitting parameters, and the cross-polar response is the ratio of the peak of the cosine curve to the trough of the curve, thus \( \epsilon \) is given by

\[ \epsilon = \frac{B - A}{B + A} \]  \hspace{1cm} (5.2)

The model, however, can be redefined using Equation 5.2, such that \( \epsilon \) is one of the model parameters. This results in a new model, \( M_1 \), given by

\[ M_1(\theta) = C \left[ \cos(2(\theta + \psi)) - \frac{\epsilon + 1}{\epsilon - 1} \right] \]  \hspace{1cm} (5.3)

where \( C \) is a nuisance parameter and, \( \psi \) and \( \epsilon \) are the desired values: polarization response angle and cross-polar response, respectively. This model was fit to the data, depicted as the blue curve in Figure 5.2. The residuals, calculated as \( M_1 - D \), where \( D \) is the measured value, are also shown in Figure 5.2. As can be seen from the residuals of the Model 1 fit, there is a distinct pattern to the residuals, which suggests that a different model will fit the data better. A systematic effect in the operation of the RPS is the likely culprit of the residual pattern.

The most probable systematic effect to explain this feature in the data is the misalignment of the horn antenna of the source with the axis of rotation of the stage. This misalignment would result in a precession of the horn, and thus a change in the power of incident radiation on a given detector as a function
Figure 5.2: Testing Model Fits- The first attempt at fitting the data was done using a simple 180° period cosine curve model (blue curve), but as can be gleaned from the residuals, there is a prominent systematic effect that the model does not take into account. The precession of the horn antenna about the axis of rotation in the RPS was added to the model as another cosine with a period of 360° (red curve). As can be seen from the residuals, this model fits the data much better. The second model was used to fit all of the 32 detectors in the row the row being analyzed.
of the horn’s position in its precession. This precession can be modeled by a cosine curve with a period of 360°, and by taking this systematic effect into account, a more accurate model, $M_2$, is given by

$$M_2(\theta) = C \left[ \cos(2(\theta + \psi)) - \frac{\epsilon + 1}{\epsilon - 1} \right] \left[ D \cos(\theta - \gamma) + 1 \right]$$

(5.4)

where $C$, $D$, and $\gamma$ are nuisance parameters. This model fits the data much better and no obvious pattern in the residuals is present, as can be seen in Figure 5.2, with Model 2 depicted as the red curve.

---

**Figure 5.3: Model Fitting for Detector Row**- The model was fit to all 32 detectors in the row. As can be seen from the plot, some of the detectors show an anomalous response. One detector has two points that are obvious outliers to the rest of the data, that prevent the model from properly fitting. These outliers could be caused by a flaw in fitting the 2-dimensional Gaussian, as the fit may have been made to an nonphysical artifact in the data. The detectors with anomalous responses were not used in the analysis presented here. Among the detectors that the model did fit well, the variation in the amplitude of the detector response is expected for the observing setting of BICEP2 while observing the RPS.
5.1. MODELING

Model 2 was used to fit curves to all 32 detector pairs (16 A detectors, 16 B detectors) in one row of detectors on the focal plane. These 32 fits are shown in Figure 5.3, where A detectors are depicted by blue curves and B detectors are depicted by red curves. The model appears to fit most of the 32 detectors quite well, though one A detector has two outlier data points that appear anomalous and do not fit the model well, and another A detector is uniformly zero. One B detector in the set of 32 is also not plotted as a problem with the detector prevented it from collecting data. These three anomalous detectors were not used in further analysis, but the detector with two anomalous points throwing off the model fitting, is likely not a faulty detector, but a flaw in the Gaussian fit that was done for that detector response.

The fits to the remaining 29 detectors all showed comparable residuals to that shown in Figure 5.2 for the first A detector. From the fit parameters, the cross-polar response and polarization response angles can be determined. Figure 5.4 and Figure 5.6 shows the distribution of cross polar response values, \( \epsilon \), across the row of detectors. Figure 5.5 and Figure 5.7 shows the distribution of polarization response angles, \( \psi \), across A detectors and B detectors. From these figures, it is easy to identify outliers, and in fact the most obvious outlier in both figures correspond to the same detector.

It is important to note that the free parameters, D and \( \gamma \), have a particularly high scatter from detector to detector. This is surprising, because both D and \( \gamma \) are supposedly due to the same physical effect, namely the precession of the horn antenna, and thus variation from detector to detector would not be expected. This oddity requires further investigation, and another systematic effect may be at play.
Figure 5.4: Distribution of Cross-Polar Responses- The distribution of cross polar responses for the row of detectors being analyzed. The distribution of values appear to follow a Gaussian distribution which is expected for these values. A number of cross-polar response values came out to be negative values, this is not surprising in that since the expected cross-polar response values are so close to zero, statistically some detectors would show a negative value. In the case of cross-polar response, negative values have no physical meaning.
Figure 5.5: Distribution of $\psi$ for A and B Detectors- The $\psi$ values reported here are treating 76.50° as zero. It is difficult to determine whether or not these distributions are Gaussian or not, because of low number statistics. It is interesting to note, however, that for both A and B detectors the values for $\psi$ do not distribute around 0° for A detectors and 90° for B detectors, which would be expected, instead, in both cases, the values are systematically shifted to values lower than anticipated.
5.2 Error Analysis

The error analysis was done using a likelihood analysis, in order to assign 1σ uncertainties to the fitted parameters $\epsilon$ and $\psi$. To do this, the residuals calculated from the fits described in the previous section were used to calculate the variance on the best fit model, where the variance for each detector, $\sigma_{\text{det}}^2$, is defined by

$$\sigma_{\text{det}}^2 = \frac{\sum_{i=1}^{N} (M - D)^2}{N - 5}$$

(5.5)

where $M$ is the model value (as defined in Equation 5.4), $D$ is the measured value, and $N - 5$ is the degrees of freedom. This variance can then be used to calculate $\chi^2$, which is defined as

$$\chi^2 = \sum_{i=0}^{N} \frac{(M - D)^2}{\sigma_{\text{det}}^2}$$

(5.6)

The $\chi^2$ value was calculated for the model described in the previous section. To determine the error in a given parameter, in this case $\psi$, the parameter value was varied, and a new $\chi^2$ was calculated until $\Delta \chi^2 = 1$, where $\Delta \chi^2$ is defined by the difference between the original model fit $\chi^2$ and the parameter-varied fit $\chi^2$. Since the likelihood is $\sim e^{\frac{1}{2} \chi^2}$, when $\Delta \chi^2 = 1$, this corresponds to a change in likelihood of 1σ. The change in the parameter value, $\Delta \psi$, that corresponds to this 1σ value is the reported uncertainty for a given parameter value. This same procedure was carried out for $\epsilon$. The uncertainties determined from this method are reported in Table 5.1, along with the parameter values.

The above analysis deals with the statistical errors in the measurement made, but systematic errors are also a major concern regarding the uncertainty of the measurement. Likely, the most dominate source of systematic error is the uncertainty in the absolute orientation of the RPS. The stability of the RPS,
5.2. ERROR ANALYSIS

Figure 5.6: Cross Polar Response with Uncertainties- The cross-polar response plotted as a function of detector position, with error bars reported from the likelihood analysis carried out for each detector.

Figure 5.7: Polarization Response Angles with Uncertainties- The polarization response angle plotted as a function of detector position, with error bars reported from the likelihood analysis carried out for each detector.
Table 5.1: Results- Cross-polar response, $\epsilon$, and polarization response angles, $\psi$, are reported with uncertainties, $\sigma_\epsilon$ and $\sigma_\psi$, respectively.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Pair</th>
<th>$\epsilon$ (%)</th>
<th>$\sigma_\epsilon$</th>
<th>$\psi$ (°)</th>
<th>$\sigma_\psi$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>A</td>
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<td>0.2</td>
<td>-0.94</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.25</td>
<td>0.1</td>
<td>89.17</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
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<td>-0.69</td>
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</tr>
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<td>89.38</td>
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<tr>
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<td>-1.14</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
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</tr>
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<td></td>
<td>B</td>
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<td>-</td>
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</tr>
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while in use on the mast at the South Pole, is dependent on several factors. The orientation of the RPS on the mast is stabilized by three guy-wires with turnbuckles to adjusted the tension in the wire. The guy-wires are adjusted until the reading of the tiltmeter is within 30 mV of level, which corresponds to an orientational uncertainty of 0.02°. The stability of the mast over a given data collection run is dependent on the environment conditions, such as wind speeds and solar heating. It was determined that a change in tiltmeter temperature of $\Delta T = 15$ K, corresponds to a change in the orientation reading of 0.01° on the tiltmeter. Over an 8-12 hour data collection run, the drift in the orientation of the RPS, due to weather conditions, was never more than 100 mV, which corresponds to 0.06°. This is likely the largest systematic error, but it still keeps the absolute orientation uncertainty of the source within the 0.1° design goal of the RPS.

Another possible source of systematic error is in the temperature dependence of the power output of the broadband noise source. It was observed during broadband noise source testing in the lab, that as the microwave components warm, there is a drift in the power output of the source. Within the heated enclosure of the RPS, convection may cause a temperature gradient between variation parts of the inner assembly of the RPS. As the assembly is rotated, this temperature gradient may shift, which would affect the power output of broadband noise source, thereby creating a systematic effect of beam amplitude as a function of source orientation angle. Based on the signal drift observed under lab conditions, the source power likely only has a variation of a few percent due to temperature variation, so this systematic effect is quite small.

The values determined in the analysis in the previous section need to be translated into coordinates in the focal plane, so that accurate orientation an-
gles can be applied to observation of the CMB. This involves using complicated parameter fitting in the pointing model of the telescope. This transition from one frame to another will likely introduce a systematic error.
Chapter 6

Discussion and Conclusions

With the need for reduced systematic contamination to support the sensitivity goals of BICEP2 and the Keck Array, a device was needed to characterize the polarization response of the detectors to a high degree of precision. This characterization prevents systematic uncertainties caused by E-mode to B-mode leakage due to miscalibration from dominating the uncertainty in measurements of the CMB. A rotating polarized source was designed and constructed to carry out the needed characterization, which exceeded the design goals needed for the sensitivity goals of BICEP2 and the Keck Array. The device was sent to the South Pole, and data was collected with it for BICEP2. The analysis of the data collected gives us the needed values for taking into account the imperfection in the detectors. This characterization endeavor has been successful and the resulting instrument will be useful for years to come.

6.1 Future Work

The analysis presented here was only carried out for 1 row of detectors, the other 15 rows still need to be analyzed. Furthermore, as previously discussed, the analysis brought to light a few concerns that warrant further investigation,
such as the anomalous parameter values for the antenna precession model.

The data collected using this source can also be used to better understand a subtle polarization dependence that was discovered in BICEP2 by observing the RPS. This effect is currently being investigated further, using the data collected.

In the coming years, the RPS will be used at Harvard, as well as Caltech, for pre-deployment testing and, during the austral summers, the RPS will be used with the Keck Array for the same characterization that was carried out for BICEP2. The design of the RPS could also prove useful for other polarization experiments. The source was already observed by South Pole Telescope (SPT) during the 2011-2012 austral summer. The SPT group, as well as the SPIDER and POLARBEAR experiments have requested the designs of the RPS, for use with their experiments.
Bibliography


