Abstract

The Atacama Cosmology Telescope (ACT) is a six meter diameter telescope designed to measure the millimeter sky with arcminute angular resolution. The instrument is currently conducting its third season of observations from Cerro Toco in the Chilean Andes. The primary science goal of the experiment is to expand our understanding of cosmology by mapping the temperature fluctuations of the Cosmic Microwave Background (CMB) at angular scales corresponding to multipoles up to $\ell \sim 10000$.

The primary receiver for current ACT observations is the Millimeter Bolometer Array Camera (MBAC). The instrument is specially designed to observe simultaneously at 148 GHz, 218 GHz and 277 GHz. To accomplish this, the camera has three separate detector arrays, each containing approximately 1000 detectors. After discussing the ACT experiment in detail, a discussion of the development and testing of the cold readout electronics for the MBAC is presented.

Currently, the ACT collaboration is in the process of generating maps of the microwave sky using our first and second season observations. The analysis used to generate these maps requires careful data calibration to produce maps of the arcminute scale CMB temperature fluctuations. Tests and applications of several elements of the ACT calibrations are presented in the context of the second season observations. Scientific exploration has already begun on preliminary maps made using these calibrations. The final portion of this thesis is dedicated to discussing the point sources observed by the ACT. A discussion of the techniques used for point source detection and photometry is followed by a presentation of our current measurements of point source spectral indices.
Acknowledgments

I am very grateful for the opportunities I have had to learn and grow as a researcher thanks to Princeton University. The atmosphere of excitement for discovery in the Physics Department is like nothing I have ever experienced before. Through my years of graduate work, I have been guided and supported by Lyman Page, Suzanne Staggs, and my advisor, Joseph Fowler. I truly appreciate having the opportunity to study under such a brilliant trio of scientists. I especially would like to thank Joe for helping me through my years of graduate work and for spending countless hours having discussions with me on topics ranging from cosmology to coffee.

I owe very much of this thesis to the work of so many other individuals. I have been lucky to both follow in the footsteps of many great scientists who have come before me, and walk the path with the most excellent of peers one could wish for. In particular, I have had the pleasure of working with and learning from the many members who have been a part of the ACT collaboration including: Mike Niemack, Judy Lau, Toby Marriage, Asad Aboobaker, Yue Zhao, Tom Essinger-Hileman, John Appel, Lucas Parker, Sudeep Das, Amir Hajian, Viviana Acquaviva, Beth Reid, Kevin Huffenburger, Elia Battistelli, Rolondo Diinner, Matt Hasselfield, Mike Nolta, Jon Sievers, Neelima Sehgal, Matt Hilton, Jo Dunkley, Norm Jarosik, Kavi Moodley, David Spergel, Omelan Stryzak, Daniel Swetz, Danica Marsden, Krista Martocci, Alex Dahlen, Leizhi Sun, Sarah Denny, Mark Halpern, Jeff Klein, Michele Limon, Robert Lupton, Randy Doriese, Gene Hilton, Jay Chervenak, Ryan Warne and Audrey Sederberg, to name but a few.

I would like to thank all of the staff of the Physics Department, and especially those who are always so friendly and helpful to me: Barbara Grunwerg, Claude Champagne, Mary Santay, Laurel Lerner, Angela Glenn, John Washington and Mike Peloso. I would also like to particularly thank the members of the machine shop lunch crew, Glenn, Bill, Ray, and occasionally Bob Austin, who have shared many an excellent conversation with me.

I would like to especially thank the two individuals who have shared far more than just an office with me over the last few years, Eric Switzer and Adam Hincks, for their camaraderie, help and friendship.

My years at Princeton have gifted me with so many friends, including many whom I have already acknowledged as peers. I could hardly imagine listing the countless number of individuals who have brought an ounce of happiness to my time at Princeton, but I would like to point out a few individuals who have been truly good friends. First, I would like to thank the basement crew of Justin Brown, Rajat Ghosh, Scott Seltzer, Hoan Dang, and Giorgos Vasilakis, for providing me with both friendship and entertainment on the many occasions when I required it. Next I would like to thank Omelan Stryzak and Ted Lewis for always providing me with the help I needed, but more importantly by far for their friendships extending beyond the walls and topics of Jadwin Hall. Finally, I would like to thank Sam Taylor, Lewis Andrew Wray, Nick Pavlov and Jeremy Booher for all of the fun times we’ve spent together. To Nick and Justin and Jeremy, thanks for all of the laughter you have brought into my life all these years. To all of my friends: I will miss you dearly.
when I move on, and I hope that our paths will cross again.

I owe so very much to the love and support of my parents, Jackie and Gary Fisher. Thank you both for helping me through everything that I have done.

Throughout my years of study, I have always had the love of my life by my side. She has always helped me through my greatest times of need and given me a reason to be happy every day. My greatest thanks go to you, Julie, I love you, and I dedicate this thesis to you and our future together.
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Chapter 1

Cosmology, the CMB, and the Atacama Cosmology Telescope

The Atacama Cosmology Telescope (ACT) will be used to expand our current knowledge of the history of the universe. Modern cosmology, as the study of this history, uses models for the composition, structure and evolution to describe the universe observed today. The current commonly accepted model is that of a Big Bang cosmology, where the universe begins as a complete or near singularity, and then expands and cools with time. The composition of the universe in this cosmology is described by four primary components. These are baryonic matter, including electrons and protons, cold dark matter (CDM), which interacts with baryonic matter only through gravitational potentials, dark energy, which has a negative pressure and fixed density with scale variations of the universe, and radiation, including photons and neutrinos. The structure of the universe is approximately both homogenous and isotropic. This model is known as a $\Lambda$CDM cosmology, as the dark energy is commonly proposed to be in the form of a non-zero cosmological constant, $\Lambda$ in Einstein’s field equations. The components and structure evolve according to these field equations using the Friedmann-Lemaître-Robertson-Walker (FLRW) metric.
solution,

\[ ds^2 = dt^2 - a(t)^2 \left( \frac{dr^2}{1 - Kr^2} + r^2 d\Omega^2 \right), \]  

where \( K \) represents the curvature of the universe and is zero for a flat geometry, \( r \) and \( \Omega \) are the spherical coordinates of the metric, and \( a(t) \) is a scale factor that is allowed to change in time. The FLRW metric is the solution to the field equations for a homogenous and isotropic universe. These conditions agree with all astronomical observations made thus far for the large scale structure of the universe. The solutions to the field equations in this metric allow the universe to either expand, shrink or remain fixed in size with the variation in \( a(t) \). Beginning with the early observations conducted by Edwin Hubble of receding galaxies, the universe is known to be expanding at present. Additionally, in the Big Bang model, the universe has been expanding since its origin. In addition to this, in 1998, two research groups discovered that the expansion rate of the universe is currently accelerating through observations of supernovae [65, 58]. This evidence supported the notion of a dark energy that propels the expansion of the universe, thanks to its dominance at late times in the universe’s history. This dominance is linked to the lack of scale variance, while all other components reduce in energy density as the scale increases.

The measurements of parameters in cosmological models from fits to astronomical data sets have provided the basics of the understanding of the physical nature of the universe described above. Such measurements have helped to separate valid and invalid models for the composition, structure and expansion of the universe. Within the last decade, there have been many substantial cosmological findings from studies of galaxy clusters [13], Active Galactic Nuclei (AGN) [59], the Cosmic Microwave Background (CMB) [35], Baryon Acoustic Oscillations (BAO) [88], gravitational lensing [26] and several other sources. The Atacama Cosmology Telescope experiment seeks to explore cosmology through millimeter-wave observations of the CMB.
1.1 The CMB

The CMB is the blackbody radiation field emitted by the cooling of the hot plasma that filled the universe immediately after the Big Bang. To describe the origin of this radiation, we begin with a universe made up of dark matter, neutrinos, baryons and photons expanding from a near or complete singularity. Initially, the temperature of the universe is high enough that all baryons form an ionized plasma, and the temperature of the plasma is too great for any atoms to form. The free electrons in this plasma frequently Compton scatter the photons, providing them with only a negligibly small mean-free path. This repeated scattering causes the two components to be coupled such that the photons are not free to flow separate from the baryons, and any perturbations in their otherwise isotropic distributions are shared. The dark matter is only coupled weakly to these components by gravitational potentials, and neutrinos are free to stream evenly throughout space. The short mean-free path between Compton scatterings causes the photons to have a blackbody spectrum.

As the universe expands, it also cools. Eventually, the temperature of the plasma reaches the point at which electrons are able to bind to protons and form atoms. This “recombination” occurs over a relatively short period of time. When this occurs, the photons are no longer impeded by the ionized electrons, and so they decouple from the baryons and begin to freely stream throughout the universe. The photons emitted at decoupling thus serve as an effective snapshot of the state of the universe at the time of this last scattering. From here, the photons are free to stream through the expanding universe. Their spectrum remains a blackbody, and becomes redshifted by cosmic expansion to the 2.75 K background we observe today. The redshift of the photons, $z$, is defined by:

$$1 + z = \frac{\lambda_o}{\lambda_i} = \frac{1}{a}$$  \hspace{1cm} (1.2)

where $\lambda_o$ and $\lambda_i$ are the observed and initial wavelengths of the radiation. Although the
1.1 The CMB

CMB is nearly isotropic, there are anisotropies within the otherwise uniform background radiation. These anisotropies are attributed to overdensities of the primordial plasma that are generated by quantum fluctuations. It is these overdensities which eventually collapsed gravitationally to form the structure we observe in the universe today.

The initial discovery of the CMB occurred as an unintentional measurement acquired by Arno Penzias and Robert Wilson of Bell Laboratories in 1965. Penzias and Wilson were studying radiation received by a large feed horn antenna located in New Jersey with a center frequency of $\nu = 4.080 \text{ GHz (} \lambda = 7.353 \text{ cm)}$. In their measurements, they found that there was an excess background radiation of $3.5 \pm 1.0 \text{K}$ isotropically distributed on the sky [57]. They contacted Robert Dicke and Jim Peebles of Princeton University to seek an explanation for this excess power. Through this contact, they learned that such a primordial background radiation field might be of cosmic origin, and likely would have been emitted at an earlier time when the universe was nearly isotropic. Although not realized initially, such a radiation field had been predicted as a product of the Big Bang by George Gamow, Ralph Alpher and Robert Herman in 1948 [25, 4, 5]. Penzias and Wilson reported their results in their 1965 letter. A companion letter by Dicke, Peebles, Peter Roll and David Wilkinson that described the necessary Big Bang cosmology to produce this isotropic background radiation was published in the same volume of the Astrophysical Journal [17]. In this paper, the correct basic concept of the CMB as accepted today is presented. This includes that the CMB is cosmologically redshifted blackbody radiation that fills the universe. Additionally, the radiation was thought to have originated from a very high temperature and density state of a near or complete singularity corresponding to the Big Bang picture [17]. The redshifting is generated by the expansion of the universe from the initial dense state to the present age and size.

From these beginnings, measurements of the CMB have been conducted with many other experiments. Anisotropies in the temperature of the CMB were first detected by the Cosmic Background Explorer (COBE) satellite's Differential Microwave Radiometer (DMR) instrument, and reported in 1992 in Smoot et al. [71]. Additionally, the Far-Infrared
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Absolute Spectrophotometer instrument on COBE measured the absolute temperature of the CMB blackbody radiation to be \(2.725 \pm 0.002\) K \([53]\). Several other experiments using both ground-based and balloon-borne instruments contributed to CMB measurements after COBE \([33]\), before the next satellite mission was launched. The next satellite mission, the Wilkinson Microwave Anisotropy Probe (WMAP) experiment, has produced full-sky maps of the CMB in five frequency bands spanning the microwave observation range from 23 to 94 GHz \([35]\). The WMAP instrument has beam sizes ranging from only 0.21 to 0.82 degrees for the 94 through 23 GHz observations, producing the first all-sky sub-degree maps of the CMB. Figure 1.1 shows a map of the CMB made from the WMAP 5-year data. This map clearly shows both the nearly isotropic nature of the CMB and its primary anisotropies. From the WMAP observations and continued measurements of the CMB anisotropies combined with other observations, a full history of the universe has been developed.

1.2 Primary Anisotropies of the CMB

As first observed by the COBE satellite, the CMB is not completely isotropic. The observed temperature fluctuations in the CMB are very small, with \(\Delta T / T\) on the order of \(7 \times 10^{-5}\). A useful way to characterize these temperature fluctuations is by measuring the variation of the CMB over different angular scales. The commonly used and most convenient representation for the fluctuations is an expression in terms of Laplace’s spherical harmonics, \(Y_{\ell,m}(\theta, \phi)\). Represented in angular coordinates, these harmonics form an orthogonal set of bases in which the temperature fluctuations are represented as:

\[
\Delta T(\theta, \phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell,m} Y_{\ell,m}(\theta, \phi) .
\] (1.3)
1.2 Primary Anisotropies of the CMB

Figure 1.1: A map of the combined 5-year WMAP data. This map uses data from all of the WMAP frequency bands, combined in order to minimize foregrounds including galactic emission. The CMB signal is very nearly isotropic, despite the appearance of the map. The temperature fluctuations shown are less than $\pm 200 \mu K$ out of the $\sim 2.7 K$ average radiation temperature. Image retrieved from the LAMBDA website [34]. Image courtesy of the WMAP science team: Hinshaw et al. [35].
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The power spectrum of the CMB fluctuations, which measure the anisotropy of regions separated by a given angle, $\theta \sim \pi/\ell$ radians, is defined from this as:

$$C_\ell \equiv \langle a_{\ell,m} a_{\ell,m}^* \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{m=\ell} |a_{\ell,m}|^2,$$

where the ensemble average over the quantity in brackets is taken over all $m$. This average is computed over all universes with the same distribution of possible values for $a_{\ell,m}$. We live in only one such universe, so measurements of our universe suffer from the limitations of cosmic variance. Finally, the temperature fluctuations for a given multipole $\ell$ are expressed as:

$$\left(\Delta T_\ell\right)^2 = \frac{\ell (\ell+1) C_\ell}{2\pi}$$

where the extra factor of $\ell$ flattens the spectrum when taken over logarithmic intervals of $\ell$, and $(\ell + 1)/2\pi$ effectively replaces $(2\ell + 1)/4\pi$ for consistency with historical representation.

Figure 1.2 shows several observed power spectra of the CMB anisotropies. The figure includes measurements from WMAP [55], the Arcminute Cosmology Bolometer Array Receiver (ACBAR) [61], the Cosmic Background Imager (CBI) [70], the QUEST on DASI (QUaD) experiment [24], the Atacama Pathfinder EXperiment (APEX) [62], the Sunyaev-Zeldovich Array (SZA) [69], and the Berkeley-Illinois-Maryland Association (BIMA) array [15]. Additional experiments are excluded to reduce clutter in the figure. Additionally, it includes predicted power spectra for the kinetic and thermal Sunyaev-Zel'dovich effects (green dashed curve), infrared foreground galaxies (red dashed curve), and the primary anisotropies of the CMB (blue dashed curve). A relatively simple perturbative model is sufficient to roughly describe the measured primary anisotropies of the CMB.

As previously mentioned, the temperature anisotropies result from overdensities in the primordial baryon-photon plasma that existed directly after the Big Bang. The initial density fluctuations are affected by the competing influences of increased gravitational at-
1.2 Primary Anisotropies of the CMB

Figure 1.2: Measurements of the CMB power spectrum from WMAP, the Arcminute Cosmology Bolometer Array Receiver (ACBAR), the Cosmic Background Imager (CBI), the QUEST on DASI (QUaD) experiment, the Atacama Pathfinder EXperiment (APEX), the Sunyaev-Zeldovich Array (SZA), and the Berkeley-Illinois-Maryland Association (BIMA) array shown with predicted power spectra for the kinetic and thermal SZ effects, infrared foreground galaxies, and the primary anisotropies of the CMB. On the y-axis is plotted the $(\Delta T)^2$ of the CMB temperature fluctuations both expected and measured for a given multipole $\ell$. Oscillations due to primordial inhomogeneities are located at regular intervals described by $\ell \sim 220n$. Image Credit: Joseph Fowler
traction and increased pressure that the overdensities generate. These competing forces generate oscillations in the density of the baryon-photon plasma. The oscillations propagate through the plasma as acoustic waves. The overdensities begin to collapse when the horizon of the universe becomes greater than the size of the oscillations. The propagation of the waves is explained by complicated plasma physics, but the result is that oscillations propagate at a rate that can be parametrized by their wavelength. The modes with the largest wavelengths oscillate most slowly, while the smallest wavelengths have the opportunity to oscillate many times before the baryon-photon plasma becomes decoupled. Additionally, modes with the same frequency begin oscillating with the same phase. At decoupling, the photons released indicate the state of these oscillations. The angular power spectrum of the temperature anisotropies therefore represents the state of these oscillations at the surface of last scattering.

The initial perturbations in the dark matter density do not propagate along with the acoustic waves. After the decoupling, the baryonic matter and dark matter gravitationally attract, and both concentrate at the resulting dark matter and baryonic matter overdensities [20]. The photons released at the surface of last scattering continue to interact with the gravitational potential, \( \Phi \), created by the overdensities in the baryonic and dark matter. Where the potential is greater, the photons must climb out of the potential wells, and this produces a gravitational redshift corresponding to a temperature fluctuation equal to \( \Delta T/T = -\Phi \) [85]. The initial temperature in these locations is, however, greater due to the overdensity of photons. The net effect of a perturbation to the potential is that the temperature fluctuation is [85]:

\[
\frac{\Delta T}{T} = -\frac{1}{3}\Phi.
\]  

(1.6)

This indicates that overdense regions appear as cold spots in the CMB.

The peaks in the measured power spectrum of the CMB correspond to the extrema of the plasma oscillations. The peak positions in multipole, \( \ell \), can be shown to inversely proportional to the wavelengths of the oscillations that produce them through analysis of
1.2 Primary Anisotropies of the CMB

the acoustic wave propagation through the baryon-photon plasma [40]. More specifically, the rate of oscillation of an acoustic wave in the plasma is proportional to the wavenumber of the oscillation. The first peak of the power spectrum corresponds to a wave that has undergone one compression before recombination. The second peak corresponds to a wave that has been able to both compress and rarify in the same amount of time. This wave must therefore have half the wavelength and double the multipole value. This regularity of the peaks is clearly seen in the primary anisotropy power spectra that are shown in Figure 1.2.

The absolute peak positions, and both the absolute and relative amplitudes of the peaks and troughs serve as excellent indicators of the evolutionary history and composition of the universe. Specifically, the power spectrum may be used to determine many cosmological parameters. The position of the first peak provides information on the age of the universe, and may be used to constrain the curvature of the universe, or to provide information on the density of baryonic and cold dark matter if a flat universe is assumed [56]. The measured first peak agrees well with a flat universe, with $K = 0$. The density of the universe in the flat case is called the critical density. Flatness requires that the total densities of CDM, baryons, radiation, and dark energy sum to this critical density. The amplitude of the first peak constrains the density of total matter in the universe, while the ratio of first to second peak is more sensitive to the density of baryonic matter in the universe [56]. The density of dark energy may be inferred from the combination of measured dark matter, baryons and curvature, but the measurement is degenerate with that of the curvature [40]. The dark energy density is more precisely set by combining the nearly zero curvature constrained by the CMB with measurements of the observed matter density of the universe. From this, it is clear that the total matter density is much less than the critical density, requiring a significant portion of the total density to be in dark energy.

As more peaks are observed, the constraints on all of the cosmological parameters tighten, and degeneracies among some parameter values are reduced. Although the general shape of the power spectrum at last scattering due to the plasma interactions is
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well understood, an overall envelope known as the spectral tilt may be looked for to explore additional primordial effects [84]. The spectral tilt of the CMB may be better measured as more peaks are measured. The spectral tilt of the CMB anisotropies is of particular interest in current cosmology, as it is a sensitive parameter in models of inflation. Most inflationary cosmology models predict a nearly flat spectral dependence of the power spectrum. Measurements of the CMB power spectrum over a wide range of multipoles, or comparisons of low $\ell$ to high $\ell$ measurements, provide information on both the spectral tilt, and any possible change of the spectral tilt with multipole, also called the running of the spectral index.

1.3 Secondary Effects

Recent efforts towards measuring the higher multipoles of the CMB have begun to probe the realm of secondary effects on the CMB. These effects are generated by interactions of the CMB photons with matter during its otherwise free flight between the surface of last scattering and our observations. The primary causes of secondary anisotropies are interactions with galaxy clusters and large-scale gravitational potentials.

When CMB photons interact with large-scale gravitational potentials, their trajectories are bent by gravitational lensing. Specifically, the lensing alters the measured location of anisotropies by a deflection angle, $d$. The observed CMB anisotropies are affected by these deflections, but there is no method of directly observing the anisotropies without the deflections in order to determine their magnitudes and locations. Instead, the lensing signal is measured by looking for correlations between temperature multipole moments with different values of $\ell$ or $m$ [36]. Measurements of CMB lensing at high-multipoles are likely to provide much better constraints on dark energy than achievable with current measurements [37].

Galaxy clusters interact with CMB photons through the thermal and kinetic Sunyaev-Zel'dovich (SZ) effects. Galaxy clusters are the most massive virialized structures in
1.3 Secondary Effects

The universe once they have stabilized into dynamical equilibrium. Their high mass \( \geq 10^{14} M_{\odot} \) makes them an ideal probe of both the growth of density perturbations and the evolution of the scale of physical volumes as functions of redshift. The average galaxy cluster angular size is approximately \( 2' \), and thus CMB observations must have resolution better than this to begin resolving maps of the thermal SZ effect.

Galaxy clusters appear distinctly in CMB maps through the thermal Sunyaev-Zel'dovich effect (tSZ). As the relatively low-energy CMB photons pass through a galaxy cluster, they interact with hot electrons. The interaction occurs through inverse Compton scattering. The scattering boosts the average photon’s energy as opposed to decreasing it due to the combination of the higher energy electrons interacting with the low-energy CMB photons. The net effect of the tSZ on the CMB photons is a change in the intensity of the photons transmitted through the cluster at a given wavelength. The intensity of the CMB is decreased below and increased above a null point of \( \sim 217 \) GHz. This distortion of the intensity is easily distinguished from temperature fluctuations if multiple frequencies are sampled. Specifically, the maximum decrement of the CMB intensity occurs at approximately \( 140 \) GHz and the maximum increment occurs at roughly \( 320 \) GHz. This distortion of the blackbody spectrum is independent of redshift, which allows clusters to be detected from any distance as long as they are massive enough.

Measurements of the tSZ signal for clusters impact cosmology in several ways. By cataloging many clusters over a wide range of redshift, measurements of the variations in cluster properties as functions of redshift can be made. The variation of these cluster properties with redshift can be used to constrain the equation of state of dark energy (the ratio of the pressure to density), the amplitude of primordial fluctuations, the density of matter in the universe and other cosmological results [13].

Using combined observations of the tSZ cluster signal with X-ray observations, other effects may be explored. First, using the surface brightness of the X-ray signal, the measured tSZ signal, and a measured redshift for the cluster, a physical size for a cluster may be computed. If the angular size of the cluster can be measured, then the angular-
Cosmology, the CMB, and the Atacama Cosmology Telescope

diameter distance to the cluster may be computed as the ratio of the physical to angular sizes. This distance provides constraints on the age of the universe and the density of matter [6]. Also using X-ray complimentary observations, the gas mass fraction of clusters may be measured. When measured over a distribution of redshifts, the gas mass fractions will provide additional constraints on the evolution of the equation of state of dark energy [13]. Another important use of supplementary observations of clusters is to determine the mass calibration for the tSZ effect.

When the CMB photons pass through a galaxy cluster with a peculiar velocity relative to the CMB, the Compton scattering produces an additional change in intensity known as the kinematic SZ (kSZ) effect. This effect is a Doppler effect. For clusters moving towards (away from) an observer, also in the reference frame of the CMB, and along the line of site, the interaction with the cluster electrons increases (decreases) the intensity of the radiation [63]. The maximum intensity of the kSZ signal is at $\sim 218$ GHz [22]. This is fortunate, as it corresponds to the null of the tSZ signal, and so may not be confused with it. Despite this, current observations have yet to determine velocities of individual galaxy clusters using the kSZ effect [39, 10], primarily because the signal is small. The kSZ effect appears in maps of the CMB with the same signature as primary temperature fluctuations. Because of this, observed fluctuations require special treatment if one hopes to separate the effect from the primary anisotropies [22].

1.4 Millimeter Astronomy

The relatively recent increase of interest in cosmology has caused a blossoming of new opportunities in millimeter-wave astronomy from sub-millimeter to near centimeter wavelengths. Many new instruments are being constructed for both ground-based and space-based observations of this previously poorly explored region of frequency space at small angular resolutions. The recent group of instruments, beginning with WMAP and eventually leading up to the PLANCK and Atacama Large Millimeter Array (ALMA) exper-
1.5 The ACT Experiment

...iments and beyond, are probing smaller and smaller angular scales in order to study the CMB at high multipoles [1, 2]. These instruments, while certainly capable of detailing new discoveries in the field of cosmology, are also providing a new window on the millimeter universe.

One use for these new high-resolution observations is the analysis of millimeter point sources. Point sources in the millimeter frequency range can now be studied with much higher positional accuracy than previously attainable in these wavebands. Many of these objects consist of galaxies that are observed as point sources ‘contaminating’ the measured CMB maps. While these sources do contaminate CMB power spectrum measurements, studies of their properties with these newer instruments have already begun to reveal a wealth of other astronomical information. Chapter 5 will describe the opportunities for research on these point sources that are becoming available, along with some methods and results of analysis concerning the point sources observed in preliminary ACT data maps and simulations.

1.5 The ACT Experiment

The primary purpose of the ACT project is to observe anisotropies of the CMB at arcminute scales. The experiment is designed to observe both the high-multipole primary anisotropies and secondary effects of the CMB. The telescope design and location, camera design, observation pattern, and the data-analysis design have all been guided with these goals in mind. The telescope has a 6 m primary mirror and currently one observing instrument called the Millimeter Bolometer Array Camera. This camera actually consists of three cameras with observing frequencies of 148 GHz, 218 GHz, and 277 GHz chosen to cover the decrement, null and increment of the tSZ signal. Each camera has its own set of optics and an individual detector array. The detector arrays and data recorded by them are often referred to as AR1, AR2, and AR3. Thus far, the experiment has been operational for two full observing seasons, and part of a third season. The 2007 season...
spanned the period of November 15 to December 16, 2007. The 2008 season, which is the focus of this thesis, covered the period from August through December, 2008. A new observing season, officially to be called the 2009 season, has begun as of April, 2009, and observations are expected to continue through December, 2009.

The first ACT data results have recently been published. The ACT experiment has successfully observed the tSZ effect of several galaxy clusters using its ability to produce arcminute resolution images of the CMB. Thus far, eight clusters have been observed that were previously detected. The measured tSZ signatures, positions, and small-scale maps of these clusters have been presented in Hincks et al. [31].

Many aspects of the ACT experiment design and the data analysis are specifically designed to reduce noise contamination, so that the small anisotropies of the CMB may be clearly identified. To measure the CMB anisotropies, an instrument must have a very precise temperature sensitivity. For the anisotropies being targeted by the ACT experiment, the instrument must have a temperature sensitivity as small as 2.5 $\mu$K [49]. This sensitivity is determined by calculating the arcminute scale RMS of the temperature anisotropies of the CMB.

The ACT telescope is located on Cerro Toco, a mountain in Chile, near San Pedro de Atacama. This site was chosen to minimize overall atmospheric loading, fluctuations and absorption of millimeter radiation, all of which are challenges faced by ground-based instruments. This location provides an altitude of 5200 m and an extremely dry environment thanks to the surrounding Atacama Desert. The environment is sufficiently dry such that during all CMB observations in the 2008 season, the median Precipitable Water Vapor (PWV) was only 0.57 mm. For a comparison, the PWV for the Green Bank Telescope in West Virginia for August 13, 2009 was approximately 30 mm [48]. For the ACT experiment, these measurements of PWV are recorded by a weather station at the nearby APEX experiment [77]. The weather station uses a “tipping” radiometer to measure the intensity of radiation emitted by the atmosphere at different angles from zenith, and hence through different thicknesses of atmosphere.
1.5 The ACT Experiment

A second important design choice for reducing atmospheric noise contamination is the method by which the atmospheric signal is separated from the sky (astronomical) signal. For the ACT experiment, this is accomplished through a scanning motion of the entire telescope. The ACT telescope scans in azimuth during CMB and planet observations in order to place the sky signal above the low frequency atmospheric contamination signal. For the 2008 season, this scanning rate was approximately 1 deg/s for the majority of CMB observations. The upper limit for the rate of the scan is set by both the strength of the telescope structure and the time constants of the camera detectors. This scanning pattern also provides for coverage of the sky in the ACT observing regions.

1.5.1 ACT Observations

The 2008 season ACT observations covered two primary regions of sky. The primary observing region is a 5° wide Southern strip. The 2008 148 GHz camera Southern observations are centered at approximately −55° declination. The secondary observation region is centered near the celestial equator. Figure 1.3 shows the sky coverage and estimated noise levels for the 2008 season. Observations are conducted by pointing the telescope to 50.5° elevation and scanning in azimuth about the desired region. The sky rotates through the scan, and the first half of each night’s observations target the rising, east portion of the region. The second half of each observing night is focused on the west, setting portion of the observing region. The full range of right ascension observed is set by these guidelines and the length of the season. For the analyses presented in this thesis, the equatorial data were not considered, as map processing efforts are currently focused on the Southern observation strip.

Both of these regions were chosen to lie far from the galactic plane, so as to minimize dust foreground contamination. Parts of the Southern observing region are also currently being studied by the South Pole Telescope (SPT), with observation frequencies of 95 GHz, 150 GHz, and 225 GHz [72]. Thanks to the overlapping regions and frequency bands...
of the two telescopes, many observational results will be able to be cross-verified. In particular, the first galaxy cluster observations by the ACT Telescope have been presented by A. Hincks in Hincks et al. [31], and thanks to the SPT coverage, the cluster candidates observed by both instruments have been compared in the results presented.

1.6 Outline of Thesis

The remainder of this thesis describes the ACT experiment in greater detail. Chapter 2 describes in greater detail the systems and design of the telescope and supporting infrastructure in Chile, with a focus on the systems relevant to the information presented in Chapters 3, 4, and 5. Chapter 3 provides a detailed description of preliminary tests of the cold readout electronics for the ACT cameras. Chapter 3 continues with a description of improvements in these testing procedures over time. Finally, Chapter 3 briefly describes the current status of the cold readout electronics operating in Chile, and concludes with some aggregate results from the testing of the cold electronics. Chapter 4 describes the development, tests, and applications of the 2008 season calibration for the ACT map-making pipeline. Finally, Chapter 5 discusses point sources observed at millimeter frequencies in detail, with a focus on the analysis of ACT foreground sources.
1.6 Outline of Thesis
Chapter 2

The ACT Telescope Systems

Overview

The ACT telescope is best described by dividing its systems into four primary components, and many secondary supporting components. Each of these systems has been described by other authors of the ACT collaboration in detail, but a brief overview of several of the system components will be presented in this chapter. The focus of the telescope systems descriptions presented in this chapter will be to elucidate the discussions presented in Chapters 3, 4, and 5.

The first primary component is the main telescope infrastructure, including the primary and secondary mirrors, the receiver cabin structure, and the robotic system that controls the telescope motion. Thornton et al. [78], Hincks [30], Fowler et al. [23] and Hincks et al. [32] provide detailed descriptions of the systems comprising this first component. The second primary component is the Millimeter Bolometer Array Camera (MBAC), which contains the focusing, filtering and other small optics, the detectors, the camera cryogenics, and the cold readout electronics for the three cameras. Swetz et al. [74], Swetz [73], Niemack [54], Fowler et al. [23] and Thornton et al. [78] describe these components in detail. The third component is the warm readout electronics and systems control electronics. The
2.1 Telescope Infrastructure

readout electronics mainly consist of the Multichannel Electronics (MCE) units developed by Mark Halpern’s research group at the University of British Columbia (UBC). Battistelli et al. [9] and Switzer et al. [76] cover these devices in detail. A group of electronics also supports the control and operations of the MBAC and MCEs from within the receiver cabin of the telescope. The fourth component consists of the computer infrastructure system that is used to collect and analyze data from the readout electronics, and is best described in Switzer et al. [76].

The process of constructing the ACT instrument has required a great deal of energy and time from a large number of dedicated individuals within and supporting the collaboration. Throughout this description of telescope systems, special notes will be made for a few of the most challenging aspects of the instrument construction. The most difficult challenges are, as expected, generated by our attempt to extend the boundaries of current astronomical knowledge through the use of new technologies. The instrument seeks to provide a new window into millimeter astronomy and CMB cosmology through its unique choice of three wavebands and arcminute resolution and ground-based observing capabilities. The three ACT cameras were also the first to use kilopixel arrays of pop-up transition-edge sensor superconducting detector bolometers. These are just two of the most prominent features that the ACT experiment has been the first to attempt, among many others. The rewards for overcoming the challenges of construction are an instrument that provides a tremendous amount of high-resolution data from which we are able to reconstruct detailed maps of the microwave sky.

2.1 Telescope Infrastructure

The ACT telescope consists of a 6 m primary arranged in an off-axis Gregorian optical design [44]. This design allows radiation to be received by the primary without interference from the secondary mirror, as shown in Figures 2.1 and 2.2. The telescope is surrounded by a ground screen which prevents pickup of ground radiation in the telescope side-lobes.
The ACT Telescope Systems Overview

and encompasses the entire telescope system. The primary telescope optics focus radi-
ation onto the windows of the MBAC, which is contained in a closed, climate-controlled
portion of the telescope known as the receiver cabin.

Before further describing the optics of the telescope, special note should be made
of the choices in other infrastructure components that allow for relatively fast scanning
motion of the telescope. The scanning rate of telescope was designed to be as high as
2 deg/s, with a maximum acceleration of 10 deg/s. The telescope mirror support structure
was built using a rigid aluminum design to accommodate these relatively large speed and
acceleration requirements, while preventing undesired resonances or failures. The tele-
scope motion is achieved through a robotic motion system designed and built by KUKA
robotics with programming maintained by Adam Hincks [32, 30]. The entire robotic sys-
tem, from the control software and programming, through to the grease application sys-
tem for the main azimuth gear, has proved to be one of the greatest challenges in the
construction and operations of the telescope. The motors and gears in this control system
are subjected to a tremendous amount of wear, and have to be thoroughly greased and
frequently maintained. The end of the 2008 season was, in fact, set by one of the ele-
vation motors failing. Frequently throughout the commissioning and observations of the
instrument, the greasing control system for the main azimuth bearing has literally frozen
due to the harsh climate of Cerro Toco. Also throughout the life of the telescope thus
far, the control software and firmware systems have exhibited many bugs and faults that
require the attention of a knowledgeable collaboration member before observations may
continue. All of these difficulties have been overcome through the hard work of many indi-
viduals, but have had an impact on the total amount of observation time achieved by the
experiment thus far. The benefit of having full-telescope scanning capabilities to reduce
atmospheric contamination of our signal band, of course, still outweighs these difficulties.

The primary and secondary mirrors of the telescope are composed of 71 and 11 alu-
minate segments, respectively. These segments (or panels) are attached to the main alu-
minate backup structure (BUS) seen in 2.1. Each panel for the primary mirror is attached
2.1 Telescope Infrastructure

Figure 2.1: A photograph of the ACT telescope structure at the Port Coquitlam construction site. The primary dish is in place on the inside of the right half of the structure. The mirrors and backup structures that support them are composed of aluminum to provide rigid support. The secondary dish is not yet installed in this photograph, but would be housed in the smaller, left half of the structure. The receiver cabin is located below the secondary mount, and houses the camera very near to the axis of rotation of the telescope.
Figure 2.2: Cross-Sectional diagram of the ACT telescope. Incoming light is focused onto the ACT detector arrays through the combination of the primary mirror, secondary mirror, and series of lenses that compose the optics tubes in the MBAC. See Figure 2.3 for a detailed depiction of the MBAC optics tubes. Image Credit: Dan Swetz
2.1 Telescope Infrastructure

through four adjustable mounting points that allow the mirror surface to be adjusted. In or-
der to produce a uniform mirror surface, a series of panel alignments has been conducted each year before observations. This has proven to be one of the most time consuming and laborious tasks of the telescope construction, deployment and maintenance. Care-
ful measurements of the mirror panels are taken using a laser tracker system, and the measurements are analyzed to determine deviations from the optimal panel alignments as determined by the optical design. A series of corrections to the individual panel ad-
justments is made based on these calculations, and new measurements are taken in an iterative process to reduce the total surface deviations. The final surface deviations were reduced to 27 and 9 µm through this process.

2.1.1 Measurements of the Telescope Beam

The telescope mirrors, combined with the series of lenses that compose the optics tubes in the MBAC, are designed to produce a telescope beam with a resolution on the order of 1’. Very roughly, one may use the primary mirror diameter, D, and the observing wavelength, λ to find an approximation to the resolution, θ = θ ∼ 1.22 λ/D. Using the middle ACT wavelength of 218 GHz, and 6 m primary mirror diameter, this is the desired θ ∼ 1’.

To properly understand the scientific results of the experiment, a full analysis of the instrument beam is needed for each of the instrument cameras. By analyzing maps made of point source observations, a model for the telescope beam has been produced by A. Hincks. The beam parameters for each of the 148 GHz, 218 GHz, and 277 GHz cameras are included in Table 2.1, modified from the results presented in Hincks et al. [31]. These measurements derive the telescope beam properties from point-spread function fits to maps of Saturn observations during the 2008 season. The best fits to the measured beams are elliptical. For the point source measurements described in Chapter 5, the larger of the two measured FWHM beam values was used.
Table 2.1. Summary of Beam Parameters for 2008 Season Observations

<table>
<thead>
<tr>
<th></th>
<th>148 GHz</th>
<th>218 GHz</th>
<th>277 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Map Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># TODs</td>
<td>16</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td><strong>Beam Centers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major FWHM (')</td>
<td>1.406 ± 0.003</td>
<td>1.006 ± 0.01</td>
<td>0.94 ± 0.02</td>
</tr>
<tr>
<td>Minor FWHM (')</td>
<td>1.344 ± 0.002</td>
<td>1.001 ± 0.003</td>
<td>0.88 ± 0.02</td>
</tr>
<tr>
<td>Axis Angle (°)</td>
<td>62 ± 2</td>
<td>137 ± 9</td>
<td>98 ± 13</td>
</tr>
<tr>
<td><strong>Solid Angles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid Angle (nsr)</td>
<td>218.2 ± 4</td>
<td>118.2 ± 3</td>
<td>104.2 ± 6</td>
</tr>
</tbody>
</table>

Note. — The table of ACT beam parameters modified from that presented in Hincks et al. [31]. The values are derived from processing maps of planet observations, with the details indicated under the Map Properties sub-heading. The solid angles and beam measurements are all derived from fits to the point-spread function in combined Saturn maps, as conducted by A. Hincks. For analyses in this thesis, particularly in Chapter 5, the Major FWHM values for beam parameters were used.
2.2 The MBAC

The MBAC contains all of the optics, detectors, electronics and associated cryogenics necessary for measuring the $\mu$K temperature fluctuations of the CMB. After reflection by the primary mirrors, incident radiation first reaches three separate windows that lead to the optics tubes contained within the MBAC.

2.2.1 ACT Cold Optics and Bandpasses

Each optics tube is designed for one of the three frequency bands of interest in the experiment. These optics tubes consist of stages of progressively cooled, high-purity silicon lenses, as described in Swetz et al. [74]. Figure 2.3 displays a model of the full set of MBAC optics from the windows to the detector arrays. Most importantly for the work described herein, the optics tubes contain band-pass filters, which define the frequencies of observation for the three arrays. D. Marsden and the group at University of Pennsylvania have conducted studies of the MBAC optics in order to accurately measure the bandwidth of each of the instrument cameras. These studies use a combination of the measurements from the filter manufacturers (Cardiff) and Fourier-Transform Spectrometer (FTS) measurement to determine the band centers and bandwidths [50]. Table 2.2 includes the relevant results for the three optics tubes.

2.2.2 Detector Arrays

For each band, the cold optics focus the radiation onto a 32 by 32 array of Transition Edge Sensor (TES) bolometers that are held at temperatures below 400 mK. The detectors are connected to a system of multiplexing DC superconducting quantum interference devices (SQUIDs), which are also contained within the camera. Each of the stages internal to the MBAC is cooled using one helium-3 and two helium-4 sorption refrigerators that are cooled by commercially purchased pulse-tube cryogenic refrigerators. One helium-4 sorption refrigerator is used for cooling all of the optics internal to the MBAC. The other is
Figure 2.3: A model of the full optics in the MBAC. Each of the three detector arrays has its own window, set of stages of progressively cooled optics, and filters. The low-pass (LP) and infrared (IR) blocking filters are also indicated. Image Credit: Dan Swetz and Robert Thornton.
Table 2.2. Summary of Band Pass Measurements for ACT Cold Optics

<table>
<thead>
<tr>
<th></th>
<th>148 GHz</th>
<th>218 GHz</th>
<th>277 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band Center</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiff Measurement (GHz)</td>
<td>146.85</td>
<td>217.29</td>
<td>273.50</td>
</tr>
<tr>
<td>UPenn ±50 GHz Measurement (GHz)</td>
<td>149.2</td>
<td>219.7</td>
<td>277.4</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPenn ±50 GHz Measurement (GHz)</td>
<td>18.4</td>
<td>17.0</td>
<td>20.9</td>
</tr>
</tbody>
</table>

Note. — Measurements of the ACT optical filter band centers and band-passes. D. Marsden and the group at University of Pennsylvania used a combination of the measurements from the filter manufacturers (Cardiff) and Fourier-Transform Spectrometer (FTS) measurements to accurately measure the bandwidth of each of the instrument cameras [50]. The band centers around which the measurements were taken were 148, 219, and 277 GHz [50].
used to cool the helium-3 sorption refrigerator, which is connected to the thermal bath for the detector arrays and associated electronics. The details of the present MBAC cooling design and performance are presented in Swetz et al. [74].

The detectors consist of a pop-up bolometer design and are produced at NASA Goddard’s Detector Development Laboratory. The pop-up bolometers each include an absorber and the TES thermometer. Thirty-two such bolometers are arranged in a single chip that is called a “column” within the collaboration. These chips are designed so that the supporting legs connected to the bolometers are bent to pop up the detectors. The legs are perpendicular to the square-millimeter absorbing areas of the bolometers. These legs carry the wiring that allow the TES devices to be read out. By designing the detectors in this manner, adjacent columns of bolometers could be placed nearly directly together to form the full detector arrays. The design also makes the detectors fragile, and the folding, array assembly, and alignment of the columns all require great care. A photograph of a completed array is shown in Figure 2.4.

The bolometers are linked through their thin legs to a thermal bath. This bath is servoed to a constant temperature of about 330 mK using heaters and the cooling provided by the helium-3 sorption refrigerator. This connection to a cold bath is necessary to remove excess heat and help hold the TES portions of the detectors at their superconducting transitions. The superconducting transition provides the TES detectors with a large resistance gradient, producing the sensitivity needed to measure the low energy photons of the CMB. The detectors are voltage biased through a nightly rebiasing routine onto their superconducting transitions. This biasing routine is described in detail in Battistelli et al. [8]. The detectors are more carefully held at their superconducting transitions through negative electrothermal feedback, as will be further described in Section 4.1. The actual detection of photons occurs as an increase in temperature of the sensors. This alters their effective resistance substantially due to the large resistance gradient, and the change in resistance is recorded as a change in current through the TES circuit. The full thermal model and initial tests of these detectors are presented in Zhao et al. [89].
2.2 The MBAC

Figure 2.4: A photograph of the completed 218 GHz detector array. The detector “columns” (or sets of 32 physically connected devices per fabricated chip) are stacked to form rows in the array. The pop-up bolometer faces are facing forward in the photograph, with the remaining portions of the chip bent behind and attached to the detector circuit electronics. The bolometers are extremely fragile, making failures during assembly probable. Despite this, very few detectors are lost due to mechanical failure during the assembly process, as can be seen.
2.2.3 Detector Circuitry

A more complete description of the detector biasing and readout circuits, including their particular implementation in the ACT observing seasons, is important for understanding the calibration work to be presented in Chapter 4. The detector biasing circuit is shown in Figure 2.2.3. As this figure demonstrates, the TES detectors \( R_{\text{TES}} \) of order \( 5 - 10 \, \text{m} \Omega \) are biased in a parallel circuit with a small \( R_{\text{sh}} \sim 0.7 - 0.8 \, \text{m} \Omega \) shunt resistor, which allows for a voltage biasing configuration. These shunt resistors are fabricated by Goddard Space Flight Center (GSFC) on chips of 32 resistors, which are paired with columns (32 by 1 linear arrays) of TES detectors. Each individual chip was quality tested at Princeton through a 4-wire resistance measurement in a liquid Helium bath. In conjunction with the tests described in Chapter 3, the resistance of the combined series of 32 shunts on each chip was recorded at input currents ranging from 0.1 to 5 mA. Every chip used in the final camera electronics passed this screening test with a recorded resistance that fell within an acceptable range of series resistance values. Additionally, among the chips tested, the shunt resistors were chosen to match the operating resistance of the TES chips where possible. In particular, chips with higher resistances were paired with the detectors comprising the 277 GHz camera array, as these had higher operating resistances on average than the other two arrays.

Each detector array is biased through two or three separate biasing lines. These lines connect to different groups of TES columns. Each column of 1 by 32 detectors is fabricated as one unit or chip. Thanks to their common fabrications, each set of 32 detectors is typically characterized by a relatively consistent bias voltage required to operate the detector at its transition. The columns that are used in the arrays are grouped according to their superconducting transition properties. These properties are measured in a TES column screening phase that is conducted in a device known as the Super-Rapid Dip Probe (SRDP). Marriage [49], Niemack [54], and Zhao et al. [89] describe these tests in much greater detail. Using these measurements, chips with the most similar properties
2.2 The MBAC

Figure 2.5: The detector biasing circuit model. The detectors are arranged in a parallel circuit with a small shunt resistance, allowing for voltage biasing. The bias voltage is applied by the MCE electronics. The readout SQUID adjacent to the inductor is the first portion of the cold readout electronics.

are arranged to be adjacent within the detector arrays. Thanks to the similar transition properties for the 148 GHz and 218 GHz detector arrays, the final arrays of 32 chips may be biased by only a few voltages.

This bias grouping is done using a combination of distinct biasing voltage lines and added resistances in the cold wiring. The voltage lines for season 2008 are shown in Figure 2.6. For the 277 GHz camera, the three different voltages applied by the warm electronics are insufficient to properly bias all of the detector columns. Due to fabrication difficulties, this array has a greater spread in transition properties. To better accommodate this spread, additional resistances were added in the cold electronics, where the bias lines are split before connecting to the detectors. These additional resistances allow columns that are biased by the same warm bias line to receive different bias currents. Table 2.3 indicates the division of the columns according to the different total resistances between the warm electronics and the detectors.

The detectors are biased in series with inductors, so that as an increase in photon loading creates an increase in resistance, a corresponding decrease in the magnetic flux
Figure 2.6: Bias line numbering for the three MBAC detector arrays. The colors represent the bias lines as follows: dark blue = line 1, light blue = line 1 split, cyan = line 2, yellowish green = line 2 split, orange = line 3. The warm electronics bias each line independently. The groups of detectors that share a bias line have similar transition properties, allowing for a common bias. Note that for the 277 GHz camera, the bias lines are further divided by using different resistors after the wires split in the cold portion of the detector bias lines. This allows a different, but directly proportional current to reach these sets of detector circuits. Table 2.3 describes these splits in more detail.
### 2.2 The MBAC

#### Table 2.3. 277 GHz Camera Detector Bias Line Resistances

<table>
<thead>
<tr>
<th>Columns</th>
<th>Effective Bias Resistance (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:3</td>
<td>1337.6</td>
</tr>
<tr>
<td>4:7</td>
<td>1218.6</td>
</tr>
<tr>
<td>8:12</td>
<td>1337.6</td>
</tr>
<tr>
<td>13:15</td>
<td>1218.6</td>
</tr>
<tr>
<td>16:19</td>
<td>1862.6</td>
</tr>
<tr>
<td>20:23</td>
<td>969.6</td>
</tr>
<tr>
<td>24:31</td>
<td>620.6</td>
</tr>
</tbody>
</table>

Note. — Bias line divisions for the 277 GHz camera detector array for 2008. These resistances are the total effective resistance from the MCE voltage source to the split of the parallel circuit containing the shunt resistor and the TES. The resistances are measured using a cold continuity check.
The ACT Telescope Systems Overview

is generated by the inductors. These inductors are linked to the stage 1 (S1) SQUID cold readout electronics, which are part of the multiplexing chip (mux) assemblies. This begins the chain of cold electronics that provide the readout of our telescope signals.

2.2.4 Cold Readout Electronics

The primary cold readout electronics consist of mux chips and series array (SA) readout modules. These readout systems are all composed of SQUIDs, because SQUIDs allow for the extremely sensitive measurements of changes in magnetic flux that are needed in order to discern the small fluctuations caused by photon loading on the detectors. A SQUID device consists of two relatively large superconducting elements that form a loop and are separated by insulators or constrictions on opposite sides of the loop. The first unique property of SQUIDs is that they respond to changes in magnetic flux through them as (from Tinkham [79]):

\[ I_m = 2 * I_c * | \cos(\pi * \phi / \phi_0) |, \]  

(2.1)

where \( I_m \) is the maximum supercurrent of the SQUID, \( I_c \) is the critical current of one Josephson junction, \( \phi \) is the flux applied through the loop, and \( \phi_0 \) is the standard flux quantum, \( \phi_0 = h/2e \). This leads to a periodic current response to flux input as indicated in Figure 2.7. The second important formula governing the SQUIDs is their voltage response to magnetic flux (from Tinkham [79]):

\[ V = \left( R/2 \right) * [ I^2 - (2I_c \cos(\pi * \phi / \phi_0))^2 ]^{1/2}. \]  

(2.2)

Here \( R \) is the resistance of one of the the junctions, and \( I \) is the current applied to the SQUID. The response of the SQUIDs when the flux term is greater than the bias current term is such that they are still in a fully superconducting state with no output voltage. This formula is quite important in understanding how the ACT electronics work, as all the SQUIDs respond to changes in flux by changing their effective resistance in the circuit, and
2.2 The MBAC

Figure 2.7: Normalized plots of SQUID V-φ curves for underbiasing, optimal biasing, and overbiasing. The tiny peaks at odd half $\phi_0$ values are the underbiased response. The large peaks are the optimal biasing response at a bias current of $I_{c\text{Max}} = 2\times I_c$. The smaller curve above the first two is the overbiased response.

This formula indicates how that change occurs. When a SQUID is described as voltage biased, it means that there is a small parallel resistance to the SQUID that holds the voltage constant across the SQUID, and so the current that passes through the SQUID is the primary circuit parameter affected by a change in flux. If a SQUID is current biased, however, the current can be applied directly through the SQUID, and changes in output voltage can be measured directly as suggested by Equation 2.2. Another important feature to note in this case is the reduced response to flux change that occurs as the current becomes larger than $I_{c\text{Max}} = 2\times I_c$. This is demonstrated by the plots in Figure 2.7. These plots represent the V-φ curves of the current biased SQUID, which are named after the SQUID's voltage response to flux input.

In the readout electronics for the detectors, three stages of SQUIDs are used to handle the large number of detectors in the arrays in a manageable way. In order to read out the signal from the TES array directly, each pixel would require several wires to carry bias, output and feedback voltages to and from the SQUID. These wires would need to lead to external electronics held at room temperature, and this would put a large thermal load on the cold electronics. To avoid this, we couple the inductors from each of 32 detectors in one column of an array to one of 32 matching stage one (S1) SQUIDs. These SQUIDs
are all contained on one device called a multiplexer (mux) chip. The mux chips include one additional SQUID, called the dark SQUID, with no input for testing and noise analysis purposes both in the laboratory and in the field. One of these mux chips is shown in Figure 2.8.

Of these 33 (S1) SQUIDs, the bias current is only turned on to \( \approx I_{c\text{Max}} \) for one at a time, and they are cycled through at a high rate (\( \sim 15 \text{ kHz} \)). The cycling allows the outputs of 32 of the S1 SQUIDs on a mux chip to be coupled to a single loop leading to the following SQUID stage (see 2.9). This cycling is why the readout electronics are described
2.2 The MBAC

as multiplexing. This time-domain multiplexing allows a large amount of information from multiple sources to be read out through one readout device with far fewer needed wires.

These S1 SQUIDs operate in a regime between voltage and current biasing and are configured as shown in Figure 2.9. The SQUIDs have an operating resistance range (dynamic resistance) of about 2 to 4 $\Omega$, and they are in parallel with 1 $\Omega$ resistors that are in series with inductors. These SQUIDs are not purely voltage biased because this would mean that the current would change little in the parallel loop. They are also not purely current biased, as this would force the parallel resistance to be large, and consequently reduce how sensitively the current changes in the parallel circuit. By intermediately biasing these SQUIDs, the current in the parallel loop of their circuits is sensitively affected by the changing input flux from the TESes.

In addition to reducing wiring demands, the three stages also serve to amplify the signals before they are read out by the relatively noisy warm electronics. The inductors in the parallel loops to the first stage SQUIDs are all connected in series to an extra inductor that generates a magnetic flux for the second stage (S2) SQUID on each mux chip to measure. This stage is voltage biased, by having a 0.1 $\Omega$ resistor in parallel with the bias line. This allows for small changes in flux through the SQUID to produce large changes in current. This current runs to a Series Array (SA) module, which contains a series of identical inductors that are each coupled into a SQUID. Each of these third stage SQUIDs is biased in series. With the application of an identical flux to each, their responses are thus summed and they serve to amplify the signal by a factor of about 100 [42]. This final amplification generates a signal that is both strong enough and with low enough noise to allow for amplification by warm electronics without dwarfing the signal in added noise. A schematic of the full multiplexing readout circuit including these SA modules and the TES connections is shown in Figure 2.9. This schematic indicates both the multiple stages of SQUIDS and the multiplexing connection layout.

This complex series of electronics to read out the signal from the TESes has one final component that is vital to making the entire system work. Ideally, all the SQUIDs should be
The ACT Telescope Systems Overview

Figure 2.9: Schematic layout of two columns of multiplexed detector readouts. $V_{er} = \text{differential voltage measured.}$ $V_{fb} = \text{voltage applied to return the SQUID to its operating point on its } V - \phi\text{ curve.}$ The feedback voltage is applied in response to the measured error voltage. The final measured signal voltage in our data stream is the feedback voltage. Each column of detectors is readout by one mux chip containing one stage 1 (S1) SQUID per detector, and one additional S1 SQUID not connected to any detector. All S1 SQUIDs on a chip are coupled to the single stage 2 (S2) SQUID on the chip. This SQUID output is connected to the Series Array (SA) SQUID readout, which leads to the warm readout electronics. (Figure courtesy of R. Doriese)
2.3 Receiver Cabin Electronics

operated such that an increase in flux generates a positive (or negative, but one sign must be chosen) change in voltage output. Additionally, the optimal setting for the SQUID inputs is such that the response to flux changes is linear in voltage output. Given the periodicity and trigonometric curvature of the response curves, this can only be approximated by maintaining a very small range of input flux values where the curve is both relatively flat, and not near a turnaround point. This requires that there be a flux feedback loop and inductor associated with every SQUID in the system. This feedback loop provides an amount of flux to oppose changes in flux through the SQUID loops due to any sources. In particular, the signal that is to be measured from the TESes is the primary source of flux that must be cancelled. The change in voltage output is measured to determine the feedback, and is known as the error signal. Despite this, the feedback signal is actually the signal recorded and stored during our normal operations. The feedback current provides an integrated measurement of all the current adjustments required to cancel the changing flux (as a consequence of changing TES power) measured by the SQUIDs. The error signal is differential in nature. It will only record the small changes in output current from the SQUID series array that occur before the feedback is applied. These changes in flux from the lock point are kept very small through fast multiplexing feedback and automated PI loop locking handled by the MCEs. Figure 2.9 indicates these two signals as connected to the MCE readout electronics.

2.3 Receiver Cabin Electronics

The receiver cabin, in addition to housing the MBAC contains the warm readout and control electronics for the detectors, SQUIDs, cooling and heating elements. The heating and cooling readout and control devices are part of the system known as the housekeeping support. In the receiver cabin, these include a thermometry preamplification and heater control electronics systems and a synchronization signal driver. This latter is known as the Sync Box, and produces an effective “heartbeat” for all of the housekeeping and
data readout systems, which allow for later recombination of data taken concurrently. One important stage of the ACT experiment’s development was learning that all of the devices and interconnecting wiring in the warm readout system were very sensitive to external noise. To prevent this pickup, a significant effort was made to bundle and shield all wires and provide RF noise protection to all warm electronics in the receiver cabin. This effort, appears to qualitatively have helped improve the noise level of data taken during the 2008 season, although the direct impact was not studied.

2.3.1 The MCE Readout System

The warm electronics that control and read out the detector and SQUID systems are known as the MCE devices, and have been developed by the University of British Columbia (UBC) [9], as previously noted. The electronics serve to control all of the direct application of bias currents to the detectors and SQUID readout systems. These devices are specially designed to operate on a 50 MHz clock to control the multiplexing of the S1 biasing, readout, and feedback voltage control. This control uses a PI loop to determine the appropriate feedback voltage based on samples of previous signal voltages (the error signal or voltage). Thanks to the sophisticated firmware controlling the MCEs, all of the biasing and readout tasks may be predefined and stored, and acquisitions are simply queued by a connected computer system.

2.3.2 Data Modes in the MCE

The MCEs are capable of reporting any combination of the S1 feedback and S1 error voltage signals, as well as other derivative quantities of these readouts. The MCEs temporarily store both the feedback and error signals for each detector at every sample internally, and the signals are internally time-domain filtered. This filtering reduces the data rate from the internal sampling rate of 15.15 kHz down to our measurement sample rate of approximately 400 Hz. This filtering is done through a low-pass 4-pole Butterworth
2.3 Receiver Cabin Electronics

filter for ordinary CMB observing data. For other readout modes, the signal is simply sampled on every 38th internally recorded data point for each detector. The 400 Hz readout rate is sufficiently high to reduce aliasing of high frequency noise into the ACT primary signal band of $\sim 0 - 200\,\text{Hz}$. Additionally, the MCEs are capable of reporting raw 50 MHz data, which is occasionally used for testing.

The different options for reporting data to the control and storage computer systems are called data modes. In all data modes, the signal is reported in digital to analog converter (DAC) units. For the ACT observations and system tests, five of these modes have been primarily used. In the 2007 observing season, data mode 2 was used for recording primary observations. This data mode includes signed, Butterworth filtered S1 feedback data. For the 2008 observing season, several new data modes were created to account for the SQUID flux jumps. Both data modes 9 and 10 include a combination of Butterworth filtered feedback data and a count of the number of flux jumps incurred in the SQUIDs, which allows for easy recreation of the total integrated change in flux throughout a file.

Finally, data modes 1 and 4 are used specifically for daily system tests, including the load curve tests (4.2) and bias step tests (4.3). Both of these data modes report the S1 feedback data with the 38 data frame sampling (where one frame is a collection of a data point for every detector in the array) as opposed to Butterworth filtering. Data mode four also includes data for the absolute error signal, on which the feedback loop calculations are done. Several other data modes exist that are not used routinely by the ACT experiment. For these other data modes and recent updates, a record of the full set of data modes supported by the MCEs is maintained by M. Hasselfield and the UBC team at http://cmbr.phas.ubc.ca/mcewiki/index.php/Data_mode.

For data analysis needs, the conversions between data modes must be well understood. The primary portion of these conversions involves using bit shifts and handling of special data such as the flux jumps. The secondary concern in these conversions is taking into account the filter gain of the 4-pole Butterworth filter. The filter is fully described at http://cmbr.phas.ubc.ca/mcewiki/index.php/Digital_4-pole_
Butterworth_Low-pass_filter. The most important component of this filter for data conversions, and eventually calibrations, is the DC filter gain. For the filter used in the 2008 season, this DC filter gain is $1217.9148$. Explicitly, this means that to use data taken in one of the modes using the 4-pole Butterworth filtering, one of two options must be used. The first choice is that the full filter must be deconvolved, with no prior normalization of the filter or adjustment of the data (aside from bit shifting as appropriate). The second choice is to deconvolve a normalized filter, such that the filter has a DC gain of unity. The data must then be divided by the innate DC filter gain for appropriate calibrations. This option is the one chosen for our standard data analysis pipeline. The distinction is important, as we have multiple pipelines in the ACT collaboration, and ensuring that the gain is properly handled in either choice of deconvolution is necessary. Table 2.4 describes the conversions needed to match data taken in all modes to that taken in data mode 2 (DM2). This is our default mode, due to its use in 2007, and all calibration routines assume data has been adjusted to the same calibration base as this mode. To covert to physical units of current change in the TES, the following formula may be used on data converted to DM2:

$$I = \frac{V_{fb}}{R_{fb}M_{\text{ratio}}} \left( \frac{1}{0.02} \right) \left( \frac{1}{50. + \frac{1}{R_{fb}}} \right)^{-1},$$

(2.3)

where $[\text{DAC}]/[V] = 2^{14}$, $V_{fb}$ and $R_{fb}$ are the feedback voltage and resistance of the feedback circuit, $M_{\text{ratio}} = 8.5$ is the mutual inductance ratio between the feedback inductor and the S1 SQUID readout inductor, and the last portion accounts for a scaling of the maximum output amperage of the feedback source (.02 A), which uses a 50 Ohm resistance in parallel with the feedback resistance (of order 7 kΩ). The equation accounts for both the S1 SQUID readout method and feedback circuit parameters that are required to reconstruct changes in the TES voltage. Chapter 4 will describe the readout circuit and data conversions in more detail.
### Table 2.4: Data Mode Conversions to DM2

<table>
<thead>
<tr>
<th>Data Mode</th>
<th>Brief Description</th>
<th>Description and Conversion to DM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feedback</td>
<td>32b (unsigned) SQ1 Feedback data; The top 6 bits are not used, the next 14 bits are used and the bottom 12 are used, but are the fractional portion of the number. The data should be divided by $2^{12}$, and then a multiplication of $1218$ to get to data mode 2.</td>
</tr>
<tr>
<td>2</td>
<td>Filtered feedback</td>
<td>32b (unsigned) SQ1 filtered feedback data: This is the raw data mode all the conversions in this table are referenced to.</td>
</tr>
<tr>
<td>4</td>
<td>18:14 Mixed</td>
<td>Signed 18b SQ1 feedback [bits 31:14] + signed 14b co-added error signal [bits 13:0]; Here, the data needs to be bit shifted by 14 bits, and then multiplied by $1218$.</td>
</tr>
<tr>
<td>9</td>
<td>24:8 mixed</td>
<td>Signed 24b filtered data [bits 31:8] + signed 8b number of flux jumps [bits 7:0]. This data should be bit shifted by 8 bits, and then multiplied by 2 to account for a difference in the filter gain compared to data mode 2.</td>
</tr>
<tr>
<td>10</td>
<td>25:7 mixed</td>
<td>Signed 25b filtered data [bits 31:7] + signed 7b number of flux jumps [bits 6:0]. This data should be bit shifted by 7 bits, and then multiplied by $2^7$ to account for a difference in the filter gain compared to data mode 2. This was the primary observing data mode used for 2008.</td>
</tr>
</tbody>
</table>
2.4 Data Readout Computers

The initial data processing for all files acquired by the MCEs is done on-site through computers housed in the site operations trailer. These computers command the MCEs to conduct daily operations. These include nightly startup processes, detector array (using load curves) and SQUID biasing, system tests including bias step tests, data acquisition, and data processing. The readout system is designed to directly process data taken during nightly startup system tests and to properly set up the biases for all detector and SQUID lines to prepare for CMB observations. Among these tests, a load curve for each detector is acquired to determine the bias voltage required to place the detectors on their transitions. Section 4.2 describes this test in further detail. The second primary startup task performed is an automated SQUID tuning for all of the SQUIDs in the cold readout electronics. Niemack [54] and Battistelli et al. [8] fully describe this nightly tuning procedure.

In addition to setting up the detector arrays and readout electronics for nightly observations, these computers collect and store all of the data for all sky observations. A separate computer collects all of the system housekeeping variables, including telescope pointing, temperatures of many cooling stages in the MBAC, temperatures of the telescope structure, and many other system parameters, which may later be used in the map making data analysis or studies of system properties.

The signal data from each camera, the housekeeping data, and the results of the analysis for the nightly systematic checks (including all of the biasing parameters) are all merged into our common data file types, known as dir files. The merging requires a synchronization of the data and appropriate resampling of the housekeeping data to match the recorded signal data. This is handled by a complicated process with a dedicated external computer known as the merger computer. Switzer et al. [76] more fully describes all of the computer infrastructure which controls the full ACT system and manages and stores the recorded data.
2.5 Data

The total data acquired over a full observing night for each of the ACT cameras is approximately 50 to 60 GB per night. Figure 2.10 indicates the number of hours that were spent taking CMB observations per night during the 2008 season. Combined with the 2007 season data, the total raw data acquired is roughly 20 TB. This massive amount of data presents many challenges.

The first step in handling the data is a lossless compression routine implemented by Joseph Fowler. This is now implemented during the merging step, and significantly (reduction ratio of $3/8$) reduces the size of all stored data files. The data then must be transported from the observing site on Cerro Toco to our North American computers. This transfer begins with a radio ethernet link established between the observing site and our Chilean base of operations in the town of Sad Pedro de Atacama. The data are stored on a raid server at our San Pedro location. From here, the data are copied onto hard disks for physical transport by collaboration personnel to our North American data storage at Princeton University. Finally, it is copied from the transport disks onto the large map-making computer infrastructure developed by Tobias Marriage at Princeton. Within the last year, our collaborators Jon Sievers and Mike Nolta at the Canadian Institute for Theoretical Astrophysics (CITA) in Toronto have developed a parallel analysis pipeline
The ACT Telescope Systems Overview

using a portion of the 30240 core SciNet supercomputer. The data are carefully tracked during all transfers by a sophisticated system developed by Mike Nolta. This tracking system ensures that no data are erased before being successfully received at their next destination, and also ensures that there is at least one backup for each set of data until the data reaches the Princeton computers.

Once the data are available on our North American computers, data analysis begins. The data will primarily be used to construct sky maps of the CMB. The sky maps will be used to produce many data products. The most prominent of these will be the power spectrum of the CMB. Other products will include catalogues of galaxy clusters and the observed magnitudes of their tSZ signatures, estimates and parameterization of observed weak lensing, measurements of the kSZ effect across our observing fields, catalogues of point sources with flux estimates, and several other results. One example product of the ACT observations has already been published in Hincks et al. [31]. In this paper, lead by Adam Hincks, maps of several galaxy cluster candidates are presenting using the ACT 2008 season observations. Chapter 5 will include the results of a preliminary study of the bright point sources seen in the current 148 GHz and 218 GHz data maps.

In order to achieve the desired experimental goals, a great deal of instrument development, testing and characterization has been and continues to be required. Chapter 3 will describe one portion of the many tasks involved in the instrument construction. This chapter will cover the several tests and the screening process conducted for the primary MBAC camera cold electronics. Similar test and screening processes were conducted for nearly all components of the MBAC instrument, from the magnetic shielding encasing the optics tubes to the TES detector chips themselves. Each of these tests has been vital in order to maximize the number of working detectors and develop the, overall, highly successful instrument that we observe with in the field today.
2.5 Data
Chapter 3

Tests of Multiplexing Electronics for the Atacama Cosmology Telescope

The cold readout electronics for the MBAC have undergone several iterative developments in design over several years of production. Particularly, the mux chip design has evolved over time to become much more reliable and less sensitive to magnetic pickup from external sources through changes to the chip wiring and lithography processes. Stemming from the work begun by M. Niemack as described in Niemack [54], several studies have been conducted during screening of the mux chips produced by NIST, Boulder. Throughout the development phase of the MBAC camera arrays and the Column Camera (CCAM) prototype for the MBAC, these mux chips have been screened at Princeton for SQUID failures, SQUID critical currents, magnetic pickup, and many other properties. The screening process has been used primarily to determine if each mux chip has a sufficient number of SQUIDs that operate properly within our desired biasing range. Early mux testing began at Princeton with work by Z. Kermish and J. Burwell, and continued with further testing by T. Marriage and M. Niemack with guidance from the NIST team. During my screening and studies of the mux readout electronics over a period of roughly two years, I was aided by A. Dahlen, K. Martocci, L. Sun, S. Denny and S. Iyer.
3.1 Mux Chip Testing Experimental Setup

The automation system described in Section 3.4 was designed and developed with the aid of A. Dahlen during this time as well [14].

This chapter will begin with a full description of the initial testing procedure and series of studies conducted during my first several months of screening mux chips. The automated testing development will then be briefly described. Finally, some aggregate results of all mux chip testing done will be presented, along with some descriptions of the quality of the chips finally selected and currently being used within the three ACT cameras.

3.1 Mux Chip Testing Experimental Setup

A full understanding of the readout electronics was very important for the successful development of the final camera for the ACT project. The experimental work presented in the Sections 3.2.1 through 3.2.4 focus on the initial testing of the mux chips and SA modules conducted during the summer of 2006. The purpose of this initial experiment was to choose a sufficient number of optimal mux chips for the assembly of an 8 by 32 test array. These tests were done simultaneously with shunt resistor and TES testing at Princeton over this period of time. The testing of all three camera components continued until the completion of the final full detector array assembly. The main goal of the work was to develop a database of characteristic values that describe the quality of the mux chips. This database was then analyzed to determine which chips were useful for both the prototype and eventually the final camera assemblies. In addition to determining the usefulness of individual chips, several other properties of the chips were measured in order to gain a better understanding of how they would function within the full readout electronics. Also, using the data collected during the initial tests, predictions were made concerning the number of chips that needed to be fabricated in order to fully read out the three MBAC detector arrays.

All the tests of the mux chips and SA modules were conducted in a liquid helium Dewar operating at near atmospheric pressure. Eight mux chips and one corresponding SA
module were attached through wire bonding and pins onto a test card that was held at 4 K through direct dipping into liquid Helium. Because of this, the complete testing assembly was called the “4K Dip Probe”. The chips and SA module were wired in almost the same manner as described for the final camera arrangement, but with open inputs where the TESes would ordinarily be connected to the mux chips’ S1 SQUIDs. Additionally, the S1 bias lines for each effective row of eight SQUIDs for all eight chips were connected in series, as only one chip needed to be tested at a time. The card was connected through flexible wiring known as flexline to a tower (a box for mounting the cards) that was held at room temperature. The connections to the card were formed through pressing the contacts of the flexlines onto pads on the test card, which allowed us to avoid permanently wiring to the test cards. This connection can be seen in Figure 3.1. These connections often were a source of faulty channels as the circuits can be complete before dipping, but become disconnected after cooling. The circuits that were lost due to flexline problems significantly reduced the amount of data available for drawing conclusions at the end of this experiment. The benefits of using flexline to avoid bonding or permanently wiring connections to the test cards far outweighed the losses associated with the method.

The tower consisted of a bank of feedthrough and bias cards with one preamplification card and one power card. This tower can be seen in Figure 3.2. The labels in the figure show which inputs of the chips are connected to each SubMiniature B (SMB) connector and card. Each programmable card has eight inputs, with one for each mux chip. The power card provided the voltages needed by the other cards in the tower. The bias and preamplification cards both allowed voltages to be applied to the test card through programming from external computer commands or directly through their SMB connectors. The feedthrough cards simply consisted of approximately 5 kΩ resistors connected in series to the flexlines. Thirty-three of the feedthrough inputs were each connected to one row of bias lines for the 33 SQUIDs on each chip. These input lines were known as the Row Selects (RS), as they connected to one SQUID from a specific row on each of the 8 chips to be turned on. The convention developed by NIST was to call each 1 by 32
3.1 Mux Chip Testing Experimental Setup

Figure 3.1: The assembled test card. The flexlines are connected to the card through pressure contacts where the figure is labeled NIST Clamp. (Image Credit: Krista Martocci, [51])

TES detector chips and mux chip a column, and the individual devices on the chips are thus known as rows (more logically when many columns are placed next to one another). The programmable cards were all capable of producing up to 0.5 mA of current by placing voltages up to 2.5 V through their $\sim 5\, \text{k}\Omega$ resistors. As these were computer controlled, this 2.5 V corresponded to a maximum input value of 65536 for a 16-bit serial word digital to analogue converter (DAC) value that the computer programs supplied to the tower [42]. The conversions between the voltage applied to the resistor $V_{\text{applied}}$, the current supplied $I_{\text{supplied}}$, and the DAC value:

$$I_{\text{supplied}} \frac{5000}{\text{Ohms}} = V_{\text{applied}} = \frac{\text{DAC} \times 2.5}{65536}$$

are useful, as conventions within the research group have changed over the course of the screening process, and some measurements are recorded in these DAC units.
Figure 3.2: The dip probe tower. The function of each SMB is indicated. The RS lines, S1 Inputs, and S1 Feedback lines are all feedthrough cards. The SA Output card contains a preamp and programmable bias control. The remaining cards all have programmable bias controls. The description of each type of card is included in Section 3.1. Image Credit: Krista Martocci, [51]
3.2 \( I_{c_{\text{Max}}} \) Characterization

The primary purpose of this initial experiment was to choose a sufficient number of optimal mux chips for the assembly of an 8 by 32 test array. This set of muxes and detector array was specifically designed for installation into the CCAM prototype [54, 46, 3].

3.2.1 Selection Criteria

The mux chips are primarily characterized by the values of \( I_{c_{\text{Max}}} \) for each of their 33 S1 SQUIDs. As mentioned earlier, \( I_{c_{\text{Max}}} \) is the bias current at which the SQUIDs no longer show a zero voltage supercurrent and have the largest peak to peak response in their \( V-\phi \) curves. Ideally, all the SQUIDs would be biased at \( I_{c_{\text{Max}}} \) to maximize their response. Due to the need for minimal wiring to the cold electronics, however, one bias current is applied to the S1 SQUIDs on eight mux chips at a time. This restriction requires chips to be chosen such that the values of \( I_{c_{\text{Max}}} \) for all eight chips on a given RS are relatively close to one another. A harder restriction is placed on the upper bound of the \( I_{c_{\text{Max}}} \) values, such that a reduced response due to overbiasing is preferred over a SQUID that is not fully biased to \( I_{c_{\text{Max}}} \). This restriction was set because of prior testing showing that the SQUIDs exhibited oscillations when biased below their critical currents.

The values of \( I_{c_{\text{Max}}} \) were measured for all S1 SQUIDs on three test cards. Of the first card, only two chips were sufficiently characterized to be considered complete. The other chips had bad S2 SQUIDs, shorted S1 feedback (FB) lines, or were removed for retesting on a later card. The second and third test cards, known as Dip Probe Versions (DPV) 2.3 and 2.4 had a total of 14 chips on which all of the available \( I_{c_{\text{Max}}} \) data were taken. In addition to the data from these 16 measured chips, \( I_{c_{\text{Max}}} \) data taken in earlier tests using the same test system were analyzed from five additional chips. The \( I_{c_{\text{Max}}} \) values are shown in Figure 3.3. From this figure, it is clear that some of the chips have high \( I_{c_{\text{Max}}} \) outliers, and that there was a significant fraction of missing or bad channels on these initial mux chip batches. RS 15 had many such failures across the chips shown in Figure 3.3.
Figure 3.3: The values of $I_{c\text{Max}}$ plotted against RS channel number for all of the data examined in the experiment. The legend shows the chip numbers, according to their positions on the wafers they are fabricated on (see 3.2.3 for additional details). The letters in the legend represent the different wafers. The goal of the screening process is to find chips with similar values of $I_{c\text{Max}}$. Higher priority is placed on S1 SQUIDs for a given row having similar optimal biasing current across the selected chips.
3.2 $I_{c\text{Max}}$ Characterization

<table>
<thead>
<tr>
<th>Chip Number</th>
<th>Wafer</th>
<th>Avg. $I_{c\text{Max}}$</th>
<th>Bad</th>
<th>Too High</th>
<th>Flexline</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2</td>
<td>mux05c 00.00.06 C</td>
<td>127.7 µAmps</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>14.3</td>
<td>mux05c 00.00.06 C</td>
<td>133.2 µAmps</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>16.3</td>
<td>mux05c 00.00.06 C</td>
<td>144.0 µAmps</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>14.3</td>
<td>mux05c 00.00.06 E</td>
<td>141.9 µAmps</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
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<td>145.2 µAmps</td>
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<td>0</td>
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<td>146.7 µAmps</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
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<td>8.2</td>
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<td>129.8 µAmps</td>
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<td>1</td>
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</tr>
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<td>145.1 µAmps</td>
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<td>148.4 µAmps</td>
<td>1</td>
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</table>

Table 3.1: Best 12 mux chips tested for initial screening for the CCAM prototype. For each chip, the number of each possible type of bad S1 SQUID is indicated. The chips are fabricated in batches, distinguished by their wafer label (see 3.2.3 for details about wafers). The chip numbers correspond to the chip positions on these wafers.

From the 21 chips examined, the eight best were selected and four were appointed as back-up chips for these eight. These chips were chosen by minimizing the total combined number of bad SQUIDs, SQUIDs with high optimal biasing currents, and SQUIDs with unknown $I_{c\text{Max}}$ values caused by disconnected flexline leads. A high value was specifically defined to be more than 1.2 times the average $I_{c\text{Max}}$ value for the 21 S1 SQUIDs with the same RS number out of the group of chips. Table 3.1 shows the chips selected, with the number of problematic S1 SQUIDs of each type indicated. The $I_{c\text{Max}}$ values for the best eight chips are shown in Figure 3.4.

3.2.2 Analysis of Desired Biasing Currents

Another goal of this initial project was to characterize the statistics of the S1 SQUIDs by examining the effects of choosing a single bias current for a large group of rows or chips. A useful way to approach this was to generate a histogram of the $I_{c\text{Max}}$ values. A histogram containing the $I_{c\text{Max}}$ data for the 21 chips is presented in Figure 3.5. By examining this histogram, a bias point was selected such that most of the S1 SQUIDs
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Figure 3.4: The values of $I_{c\text{Max}}$ plotted against row select channel number for the eight best chips in the initial study. These chips were used for the CCAM prototype, and all come from the older style of mux chip, called mux05c. The mux chips for use in the final ACT readout electronics were a newer design, known as mux06a.
3.2 $I_{c\text{Max}}$ Characterization

Figure 3.5: All but one outlying value of the $I_{c\text{Max}}$ data examined in the initial experiment. The optimal currents are reasonably well grouped.

were fully turned on. The chosen point for this analysis was 177.13 $\mu$A. If all of the S1 SQUIDs were biased to this value, then only eight of the S1 SQUIDs from all 21 chips would not be fully biased to their $I_{c\text{Max}}$. Additionally, at this value, none of the SQUIDs would be biased beyond $1.5 \times I_{c\text{Max}}$. This is desirable due to the decrease in responsivity that begins to occur beyond $I_{c\text{Max}}$. This detrimental fractional response of a SQUID due to over or under biasing is shown in Figure 3.6. Although this figure indicates that the response below $I_{c\text{Max}}$ falls less slowly than above $I_{c\text{Max}}$, tests conducted by the NIST SQUID fabrication group indicated that biasing below $I_{c\text{Max}}$ could cause oscillations in the SQUID response.

A more useful analysis of the data involved examining only the eight best mux chips. Understanding how to bias these chips with one current bias is much more realistic, as for each row, only one bias can be chosen for each set of eight chips. First, the data was
Figure 3.6: The fractional voltage response of a SQUID relative to its maximum at a bias current of $I_{c\text{Max}}$. SQUIDs can be biased below $I_{c\text{Max}}$, however the characteristics of how they behave with the other electronics in the system is not as well studied as for SQUIDs biased above their $I_{c\text{Max}}$. 
3.2 $I_{c\text{Max}}$ Characterization

![Image](image.png)

Figure 3.7: The distribution of the $I_{c\text{Max}}$ data from the best eight chips. The currents are reasonably well grouped and the chips were selected to have the largest number of biasable S1 SQUIDs.

arranged in histogram form, as shown in Figure 3.7. From this histogram, it is clear that only one of all of the channels lies above the $181.35 \mu A = 1.5 \times I_{c\text{Max}}$ level of the lowest critical current SQUID. Ideally all of the SQUIDs for these eight chips should be operating above their critical currents. If all of the SQUIDs were biased to $193.17 \mu A$, the SQUID with the lowest critical current would be at $1.56 \times I_{c\text{Max}}$, which greatly reduces the amplitude of its $V-\phi$ response curve. A simulated plot that shows the reduction in amplitude from optimal biasing for this SQUID is shown in Figure 3.8.

A better way to bias these SQUIDs is by biasing each row to exactly the highest $I_{c\text{Max}}$ value for that row. By doing this, the overbiasing should be reduced significantly. The percentage response of the SQUIDs with the lowest critical currents in each row when biasing in this manner was calculated. Again, this is done because these SQUIDs will
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Figure 3.8: A simulated plot of the V-ϕ curves for the S1 SQUID with the lowest $I_{c\text{Max}}$ of the best eight chips. The top curve represents the flux response when the SQUID is overbiased to 193.17 $\mu$A, while the bottom curve represents optimal biasing. The resistance is taken to be 2 $\Omega$ for simplicity.

have the lowest amplitude response, due to being the most overbiased. The results are shown in Figure 3.9. Note that the row with the highest critical current of all eight chips is also the row with the lowest critical current, so there is one outlying point at 36.2%. The histogram shows that all but three of the lowest S1 SQUIDs will operate at better than 50% of their optimal response if this biasing scheme is used. The S1 SQUIDs with higher bias points in each row will all perform better than this.

3.2.3 Wafer Characterization

The mux chips were produced in large wafers, with the chips distributed across three columns. The $I_{c\text{Max}}$ data measured in this experiment verified that there are undesirable gradients across these initial sets of wafers. This is shown in Figure 3.10. The SQUIDs from the first column on the wafer tend to exhibit a decreasing $I_{c\text{Max}}$ with increasing RS number. The middle column chips tend to be relatively uniform with RS. The third column chips have a large increase in $I_{c\text{Max}}$ with RS. Unfortunately, among the chips tested, the
3.2 $I_{c\text{Max}}$ Characterization

Figure 3.9: The distribution of the percentage response of all of the S1 SQUIDs if each row is biased to exactly the highest $I_{c\text{Max}}$ for that row. The one outlying point is for a row that coincidentally contains SQUIDs with both the highest and lowest $I_{c\text{Max}}$ values out of all of the eight best chips chosen for the CCAM prototype.
Figure 3.10: Critical currents of three mux chips that are from columns 1, 2 and 3 of the wafer. A clear U-shape can be seen, indicating that the fabrication process produces undesirable gradients across the wafer. The data for the column 2 chip came from a previous experiment.

The majority of the best eight came from this third column. The third column chips also had the highest values of $I_{c\text{Max}}$ for high RS values. The increase of the critical current with RS number ensured a significant gap between the lowest $I_{c\text{Max}}$ value for a given row and the highest, thus forcing more overbiasing than if all the chips had come from sections of the wafer with a smaller gradient.

### 3.2.4 Anticipated Requirements for Mux Chips

Another of the goals of this initial experiment was to predict how many new mux chips would need to be fabricated in order to meet the needs of all of the test phases of the camera electronics and the needs of the final multiple array camera. One of the motivating factors for this goal was that the mux chips have limited bond pad space with which they
3.2 $I_{c\text{Max}}$ Characterization

can be connected to other devices. The bond pads only allow for three to four reuses of any particular circuit connection. The number of properly functioning mux chips that was actually needed to complete the testing and camera assembly phases was approximated using the results of this initial study. The final camera arrays required 96 additional chips to those described in this study to completely satisfy their readout needs.

Only 38.1 percent of the chips initially surveyed fit the selection criteria set for optimal mux chips, in that they had no known bad channels. Even among the eight good chips that fit this criteria, two have one high $I_{c\text{Max}}$ S1 SQUID and one has two high $I_{c\text{Max}}$ S1 SQUIDs as indicated in Table 3.1, making these chips less than ideal. Additionally the mux chips on a wafer could have had a preliminary warm resistance measurement performed on them with relatively minimal effort. Previous experimental testing had shown that chips with warm resistances below a certain value consistently have enough faults that they do not need to be tested cold. This value changed between wafers, but for one older wafer it was 42 kΩ. Of a given wafer, a conservative estimate provided that 25 percent of the chips would fail this initial selection criterion. Combining these results, the expected yield rate for optimal mux chips was only 28.5 percent. This result indicated that approximately 337 mux chips would need to be produced in order to yield 96 optimal chips. If the selection criteria from the cold tests was reduced to allow all 12 of the best chips to be considered good, then the number needed decreased to 224 chips, as the yield became 42.8 percent. Of the 337 chips that might be needed, approximately 252 would be need to be tested in the liquid helium Dewar in order to find 96 best chips. The initial testing process for a board of 8 chips when the flex lines did not exhibit significant failures required many man-hours of repetitive labor. Combined with the expected number of chips to be tested, a more automated system for future testing of mux chips was required. This automated screening system was eventually developed and used for chip testing, and will be described in Section 3.4.
3.3 Advancements in Mux Chip Production and Screening After the Initial Study

The initial studies of mux chips used to supply the CCAM prototype device and subsequent testing periods proved very useful in aiding the production of higher quality chips. Feedback on wafer and chip quality was provided to the NIST team after each batch of mux chips was tested, and this allowed for specific improvements in the deposition and other production processes. One dramatic improvement to the production process was the reduction in the number of columns of chips per wafer from 3 to 2. This both helped to reduce the gradients in $I_{c\text{Max}}$ seen in initial tests, and reduced the number of faulty SQUIDs that were often associated with being located near the edges of the wafer.

In addition to this improvement in wafer layout, the general quality of chips significantly improved over time. Specifically with the final several wafers of chips produced, the fraction of chips passing the screening process became both higher and much more consistent. These improvements reduced the number of wafers needed and allowed the three full MBAC arrays to be completed more quickly than expected.

3.4 Automated Testing of Mux Chip Assemblies

The standard screening process was developed into a more automated process with the help of A. Dahlen. To accomplish the automation, several key components were developed. The first step of the process involved determining a method to generate the $V - \phi$ SQUID curves automatically. Thanks to the bias cards in the dip probe tower, all feedback lines could be controlled through a fiber-optic signal provided to the tower control/power card (see Figure 3.2). The RS biases are, however, connected to simple feedthrough cards, which must have a voltage applied externally through their SMB connection. To solve the problem of providing external signals, a device developed by NIST, known as the NIST crate was used. This crate accepts signals through a fiber-optic connection from
3.4 Automated Testing of Mux Chip Assemblies

a computer and can generate voltage outputs through controlled biasing cards. This NIST crate system was originally developed to control the complete multiplexing of the CCAM system, including controlling the feedback loops that lock the SQUIDs. Although the automated mux testing does not require this level of sophistication, the system does allow for all of the needed outputs to provide each RS of the testing tower with an input bias.

The second major component to be developed for the automation process was a system for generating and recording the $V - \phi$ curves. This was developed as a python program. The program instructed the dip probe tower to ramp one S1 feedback input through the programmable bias card while applying a set bias to one of the 33 possible RS lines through voltages applied by the NIST crate. The output of the SQUID series was connected to an HP multimeter. This multimeter was connected through a GPIB interface that allowed the controlling computer to record the output voltage at each step during the sweep. One such $V - \phi$ curve was acquired for each of a set of possible biases, generally intended to cover the full range from the minimal current to activate the SQUID up through $\sim 1.5 - 2I_{c\text{Max}}$.

The final important component to the development was a program to analyze these recorded $V - \phi$ curves to determine the $I_{c\text{Max}}$ value for each of the S1 SQUIDs. This voltage is determined as the point at which no part of the $V - \phi$ curve exhibits a flat, superconducting response to the input flux. This method was determined to have a precision relative to a human determined critical current of 15 mV as applied to the feedthrough card input, or 0.003 mA equivalent passing through the feedthrough card resistor. Subsequently, the computer program recorded the $V - \phi$ curves of all S1 SQUIDs at 1.5 times the calculated $I_{c\text{Max}}$ for examination.

The entire time required for the testing procedure was reduced significantly through application of this automation program. Specifically, the number of steps required to test each dip probe card was drastically reduced. Once the SA and S2 SQUIDs were biased and set with appropriate feedback values, the cables used to deliver the NIST crate biases to the dip probe’s 33 RS inputs were connected. The output of the preamp card was
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connected to the multimeter for the mux chip to be tested, and the program was run. Each of the 33 SQUIDs could then be tested without further human intervention, and the entire set of eight chips per test board could be screened by only switching the one wire that connected the SA output for the appropriate mux chip to the multimeter input and instructing the computer to continue with the next chip (one button click). The final step of the testing procedure was to check the $1.5 I_{c_{\text{Max}}}$ curves to ensure that the SQUIDs did not exhibit instabilities. This needed to be done by an operator as the determination was often somewhat subjective. The testing of many chips was done using this relatively fast method with the assistance of A. Dahlen, S. Denny, K. Martocci, and L. Sun.

3.5 Aggregate Testing Results

Throughout the mux testing, documentation of results has evolved along with the methods and goals of the screening process. Much testing both before and after the development of the automated screening process was recorded in paper logs of SQUID parameters and failures. These logs were consulted as needed by the final array assembly team. Far more useful, however, were the large number of mux chips screening results which were electronically documented and stored using a database system developed by O. Stryzak at Princeton. Once a common format was chosen for recording testing results, nearly all chips tested that had more than half of their S1 SQUIDs operational had their S1 $I_{c_{\text{Max}}}$ values stored in this database system. From this database, the values for all recorded chips may be examined in some aggregate studies of the average chip quality.

Of all of the chips tested, 228 were entered into the database. Among these chips, varying levels of data were recorded. As the database was more fully developed, the recorded data became much more standardized. Additionally, the automated testing system greatly simplified the recording of $I_{c_{\text{Max}}}$ values for the chips tested using this system. Figure 3.11 shows $I_{c_{\text{Max}}}$ values for 73 chips tested using the automated screening system. These chips were all taken from mux06a wafers produced in 2007. The automated
3.5 Aggregate Testing Results

Figure 3.11: The values of $I_{c,\text{Max}}$ plotted against row select channel number for the 73 chips that were both entered in the final mux database and were screened using the automated procedure. These chips were all taken from mux06a wafers produced in 2007. One hundred fifty S1 SQUIDs had $I_{c,\text{Max}}$ below 200 DAQ (as applied by the NIST crate) out of 2376 SQUIDs tested. Very high currents and currents below 200 DAQ are excluded from the plot. The chip quality is significantly improved from original mux wafer batches, as can be seen from the spread of the data points and small number of dead SQUIDs.

The testing system greatly reduced the amount of work required to collect all of this data. In generating the figure, the total number of S1 SQUIDs that were dead or had $I_{c,\text{Max}}$ below 200 DAQ (as applied by the NIST crate) was determined. Only 150 out of 2376 S1 SQUIDs tested were dead or below this cutoff.
3.6 Final Array Chip Performance

The final set of 96 mux chips installed in the MBAC for the three cameras has been in operation for the full 2008 season. After installation in the MBAC, an initial period of testing and observations was used to determine all SQUIDs which fail in several possible manners. These SQUIDs must be set to have zero bias so that the MCE devices do not attempt to servo their responses with any feedback. If they are not set to zero, the servoing will cause the feedback to ramp continuously. Due to the limited range of the feedback voltage available, this ramping repeats a fast pattern of ramping over the full range and then jumping back to the minimum voltage. This sawtooth signal has been determined to have a detrimental effect on nearby signal lines, as the nearby pixels can be seen to pick up some systematic noise due to this effect. In addition to these initial tests, if at any point during the observing seasons a SQUID was noticed to behave in any of the following errant manners, it was added to the appropriate failure list and set to zero bias.

The cleanest of the failure modes is the failure for a S1 SQUID to respond at all (dead). This would occur, for example, if the value of $I_{c_{\text{Max}}}$ were above the biasing range in addition to complete failures. The second well understood failure mode is that the S2FB setting causes the SQUID to be in a state where multiple lock points are too close together. This condition occurs when the $V - \phi$ curve of a SQUID, as read out by the S2 SQUID and SA module, crosses its middle output value more than twice per $\phi_0$. This causes the SQUID responses to jump too easily, and thus, these SQUIDs are not turned on for fear of contaminating surrounding detector signals with additional noise. Finally, the two categories of less-understood mux chip failures are jumping SQUIDs without a clear explanation and a generic “poorly understood” failure category.

Among all of the 1056 S1 SQUIDs for the 148 GHz camera, 16 exhibited the dead state. 10 exhibited the multilock condition, and 12 were zero-biased due to poorly understood jumping. In the 218 GHz camera, 17 were dead, 19 exhibited multiple locking points and 8 had extra jumping. In the 277 GHz camera, 29 S1 SQUIDs were dead, 25 exhibited
3.6 Final Array Chip Performance

multiple locking points and 3 had unexplained jumping.

Among the failures listed above, special note should be made that some SQUIDs have been included in multiple categories, due to failures that have occurred in multiple ways or due to changing failures with time. For the 148 GHz camera, 4 SQUIDs were marked to be both dead and have multiple locking points due to failing different tests at different times in the 2008 season. The 218 GHz camera had 2 S1 squids counted in both multiple locking and random jumping categories. The 277 GHz camera had 11 SQUIDs falling in both the dead and multiple locking categories. One final note should be made about the failures mentioned for the 277 GHz camera. For this camera, mux chips with failures were accepted if the S1 failures could be paired with dead TES detectors. This pairing allowed for mux chips with a greater than ordinarily acceptable number of failures to be used while not decreasing the number of effective operating detectors.

Accumulating the results, while accounting for double countings, the number of lost pixels in the three camera arrays due to SQUID failures is very low. The 148 GHz camera had a total of 34 distinct S1 failures. The 218 GHz camera had a total of 43 distinct failures. The 277 GHz camera included 46 failures, while still counting those paired to dead TES detectors. Thus, the total number of lost detectors potentially due to bad SQUIDs was only 123 out of 3072, or 4%. This final result has demonstrated that the screening and selection process used for the mux chips was resoundingly successful overall.
Chapter 4

ACT Calibration for 2008

The ACT experiment uses a combined C++ and Python data analysis pipeline for primary map-making. The main map-making pipeline used at Princeton University is called Moby. This pipeline includes all steps of the data analysis that are completed beyond the initial data handling done at the telescope site. In particular, the initial analysis of the load curve tests used to determine array biasing is conducted using IDL programs on the data collection computers that are located on Cerro Toco. A secondary map-making pipeline has been developed and used by Adam Hincks for making small scale maps, and is discussed in Hincks et al. [31] and Hincks [30].

One of the most fundamental components of the data analysis is the calibration. The calibration routines developed for Moby use several steps to convert the recorded signal in DAC counts to a calibrated sky temperature in $\mu$K. The primary components of the Moby calibration include: a time-transfer calibration, a time-independent relative detector calibration, a system-wide adjustment for atmospheric opacity, and an absolute conversion from measured changes in power to changes in sky temperature. The current time-transfer calibrations adjust for changes in biasing and loading between nights, but not within a night. Fundamentally, the signal measured by the instrument is differential due to the inductively linked SQUID readout. This means that every given time stream, or time-ordered-data set (TOD), may be arbitrarily offset before calibration. The stan-
4.1 Detector and Readout Circuit Formalism

The framework for all of the instrument calibration was initially developed by E. Switzer for the 2007 season. The 2007 calibration concept and implementation is presented in Switzer [75]. From this initial structure, several new features and improvements have been made for the 2008 season. These include the development, testing and applications of a new system test for time-transfer calibrations known as the bias step test. This test is complimentary to the load curve tests that serve as the primary time-transfer calibration method. A second significant development is the computation and implementation of a time-independent, relative detector calibration. This chapter will discuss the background, development, testing and implementation of many of the 2008 Moby calibration routines. The final section will detail the procedures currently being used for map-making, with a focus on producing an accurate power spectrum from the data.

4.1 Detector and Readout Circuit Formalism

In order to properly describe all of the calibration routines and, in particular, the load curve and bias step file analysis routines, an overview of the relevant circuit physics and equations describing the detector behavior is necessary. Table 4.1 provides the definitions of variable names used throughout these and later calculations, a brief description of each, and a defining or basic formula for each of these quantities when appropriate. Figures 2.2.3 and 2.9 depict the detector, readout and feedback circuit layouts. The computations described below build from the detector formalism presented in Irwin and Hilton [41] using the simple concepts of Kirchoff’s Laws, a detailed knowledge of the detection and readout circuits, and a few underlying approximations. The first assumption needed for these derivations is that the circuit is properly designed to be voltage biased such that the detector resistance is much greater than that of the parallel shunt resistor (assum-
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Primary Formula</th>
</tr>
</thead>
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<tr>
<td>$I_o$</td>
<td>Current passing through the TES</td>
<td></td>
</tr>
<tr>
<td>$R_o$</td>
<td>Operating Resistance of the TES</td>
<td></td>
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<tr>
<td>$I, R, V_{sh}$</td>
<td>Current, Resistance and Voltage for the shunt resistor</td>
<td></td>
</tr>
<tr>
<td>$I_b, R_b, V_b$</td>
<td>Current, Resistance and Voltage for the input bias. All quantities are known</td>
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<tr>
<td></td>
<td>through direct reporting from the MCE</td>
<td></td>
</tr>
<tr>
<td>$I_{fb}, R_{fb}, V_{fb}$</td>
<td>Current, Resistance and Voltage for the feedback circuit connected to the MCE and S1 SQUID</td>
<td></td>
</tr>
<tr>
<td>$I_{sh}, R_{sh}, V_{sh}$</td>
<td>Current, Resistance and Voltage for the shunt resistor parallel to the TES</td>
<td>$V_{sh} = V_o$</td>
</tr>
<tr>
<td>$P_{Jo}$</td>
<td>Joule Power dissipated by the TES at operating point</td>
<td>$P_o \equiv P_{Jo} = I_o R_o^2$</td>
</tr>
<tr>
<td>$V_o$</td>
<td>Equivalent TES Voltage</td>
<td>$V_{TES} \equiv V_o = I_o R_o$</td>
</tr>
<tr>
<td>$T_o$</td>
<td>The TES operational Temperature</td>
<td></td>
</tr>
<tr>
<td>$M_{ratio}$</td>
<td>The Mutual Inducance Ratio between the feedback inductor and S1 SQUID readout inductor</td>
<td>$M_{ratio} = 8.5$</td>
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<td>$F_{Gain}$</td>
<td>The DC Filter gain of the 4-Pole Butterworth Filter applied by the MCE</td>
<td>$F_{Gain} = 1218$</td>
</tr>
<tr>
<td>$C_{A,DAC}$</td>
<td>The TES Current per DAC unit measured by the MCE</td>
<td></td>
</tr>
</tbody>
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Table 4.1: Definitions of Variables Associated with Detector Formulas. These formulas include the assumptions described in Section 4.1. All variables with the subscript o are the approximations for the values with the circuit in a DC or steady-state solution. Figures 2.2.3 and 2.9 depict the detector, readout and feedback circuit layouts. Many of the definitions come from or are extensions of those defined in Irwin and Hilton [41].
4.1 Detector and Readout Circuit Formalism

ing any parasitic resistance is small). The second assumption is that the detector is in a regime of strong feedback, such that the loop gain is much greater than both unity and the detector current sensitivity, which is the partial derivative of the logarithm of the TES resistance with respect to the logarithm of the TES current [41].

Under these assumptions, the circuit may be described as operating in a negative electrothermal feedback state. This electrothermal feedback arises from changes in the Joule power dissipation of the TES affecting the temperature of the TES, and changes in the temperature of the TES affecting its operating resistance, $R_o$. With the assumptions described above, particularly the voltage-biased requirement, increases in TES temperature due to internal or external loading result in increased detector resistance, and correspondingly decreased Joule heating power, $P_{J_o}$. The decrease follows the formula:

$$P_{J_o} = \frac{V_o}{R_o}$$

(4.1)

The decrease in $P_J$ relies on a nearly constant voltage with changing detector temperature and increasing detector resistance, as the formula requires. These concepts are more fully explored in terms of their full differential equations in Irwin and Hilton [41], for example.

One consequence of the negative electrothermal feedback condition and strong feedback regime is that the temperature changes of the detectors are near zero with increased loading [41]. Another property of the negative electrothermal feedback condition is that the steady-state (frequency=$\omega = 0$) voltage of the TES may be expressed in the form of Ohm’s Law, $V_{TES} \equiv V_o = I_o R_o$ [41]. For the detector calibrations, the $\omega = 0$ case is assumed, and all changes to circuit parameters are taken as small. The fact that the responsivity varies with $\omega$ is treated as a 1-pole filter response which we discuss beginning in Section 4.3.1. The zero frequency assumption allows derivatives of the steady-state circuit formulas to serve as reasonable approximations to the circuit response. This approximation will be shown to be reasonable by comparing the load curve and bias step calibration methods. The final useful property of the combined assumptions is that the re-
sponsivity of the detector circuit becomes dependent on the parameters of the bias circuit, including the voltage and resistance, but is no longer dependent on the innate parameters specific to each detector such as the current sensitivity [41].

The main goal of these derivations will be to compute the inverse responsivity, $\frac{dP_o}{dI_o}$, to calibrate the detector responses from DAC readout units to units of power. Throughout this chapter, the term “responsivity” is used for this inverse responsivity by convention, unless specifically stated otherwise. The conversion from DAC units to current is relatively straightforward. An interesting point of motivation for these calibration tests as a whole is that the circuit parameters are all known or may be derived from known quantities up to one missing component. This component can be reduced to the measured TES current at zero bias voltage. The lack of information is caused by the necessary use of an inductive coupler to read out changes in TES current through the SQUID circuity. More explicitly, due to this coupling, the detector readout has no true DC response. This is a fundamentally important point in understanding the need for the load curve and bias step testing methods. In the load curve test method, the measured TES current at zero voltage is derived from an extension of the normal branch of the TES to the zero voltage crossing. The load curve measurements and analysis will be more fully described in Section 4.2. In the bias step test method, the absolute power in the circuit is computed through the response to small variations in the circuit bias, and the actual TES current at any bias point may be derived from the power. The full description of the bias step analysis will be presented in Section 4.3, following the description of the load curves.

Using the standard relationships for voltage, resistance, current and power, we can now move forward with deriving some useful formulas for both of the methods of calibrations from DAC to electrical power in picowatts. First, the basic formulas relating the MCE measured bias quantities begin with:

$$I_b = \frac{V_b}{R_b}. \tag{4.2}$$
4.1 Detector and Readout Circuit Formalism

The bias resistors are a portion of the warm MCE units, and are known, while the bias voltages are directly measured by the MCEs. This makes the biasing current a known quantity before either the load curve or bias step tests are used. The shunt resistor naturally follows Ohm’s law as well. However, in this case only the value of $R_{sh}$ is known before using the load curve or bias step test methods:

$$I_{sh} = \frac{V_{sh}}{R_{sh}}.$$  \hfill (4.3)

Finally, recall that in the highly negative electrothermal feedback regime, the TES obeys Ohm’s Law:

$$V_{TES} \equiv V_o = I_o R_o.$$  \hfill (4.4)

The electrical power dissipated by the TES may be expressed then as:

$$P_o \equiv P_{Io} = I_o^2 R_o.$$  \hfill (4.5)

Using the parallel nature of the circuit, the currents and voltages may be related using:

$$V_o = V_{sh},$$  \hfill (4.6)

$$I_{sh} = I_b - I_o.$$  \hfill (4.7)

The detector current is measured by the feedback circuit, and the conversion to units of amps on the TES from DAC counts in the feedback MCE readout is (similar to Equation 2.3):

$$C_{A,DAC} = \frac{1}{R_{fb} M_{ratio} F_{gain}^{DAC} \text{Volts}^{.02}} \left( \frac{1}{50} + \frac{1}{R_{fb}} \right)^{-1}. $$  \hfill (4.8)

For the load curve test measurements, a direct calibration of $I_o$ is found by determining the absolute current offset at zero current input, as will be described in Section 4.2. From this, $I_{sh}$ may be derived using Equation 4.7. This leads directly to the computation of
$V_{sh}$, which is equal to $V_o$, and with both $I_o$ and $V_o$ computed, the power, $P_o$ and operating resistance $R_o$ may be computed directly. At this point, for any measured and calibrated $I_o$, all of the other desired circuit parameters are known. For clarity, the computation directly to $V_o$ from $I_o$ is:

$$V_o = V_{sh} = I_{sh} R_{sh} = (I_b - I_o) R_{sh}. \tag{4.9}$$

For the bias step test method, an absolute calibration of $I_o$ is replaced with a differential approach. In this approach, a small step, $\delta V_b$, is applied to the bias voltage. First, the MCE measured quantities are converted to units of current:

$$\delta I_b = \frac{\delta V_b}{R_b}, \tag{4.10}$$

$$\delta I_o = \delta V_{fb}[\text{DAC}]C_{A,DAC}. \tag{4.11}$$

Next, a different derivation of $I_o$ will be used in order to eventually derive a formula for $P_o$ from changes in the currents alone:

$$I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{P_o}{I_o R_{sh}} = I_b - I_o. \tag{4.12}$$

This is a quadratic equation for $I_o$, with roots:

$$I_o = \frac{I_b \pm \sqrt{I_b^2 - 4 \frac{P_o}{R_{sh} I_b^2}}}{2}. \tag{4.13}$$

The negative root is the correct choice, as shown by the following set of equations. The first is the approximation that $V_o \sim I_b R_{sh}$ (following from $V_o = V_{sh} = I_{sh} R_{sh} \approx I_b R_{sh}$). This approximation is valid so long as $R_o \gg R_{sh}$, which corresponds with the choice of a voltage biasing design. Using this first approximation, the expression for $I_o$:

$$I_o = \frac{I_b}{2} \left( 1 \pm \sqrt{1 - 4 \frac{V_o^2}{R_o I_b^2 R_{sh}}} \right) \tag{4.14}$$
4.1 Detector and Readout Circuit Formalism

becomes:

\[ I_o \approx \frac{I_b}{2} \left( 1 \pm \sqrt{1 - 4 \frac{I_b^2 R_{sh}^2}{R_o I_b^2 R_{sh}}} \right). \]  \hspace{1cm} (4.15)

Canceling terms, and taking a Taylor series approximation to the quantity in the square root results in:

\[ I_o = \frac{I_b}{2} \left[ 1 \pm \left( 1 - 2 \frac{R_{sh}}{R_o} \right) \right]. \]  \hspace{1cm} (4.16)

Now, taking the negative sign choice, this becomes:

\[ I_o \approx \frac{I_b}{2} \frac{2 R_{sh}}{R_o} = \frac{I_b R_{sh}}{R_o} \approx \frac{V_o}{R_o}. \]  \hspace{1cm} (4.17)

This final result shows that the negative root is the physically correct choice to describe the circuit.

Now, starting back at Equation 4.13, and taking the derivative with respect to \( I_b \), while treating the power as constant across the small step, we have:

\[ \frac{\delta I_o}{\delta I_b} = \frac{1 - I_b \left( I_b^2 - 4 \frac{P_o}{R_{sh}} \right)^{-1/2}}{2}. \]  \hspace{1cm} (4.18)

Rearranging, we arrive at an expression for the power in terms of measurable quantities:

\[ P_o = R_{sh} I_b^2 \frac{\delta I_o}{\delta I_b} \left( \frac{\delta I_o}{\delta I_b} - 1 \right) \left( 1 - 2 \frac{\delta I_o}{\delta I_b} \right)^{-2} \]  \hspace{1cm} (4.19)

We use this result in Equation 4.13 to solve for \( I_o \), and then the TES voltage, \( V_o \), and resistance, \( R_o \), may be computed using the power and current.

Using either the load curve or bias step test method for determining the circuit parameters, the primary goal of the calculations is to derive the detector responsivity. I define the responsivity inversely to the definitions of Irwin and Hilton [41]. We see from 4.19:

\[ \text{Responsivity} \equiv \frac{dP_o}{dI_o} = V_o - \frac{R_{sh} P_o}{V_o}. \]  \hspace{1cm} (4.20)
Finally, this conversion must be adjusted to account for the DAC units in which the data are taken as described in Section 2.3.2. As previously described, for standard CMB observations in the 2007 season, the data were recorded in MCE Data Mode 2 (DM2). This has become our standard data unit, and any data taken in another data mode is first converted to equivalent DM2 DAC units before further processing. To convert measured DAC units into a change in TES power in Watts we use:

\[
\frac{dP_o}{dI_o(DAC, DM2)} = \frac{dP_o}{dI_o(DAC, DM2)} A_{DAC, DM2},
\]

(4.21)

where Equation 4.8 defines the ratio of $A/DAC$ and

\[
F_{Gain}(DM2) \approx 1218
\]

(4.22)

defines the filter gain that must be removed. An important point to note at this stage is that the data handling in Moby removes the effect of the 4-pole Butterworth filter that is applied in the MCE electronics, but uses a DC frequency gain of unity as opposed to the filter gain defined above. The MCE Butterworth filter is used to reduce aliasing when we downsample the data acquired to our final data sampling rate of $\sim 398.7$ samples per second. The filter has a DC gain stated in Equation 4.22 for clarity. The gain is not due to any fundamental aspect of the filter or circuit components, but rather an artifact introduced by the method of filter implementation within the MCEs. The filter coefficients are multiplied by large numbers to avoid floating-point computations within the electronics, and thus must be removed before using the data.

### 4.2 The Load Curve Test

One of the detector characterization tests performed for nightly observations is a load curve measurement. These load curves sample the TES response to a large but slowly varied change in bias current. The goal of these tests is to sample the full TES response
4.2 The Load Curve Test

range through the superconducting response region (branch), through the superconducting transition, and finally through a portion of the normal resistance branch. During normal observations, such a response curve for each detector in every array is obtained before nightly observations, and just after observations have concluded. The load curves acquired at the beginning of each night are used to generate the nightly rebiasing of the arrays and are one of two methods used to compute the unknown parameters of the detector circuit. As described previously, the primary unknown detector circuit parameter is the absolute detector current, and more specifically, the offset output current at zero input bias current. This section will describe the practical acquisition and analysis of these load curves, as well as present some of the challenges that were addressed in their practical implementation for the 2008 season.

The load curve nightly tests are conducted by ramping the bias currents of the detectors slowly down from a preset value and recording the set of bias currents applied. This preset value is designed to be above the critical currents for all of the detectors, so that the curve begins where the TES is driven with too much current to be superconducting. The critical current is defined as the current at which the TES begins to transition between its normal and superconducting branches. The output feedback current is acquired over the full range of input bias currents. In practice, the bias current is slowly stepped through a set of pre-defined values, and the output feedback current is measured for each point along the step.

The first step of the analysis converts the feedback and bias currents into SI units. For the bias current, this calculation is simple and well defined by the bias resistances and voltage range of the MCE biasing cards. For the feedback current, this computation is shown in Equation 4.8. For the load curve tests, the data are acquired in MCE Data Mode 1, with no filter applied. For this mode, then, $F_{\text{Gain}} = 1$. The normal branches of the curves are then linearly fit to determine the zero bias offsets of the output currents. This is shown graphically in Figure 4.1. The fit determines the zero current offset and this is used to calibrate the actual current passing through the TES at each point on the load curves.
At this stage, the other TES parameters for each point on the curve may be computed using the steady-state approximation formulas derived in Section 4.1. The load curves, thus calibrated, are conventionally then recast as TES current versus TES voltage across the testing range. Due to this recasting, the curves are often known as IV Curves, as they are referred to frequently throughout this thesis. For the ACT experiment, the curves are also commonly plotted as $R_o$ vs. $P_{J_o}$.

Once the IV curves of all detectors are calibrated, the biasing for the night’s observations is chosen by computing the set of biases that place the maximum number of working detectors at or as near as possible to a target point on the detector transitions. This position is chosen in advance to be a set percentage of normal resistance. For the 2008 season, the target percentages were 30, 30 and 40 percent of the TES normal resistance. Once the optimal set of bias voltages is computed, the individual detector properties are computed using the formulas of Equation 4.1 and the currents as calibrated by the IV curve fits. The important quantities for the calibration are $P_o$ and $V_o$ at the steady-state input bias. The majority of the TES circuit parameters at the chosen bias points are then recorded in a file called the Run File, after its extension, ‘.run’. These parameters include the TES operating voltage, power, the fractional resistance of the TES in terms of the normal resistance, and a record of all cut detectors. These files are analyzed with a python program in our Moby analysis pipeline to compute the derived responsivity. Equation 4.20 is used to compute each detector’s responsivity at the applied bias point. Care must be taken to appropriately handle the inclusion of the shunt resistances, and to convert the responsivity to units of pW/DAC appropriate to the data mode for the observations that will be calibrated. For MCE Data Mode 2 observations, which serve as our base DAC unit, the filter gain of 1218 must be included as in Equation 4.21. For this thesis, the calibrations and other parameters derived from using the load curves output files are often referred to as both run file (RF) and IV curve tests.
4.2 The Load Curve Test

Figure 4.1: An example load curve including a superimposed example of extrapolation of the normal resistance branch to zero bias current. Each axis has been converted to units of $A$ using the resistances and output/measurement voltage ranges of the MCE electronics. The right x marks the critical current, where the normal resistance TES branch turns to the superconducting transition. The left x represents the offset current derived from the linear fit. The jumps in the data are caused by a combination of flux jumps in the SQUID readouts and exceeding the data acquisition card input range. When the input range is exceeded, the output flips from the most positive output value to the most negative. Both of these effects are carefully removed in the data analysis pipelines.
4.2.1 2008 AR1 IV Curve Problem and Solution

In the 2008 season, comparisons of IV Curve and bias step calibrations and $P_o$ values demonstrated a significant discrepancy for the 148 GHz camera array. Figure 4.2a demonstrates this disagreement. Through extensive testing of the IDL codes used to generate the run files from the IV curves for the 2007 and 2008 seasons, the faulty code was finally discovered by Matthew Hasselfield. This code defaulted to using a single, constant value of 0.7 mΩ for all shunt resistors in parameter calculations. As can be seen in the formulas in Section 4.1, the detector parameters are sensitive to the shunt resistance values. Thankfully, the relevant detector parameters may either all be shown to be directly proportional to $R_{sh}$ or not dependent on it.

First, the calculated TES current is independent of the $R_{sh}$ in the IV Curve computations, as it is uniquely determined by the feedback current and the offset current, neither of which uses the shunt resistance in its calculation. Next, the TES voltage is directly proportional to $R_{sh}$ as shown by the following:

$$V_o = R_{sh} \left( \frac{V_b}{R_b} - I_o \right)$$

Finally, $P_o$ is also directly proportional to $R_{sh}$ from the standard $P = IV$ equation.

These corrections to the derived detector parameters for the 2008 148 GHz IV Curves have been implemented in the Moby python code that handles these data files and computes the responsivity from them. With these corrections in place, the comparison shown in Figure 4.2a becomes Figure 4.2b. The 2009 IDL code has been adjusted to properly account for the shunt resistance values, and the Python code, thus, does not need to apply any corrections.
4.2 The Load Curve Test

Figure 4.2: The uncorrected and corrected IV Curve $P_v$ versus the bias step computation of $P_o$ for all detectors in the 148 GHz camera array. One data file for each type of test was used to generate the plot. Units for all axes have been converted to pW. The first panel demonstrates the result of assuming a constant value of $R_{sh} = 0.7 \text{ m}\Omega$ in the IV Curve calculations. The second panel demonstrates the result of including the properly measured values of $R_{sh}$ for each detector in the IV Curve calculations.
4.3 The Bias Step Test

The alternative method to IV curve tests for detector characterization is called a bias step test. In this test, a small square-wave pulse change in voltage is applied to a detector bias line. This pulse is added to the current bias voltage, but, by design, the pulse produces only a small fractional change in power through the detector. The detector response is a fairly complicated function, but may be modelled by a one-pole filter if a full fit to the output is desired. Section 4.3.1 will further describe the full fitting routine used to analyze the bias step files and the detector time constants that are modelled. For the majority of the measurements described here, only the amplitude of the detector response pattern to the square wave input is needed. Figure 4.3 demonstrates the output response of a detector to the bias step input, showing the amplitude of the step response and a typical level of noise contamination.

For these tests, only 30 seconds of data are acquired for any given detector, and an entire group of detector commonly attached to a bias line may be tested at the same time. Thanks to this, each array can be fully tested with only three 30 second tests. The pulse duration need only have a 2 s long period in order to far exceed all of the circuit time constants and provide a significantly long section of flat response data. More specifically, the period allows the amplitude of the detector response to the square wave to be measured with less than 2% error on average for the 148 GHz camera detectors. Over the 30 s file, 30 steps are measured and used to reduce the error on the calculated amplitude to this level. Figure 4.4 displays these fractional errors for a sample 2008 bias step file.

The full set of bias step tests to cover all biasing lines on all three cameras was taken three times per standard observing evening during the 2008 season. This allows for testing of changes in detector characteristics during the night, which is not possible with the IV Curve test method. The short duration for the full tests, and the negligible impact on the cryogenics would allow for even more frequent tests. The primary reason for not including
4.3 The Bias Step Test

Figure 4.3: An example detector response to the bias step test. The noise level is much smaller than the size of the step response, as occurs in nearly all properly functioning detectors. The average change in power in each TES is roughly 0.1 to 0.25 pW.
Figure 4.4: The fractional uncertainties in the computed amplitudes of the 148 GHz camera detectors’ responses to the bias step test. Note that this figure displays rows as rows and columns as columns contrary to standard Moby output. These errors demonstrate that the file length is sufficient to very accurately determine the amplitude response, and the period of the square wave input pulse is long enough such that the amplitudes are consistent. This implies that the flat regions of the detector response measured between jumps of bias voltage are well sampled. In this plot, dead detectors are represented as having zero error. For the 2008 season in the 148 GHz detector array, rows 2, 15 and 16 and column 22 all had such non-functioning detectors due to various reasons.
4.3 The Bias Step Test

more tests per evening is a desire to ensure even mapping of the sky during observations.

The bias step tests allow for the computation of the detector circuit parameters using the Equations 4.10 through 4.22 described in Section 4.1. As previously noted, these derivations do not require the computation of the absolute offset current, but rather use the small changes in the detector input and output to determine the absolute values of the detector power, current, voltage and resistance and finally responsivity. Due to the drastically different nature of these tests, much work has been put into ascertaining whether the resulting values correspond properly with those derived using the IV Curve tests. The tests used to compare these two methods will be further described in Section 4.3.3.

4.3.1 Analysis of Bias Step Test Files

The analysis of the bias step test files is included as a part of the Moby mapmaking analysis pipeline. The Moby pipeline code was adapted from codes written by John Appel and Mike Niemack, which were used to conduct laboratory testing of the TES devices. For each test file acquired, the first step of the processing determines the location of the first pulse. This is determined by first locating the first position, called the offset, in each TOD where the current crosses the average file value on an upward slope. From this point, the flat region prior to the crossing is used to compute a standard deviation, $\sigma$, for the detector noise. Next, the step is checked to ensure that the size is at least five times as large as the detector noise. Finally, the beginning of the pulse is defined as the first point greater in time than seven samples before the offset that is within $2\sigma$ of the flat region preceding the offset. This last check is to ensure that the beginning of the pulse is not in the very short region where the detector responds electrically as opposed to thermally. Finally, all detectors for which a beginning pulse is found are averaged to determine the best location for the start of the pulse, expressed as a number of samples from the start of the file.

The preceding and following sections will require a more complete description of the detector physics that are explored when the detectors are subjected to a fast input pulse.
on the biasing line. Niemack [54] and Irwin and Hilton [41] include a complete description of the calculations that are necessary to describe the full detector response, but these are superfluous for the needs of the analysis presented here. The important result of these calculations (and subsequent tests of the detector response using a much higher frequency sampling rate setup in Niemack [54]) is that the detector responses, when sampled at $\sim 400$ Hz, are best modelled using a single time constant, $\tau$. This single time constant, called the thermal time constant, corresponds to the circuit responding to a decrease in external current with a decrease in $V$, and in response, a slower decrease in $R$, constrained by the fact that $P_J = V^2/R$ is roughly constant across the transition [54]. This constraint causes the value of $I = V/R$ to increase, as $R$ must decrease as the square of the decrease in $V$. The detector circuit also has a second, much smaller, electrical time constant, which generates an initial increase in $I$ due to the relatively quick decrease of $V$ compared to that of $R$. This second time constant is what imposes the $2\sigma$ restriction aforementioned, as the motivation is to only measure the slow time constant when fitting the TES response to the bias step. If the restriction were not in place, occasionally the sample chosen might lie in the short-lived decrease in current due to the electrical time constant. Aside from these minor considerations, and unless specifically noted, all further discussions of time constants will be regarding the longer, thermal time constant.

The next step of the analysis involves computing the full fit to the functional form of the TES response. The detector responses as a function of time are fit to a one-pole low pass filter response of the form in Equation 4.24, where $\tau, A$, and $B$ are the effective time constant, amplitude and offset for the response:

$$A e^{-t/\tau} + B.$$  \hspace{1cm} (4.24)

This fit is computed using standard fitting functions, and then the median of all the fitted steps is used to report the final values of $\tau, A$ and the best estimates for the errors on each. The amplitudes, however, are not those used for computing the derived detector
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parameters.

The final step of the TOD processing recalculates the amplitude of the current change response for each detector. This calculation uses a difference between each subsequent flat section of data, where the value of the current in each flat section is determined by a median over 100 samples. The differences are then averaged to determine the final reported amplitude response. The error on this median step response is determined through error propagation of the noise on each flat region of the response.

Once all of the individual detector values are determined for a given bias step file, the next step of the analysis requires grouping the files together to form a full camera of values for a given set of tests. The model for this code is that the user would like to determine the detector properties associated with any TOD record, scanning or otherwise, and passes the bias step analysis program the time when the TOD record to be studied was acquired. This code and the remainder of the analysis code is contained within the Moby Python module named ProcessBiasStep.py. For the 148 GHz and 277 GHz cameras, there are three bias lines, and thus each full camera of detector responses must be assembled by combining the results of the three separate test files recorded. For the 218 GHz camera, only two bias lines are used, and only two files must be combined. The algorithm for properly locating the correct bias step test files to process required a great deal of work. The main structure of the final algorithm begins with the generation of a list of all TOD records for the night or accepting any list as a passed parameter. From this record list, all the bias step files corresponding to the desired camera array are selected. A first pass through the records finds the bias step test taken at the closest time to the input file acquisition time, within those files where the bias step was applied to the first bias line. This file is also restricted to have an acquisition time within the observing night of the input file. From this bias step test file, the files for the other one or two bias lines are found by the same process as the first file, but with the restriction that they be within 300 seconds of the first bias line file. This algorithm underwent several iterations to minimize the number of improper file choices, including day wrapping when the module was passed a very long
list of TODs that wrapped several days and the potential for mixing sets of bias tests taken at different times of the observing night.

Once the three files are selected, the full camera arrays of detector values are formed from the sizes of the input bias step, the operating bias points for all the detectors as chosen by the IV Curve tests, the set of all resistances needed for calculations, including shunt, bias and feedback resistances, and finally all of the computed results from the bias step analysis thus far. These groupings must take into account the parallel resistances used to split up detector bias lines for the 277 GHz camera in order to increase the number of different biases applied to the detector columns (see Figure 2.6). At this point all of the other constants needed for calculations are assembled, and a final correction for any difference in DAC counts reported for the Data Mode used is applied. This last correction was added between the 2008 season and 2007 season, as the MCE Data Mode was inadvertently switched during a firmware update. Finally, once all the needed input values are grouped, the computations of the derived parameters, including $P_o, V_o, I_o$ and the responsivity are done following the steps described in Section 4.1. At any point during the file finding, parameter grouping, and computation steps, if a file or value is missing, the corresponding outputs of the program are set to a default error value of -1. All of the derived parameters are stored in a data depot for future retrieval, so that the fits and calculation steps do not have to be repeated every time a bias step file is to be examined. Finally, this module also contains a function for directly calibrating an input TOD file, instead of passing a ctime and reporting derived parameters.

### 4.3.2 Tests of the Analysis Code

The bias step analysis code has been tested with and without comparison to the IV Curve results. The tests of the bias step analysis code not involving comparisons to IV Curves include some completed during the process of code development and some completed to self-characterize the test itself. The first of these test sets was used to ensure
4.3 The Bias Step Test

the bias line sets used in the calculations were correct. The bias lines are split using parallel resistors on the SA electronics boards within the telescope camera for the 218 GHz and 277 GHz cameras, and these tests were used to verify that the recorded columns corresponding to each input line were actually receiving the bias step pulse. Figure 4.5 demonstrates an example of these plots, showing the responses for full columns of detectors. Such a plot was made for every column in all three arrays for each bias line, making 32 * 3, 32 * 2, and 32 * 3 such plots for the 148 GHz, 218 GHz, and 277 GHz cameras, respectively. By inspecting these plots, the columns with pulse responses for each bias line were easily cross checked, and the correct bias line divisions were used to group together the distinct bias line files into full detector arrays of results.

Another consistency test of the bias step method was a computation of the change in TES power that occurs in response to the bias step. This is important to quantify, as the assumptions of the theory rely on the power only changing by a small fraction of $P_J$. To compute the step in TES Joule power, the amplitudes from the analysis first need to be adjusted to match the standard observing MCE data mode. With the adjusted amplitudes of the detector responses converted to Data Mode 2 units, the power may be calculated by simply multiplying by the responsivity calibrated to units of pW/DAC(DM2). Figures 4.6, 4.7 and 4.8 show these measured changes in TES Joule power that are applied to the detectors during the bias step tests. The average power applied is less than $\sim 0.2$, $\sim 0.2$, and $\sim 0.3$ pW. These correspond to about 4%, 3%, and 2% of the average measured detector power. The change in power rarely exceeds 10% of the measured detector power.

The bias step test method has been used in several applications, including those presented in Sections 4.5 and 4.6. The calculations presented in these sections further test the reliability of the analysis method.
Figure 4.5: The detector responses to the bias step test square wave input function for an entire column of detectors in the 148 GHz camera. Similar plots were generated for every column in all three arrays to cross check the assignment of detector biasing lines for the bias step file processing code. This column is clearly biased by bias line 1, and has three clearly non-responsive (dead) detectors.
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Figure 4.6: The power in picowatts applied to detectors in the 148 GHz camera for the bias step tests. The average power change is about 4% of the total Joule power dissipated by the TES for an average operating point and detector, and the power changes are nearly all less than 10% of the total Joule power.
Figure 4.7: The power in picowatts applied to detectors in the 218 GHz camera for the bias step tests. The average power change is about 3% of the total Joule power dissipated by the TES for an average operating point and detector, and the power changes are all less than 10% of the total Joule power.
4.3 The Bias Step Test

Figure 4.8: The power in picowatts applied to detectors in the 277 GHz camera for the bias step tests. The average power change is 2% of the total Joule power dissipated by the TES at an average operating point.
**Time Constants**

A first test of the bias step analysis code is a comparison of the code output to the previous IDL test code generated by John Appel and Mike Niemack. This test is useful to ensure that the fitting and selection of data for the fits are equivalent enough to reproduce the results shown in Niemack [54]. Figures 4.9 through 4.11 demonstrate the bias step computed time constants and two comparisons of the computed time constants from the two analysis codes. An important note at this stage is that different texts use different conventions for expressing time constants, but formally, time constants may be converted to the equivalent $f_{3dB}$ value in units of Hz from time constants, $\tau$, in units of seconds for each detector using the relationship

$$f_{3dB} = \frac{1}{2\pi\tau}. \quad (4.25)$$

These figures show that the new map making pipeline analysis code does reproduce the appropriate time constants in the fitting routine. The original IDL test code did not have or test a separate amplitude finding method outside of the full fit to the one-pole functional form, and so the new code is an improvement over the original for the derivation of detector circuit parameters including responsivity.

As a second test of the bias step measured time constants, the values were compared to optical time constant data acquired at the beginning of the 2007 season. These optical time constants are obtained through measuring the detector responses to radiation passed through an optical chopper. The chopper explores a wide range of frequencies, and the resulting detector amplitude responses at different frequencies are fit to determine these optical detector time constants. These optical time constants were the default values used to process the telescope data for map making in the 2007 season, and were augmented by calibrated bias step measurements analyzed by John Appel where the optical chopper values were unavailable. The chopper measurements have the benefit of characterizing the detector responses to an external light source, making the measurement
4.3 The Bias Step Test

Figure 4.9: Time constants for the bias step analysis procedure in the Moby map-making analysis code. Units are Hz, giving faster detectors a higher value on the color scale. The time constants show appropriate agreement to the IDL code implementation as seen in Figures 4.10 and 4.11.
Figure 4.10: Time constants for the bias step analysis procedure implemented by J. Appel and M. Niemack in IDL code compared to time constants for the bias step analysis procedure in the Moby map-making analysis code. The $f_{3dB}$ values for the Python analysis code, in Hz, are plotted against the results for the IDL code. The two analysis codes agree well, with some scatter, and one column that has poor agreement. The data points from this column lie above the 1:1 line.
Figure 4.11: The difference in the computations of time constants between the IDL and Moby analysis codes, divided by the error in the python computations. The plots shows that the methods agree to within $2\sigma$, where $\sigma$ is the error computed in the python bias step analysis code measurement.
more similar to the expected detector responses to the sky. The process for acquiring these values is described more fully in Niemack [54], and some preliminary comparisons of bias step and optical time constants are also included within the description.

Figure 4.12a displays a comparison between the time constants derived from optical chopper measurements and those derived from an arbitrarily chosen bias step measurement in the 2007 season. A zoomed in version of the figure is shown in Figure 4.12b. These figures indicate that the time constants computed with the Moby bias step analysis appear to be directly proportional to the optical chopper values, with a ratio for Bias Step to chopper measurements of 1.864. The results clearly also show a good bit of scatter about this rough dependence, which is likely to be due in part to a combination of noise in the measurements and the difference in time between the two measurements. The optical chopper values were recorded on October 27, 2007, while the bias step measurements shown were taken from November 20, 2007. The detector time constants are known to change with bias power, which will naturally change over time. Additionally, the power received by the detectors during the optical chopper measurements is different than open-sky observations due to the chopper wheel and other implements that block background radiation during the measurements. The change in power could be measured using IV Curves recorded at both the time of the optical chopper measurements and time of the bias step tests. This, and the difference in times between the measurements, is likely to generate a significant portion of the 1.864 factor as well.

Another comparison of the measured time constants has become available in the 2008 season. The detector time constants are known to manifest as a peak shift and decrease in peak amplitude in the time ordered data for a planet measurement. The peak shift is a time delay from the expected peak of the planet signal in the time ordered data. Due to the scanning of the telescope, the peak shift is clearly seen if a difference of the positive and negative azimuth scans is used, and Matthew Hasselfield (and several other collaboration members doing similar computations both before and at the same time as Matthew) has generated time constants using a full model and fitting of observations of
4.3 The Bias Step Test

Figure 4.12: The bias step test measurements of the detector time constants compared to the optical chopper measurements for 2007. Both sets of time constants are here plotted in units of seconds. The optical chopper values were recorded on October 27, 2007, while the bias step measurements shown were taken from November 20, 2007. The factor of 1.864 is likely caused by several factors, including changes in bias power due to time and testing conditions. The second panel shows a rescaled plot of only the most dense region.
Saturn in this manner. These measurements are currently being used for all 2008 map-
making. When compared to the bias step measurements of time constants for arbitrary
times, these values still show a direct proportionality. Figures 4.13a and 4.13b show the
comparison of the two methods in the same manner as the previous comparisons. Here,
the ratio between the Bias Step and planet time constant measurements is only 1.41 if
no constant offset at zero is allowed in the fit. Explicitly, this offset is just the y-intercept
of the fit, and is forced to zero to obtain this ratio. This restriction is acceptable, as a
fit allowing an offset does not match the data significantly better, and also skews more
toward outlying data points. A positive constant offset to the fit would also mean that the
bias step measurement systematically limits the measured speed of the detectors. The
only likely cause for such a limitation would be the sampling rate of the instrument, which
should have a similar effect on the time constants measured using the planetary analysis.

Due to the unexplained coefficient factors needed to calibrate the time constants de-
rived from the electrical bias step tests to the optical time constants or planet measure-
ments, the Moby bias step fits and results are currently not being used in our final map
making pipeline. They are, however, calculated and stored to a common bias step results
depot for all observations in the 2008 season for potential future uses.

4.3.3 Comparisons of IV Curve and Bias Step Tests

Given that the IV Curve calculations are currently accepted as our default method
of calculating detector circuit parameters for map making, comparisons between the IV
Curve and bias step test methods provide some of the most relevant checks and compar-
isons of the different test methods. This section will describe many of these comparison
tests. Additionally, the comparisons shown in this section provide very good tests of the
reliability and functionality of the bias step test and Moby bias step analysis pipeline. In all
such comparison plots, missing and/or highly errant values may be distinguished quickly.

Several sets of tests were done to compare both the detector power and responsivity
4.3 The Bias Step Test

Figure 4.13: The bias step test measurements of the detector time constants compared to the planet observation measurements for 2008. The planet observation values use fits to planet crossings from throughout the 2008 season. The two different fits are distinguished by allowing or disallowing an arbitrary offset constant. The second panel shows a rescaled plot of only the most dense region.
results of the IV Curve and bias step analyses. Plots of the responsivity results for both methods and the percentage differences in their values for an individual TOD in all three arrays are shown in Figures 4.14, 4.15, and 4.16. These figures demonstrate that the bias step measurements agree reasonably well with the IV Curve analysis results. However, there are some peculiar features that appear to be specific to each detector array. For the 148 GHz comparison, there appears to be a very small systematic offset between the two calculation methods. This offset would not be important if only the bias step measurements were used, as the calibrations to units of power are eventually converted to units of temperature through calibrations to planet observations. The 148 GHz bias step responsivities otherwise agree very well with the IV Curve results. The 218 GHz array comparison shows more scatter, but less systematic offset than the 148 GHz array. Finally, the 277 GHz comparison indicates that several of the detector columns have distinct and disparate linear relationships between the two measurement methods. In general, the scatter between the two methods is also significantly larger for this array than for the other two detector arrays.

A final set of accumulated responsivity measurements and the percentage difference between the two computation methods is shown in Figures 4.17 and 4.18. These demonstrate that the bias step analysis method is within 3 to 5% of the IV Curve measurements for the responsivity for the 148 GHz array. The general agreement between the two calculation methods shown throughout this section proves that the approximations and assumptions used in the derivations of the computed responsivity for each method are generally valid for our detector biasing configuration. Figure 4.17 shows that the 148 GHz camera bias step results appear to have a systematic offset from the IV Curve measurements, as the peak of the percentage error distribution is centered away from zero. Partially due to this systematic offset, the IV Curves are still being used for all primary analysis routines in the map-making pipeline. The continued use of IV Curves is more largely a factor of inertia within the collaboration. The analysis pipeline currently relies on several results that have used the IV Curve results, and these components would need to be regenerated if
4.3 The Bias Step Test

Figure 4.14: Comparison of the bias step detector responsivity measurements to the IV Curve measurements for 148 GHz. The plots include all working measurements for one TOD. The IV Curve measurements are taken as the accepted values for the percentage difference computation in the second panel. Detector columns are color-coded in order to highlight any possible systematic effects caused by differences in the TES columns.
Figure 4.15: Comparison of the bias step detector responsivity measurements to the IV Curve measurements for 218 GHz. The plots include all working measurements for one TOD. The IV Curve measurements are taken as the accepted values for the percentage difference computation in the second panel. Detector columns are color-coded in order to highlight any possible systematic effects caused by differences in the TES columns. Two populations of detectors show disagreement. The first is the group of detectors with zero responsivity for the bias step analysis method. The second is the group of detectors with unusually low IV Curve responsivities. This second group of detectors may point to a systematic problem with the IV Curve analysis, as the responsivities appear to fall well below the ordinary spread across the other detectors. The histogram excludes some of the outliers seen in the scatter plot.
4.3 The Bias Step Test

Figure 4.16: Comparison of the bias step detector responsivity measurements to the IV Curve measurements for 277 GHz. The plots include all working measurements for one TOD. The IV Curve measurements are taken as the accepted values for the percentage difference computation in the second panel. Detector columns are color-coded in order to highlight the clear systematic effects caused by differences in the TES columns. Several of the detector columns show distinct and disparate linear relationships between the two measurement methods for this array.
the bias step results were to be used for the time-dependent calibrations. The bias step analysis, however, has proven very useful for measuring changes in detector quantities throughout any given night or period of days. Additionally, the bias step measurements of the time constants are the only method of measuring changes in the detector time constants on time scales shorter than the time between planet observations. Thanks to their ease of acquisition and the comprehensive analysis pipeline developed for the bias step tests, these measurements have recently found use in an analysis of optimal detector biasing done by R. Dunner.

### 4.4 Atmospheric Flat Fielding Calibration

#### 4.4.1 Concept

A time-independent flat fielding term must be computed for each array to augment the responsivity of the detectors to incoming sky power. The flat fielding specifically augments the time-dependent calibration, which only converts the recorded DAC units to power changes at the detectors. Several terms contribute to the need for the time-independent flattening, including uncertainty in the measurements of the shunt resistances, differences in illumination across the array due to the orientation of the optics, differences in the distance between the detectors and the optical coupling layers, and other physical effects caused by the telescope optics including uneven mirror and array illumination. The optical coupling layer is a thin anti-reflection layer that is separated from the detectors by a fraction of a wavelength. The flat-fielding terms for responses to diffuse signals are computed through analysis of the large atmospheric signal observed in all detectors across the three camera arrays. Flat-fielding terms for the detector responses to point source observations are computed for other analyses including planet calibrations, such as those described in Section 4.6.1 and Switzer [75], but will not be further discussed here. To compute the flat-fielding terms, we require that all the detectors in a single array have the same response
4.4 Atmospheric Flat Fielding Calibration

(a) Detector Responsivity Bias Step vs. IV Curve Measurements

(b) Percentage Differences Between Bias Step and IV Curve Measurements

Figure 4.17: Comparison of the bias step detector responsivity measurements to the IV Curve measurements for 148 GHz. The plots include all working measurements for all bias step tests done over the period of September 15 to 25. The IV Curve measurements are taken as the accepted values for the percentage difference computation in the second panel. Detector columns are color-coded in order to highlight any systematic effects caused by differences in the TES columns. This coloring clearly shows that measurements from one detector or section of a column in the upper portion of the array consistently do not agree between the two methods.
Figure 4.18: Comparison of the bias step detector responsivity measurements to the IV Curve measurements for 218 GHz. The plots include all measurements for all bias step tests done over the period of September 18 to 25. The IV Curve measurements are taken as the accepted values for the percentage difference computation in the second panel, and the plot is cropped to below 20% for clarity. Detector columns are color-coded in order to highlight any systematic effects caused by differences in the TES columns. This coloring shows that measurements from several detectors in the array consistently do not agree between the two methods. The same two populations of detectors appear noted in Figure 4.15 continue to show disagreement.
4.4 Atmospheric Flat Fielding Calibration

to this atmospheric signal after the flat-fielding calibration is applied.

This atmospheric signal is restricted to frequencies below a value set by a combination of the scanning rate, average atmospheric layer height, layer scale and speed, and telescope beam. To determine a rough approximation of the frequency restriction, the first step is to consider that the atmospheric layer being observed is in the near-field of the telescope optics. The average layer that produces the common-mode signal in the camera arrays is located at approximately 1 km above the telescope location. The far-field of the telescope begins at approximately $2 \times \frac{D^2}{\lambda}$. This is on the order of 30000 m, where $D$ is the telescope’s 6 m diameter, and $\lambda \sim 2$ mm is the observing wavelength. The second consideration is the speed over which the telescope scans this atmospheric layer. The telescope scanning rate is very roughly 20 m/s across the layer at 1 km. Finally, the minimum scale size of a feature passing through the atmospheric layer that may be resolved in the near-field is 3 m. The combination of these parameters sets the maximum atmospheric signal frequency to be on the order of $\sim 10$ Hz. A more complete calculation and analysis were conducted by J. Fowler, who found that the maximum signal is more closely approximated by 5 Hz. Thanks to this limitation, the time streams used in the flat-fielding computation may be downsampled to an appropriate sampling rate, which helps to remove signals coming from smaller-scale, far-field sources.

4.4.2 Implementation

The computation of the time-independent flat-fielding coefficients is implemented within the Moby python code structure. The code uses a series of steps to reduce the final uncertainty in the calibrations, and to use a high fraction of all input TODs. To begin, a standard set of TOD cuts is applied, which remove either entire 15 minute TOD sections for single detectors or smaller time sections from the analysis. These cuts are generated by R. Dunner and T. Marriage and primarily focus on removing TODs that have sudden time-stream jumps or odd noise properties. In addition to these base cuts, odd glitches
that appear as transient, unexplained jumps or dips in the data time stream are cut out of the TODs. All TODs which are only partially cut are filled with simple interpolated data with an appropriate level of noise. After the cuts are implemented, a common mode for all dark detectors is computed. This common mode is computed using a routine also developed by R. Dunner. The routine uses the data streams for all detectors that do not respond to incoming power from the sky. These dark detectors include the dark SQUIDs on the mux chips, which have no associated TES detector intentionally, and any dead detector lines that do not respond to the sky, but still have well behaving SQUIDs. These detectors typically observe a common, low frequency signal, that is largely due to small temperature variations within the MBAC.

After the data have been cleaned, the Butterworth filter is deconvolved from the time streams. Next, a calibration to units of electrical pW is applied using the results of the IV curve analyses. The routines for the flat fielding also have the capability to use the bias step calibrations if desired. Next, the data are filtered. This has been programmed in two distinct manners. The first is a full implementation of a low-frequency Wiener filter, and the second is a downsampling by a factor of two that is repeated 5 times. Both filtering methods remove signals above a cut off near 10 Hz. The flat-fields used in our current calibration routines were derived using the simple downsampling choice.

With all of the data properly prepared, the median values of the detector time streams are subtracted to remove the arbitrary offsets between detectors that are generated by the SQUID readout system. From these time streams, a median over all detectors is computed at each time sample. This is taken to be the common array response to the large atmospheric signal, and each detector TOD is linearly fit to this median TOD. By comparing the quality of the fit for each detector to the average fit quality for all detectors, a set of cuts is generated. The goal of these cuts is to remove those detectors that do not follow the average detector response to the atmosphere. Finally, a second iteration of the full process, starting with the computation of the median TOD, is run.

The final list of detector flat-fielding coefficients is output as the amplitudes of the linear
4.4 Atmospheric Flat Fielding Calibration

fits. These are equivalent to the coefficients by which the median TOD would need to be multiplied in order to best fit the individual detector TODs, but we often describe them as the relative calibrations between detectors. For the final calibration values, the inverse of these coefficients must be used. In addition to these coefficients, the offsets and $\chi^2$ values computed during the fits are stored.

To generate a final flat-field array using this method, many TODs should be used, and the relative calibrations should be averaged over. Due to the nature of the effects being modeled, the relative calibrations for each TOD should be constant, with only noise producing scatter in the values as a function of time. This median was computed using approximately 30 TODs for each detector array in the experiment. For the 148 GHz and 218 GHz cameras, the median fit amplitudes match the individual TOD relative calibrations fairly well. This was quantified by computing the RMS of the individual TOD flat field array values about the mean across the ~30 TODs. Figures 4.19 and 4.20 demonstrate examples of the median calibrations computed using roughly 30 TODs each, along with the RMS on these medians. Finally, Figure 4.21 demonstrates the variation in the flat-fielding calibration fit amplitudes over the set of TODs for one detector in the 148 GHz detector array.

The atmospheric flat-fielding calibrations generated by the process above have been successfully used within the map-making code for the 148 GHz and 218 GHz cameras for the 2008 season. These relative calibrations have helped to eliminate systematic errors in the responsivities of the detectors and are the only way to account for the changing illumination across the focal plane caused by the optics. Tests done by A. Hincks using a similar routine have shown that this calibration is necessary to remove several mapping artifacts that occur without it. Unfortunately, the 277 GHz camera data appears to have too many contaminants to effectively generate a median flat-field calibration.
Figure 4.19: The median relative detector calibrations computed for individual TODs for the 148 GHz camera. The first plot shows the amplitudes of the fits to a median TOD computed using all detectors. The second plot shows the error on the median calibration. This RMS of the median is calculated using the RMS of the calibrations computed over all TODs used in the median divided by the square root of the number of TODs that contributed to the mean for each detector.
4.4 Atmospheric Flat Fielding Calibration

Figure 4.20: The median relative detector calibrations computed for individual TODs for the 218 GHz camera. The first plot show the amplitudes of the fits to a median TOD computed using all detectors. The second plot shows the error on the median calibration. This RMS of the median is calculated using the RMS of the calibrations computed over all TODs used in the median divided by the square root of the number of TODs that contributed to the mean for each detector.
Figure 4.21: The amplitude of the fit computed by the relative detector calibration process for a sample 148 GHz detector. The plot demonstrates the low variability of the fit amplitudes with time over a portion of a standard observing night. The low variation is expected for the effects being modeled by this calibration.

### 4.4.3 Detailed Description of AR3 Difficulties

For the 277 GHz camera, the method implemented for the other two camera arrays is insufficient to generate a reliable relative detector calibration. This is likely caused by the use of two different detector types in the array. These different detectors were mainly distinguished by having lower superconducting critical temperatures and larger leg widths. These larger leg-width detectors were primarily installed in columns above column 15 of the array. These columns show systematically higher responsivity in both IV and bias step tests, which could indicate a problem with the computed responsivities. A systematic error in the responsivities would clearly also affect the flat-fielding calibration routine. In addition to the differences in detector types, the TODs for all detectors appear to be contaminated by greater noise than the 148 GHz or 218 GHz arrays according to studies on planets done by A. Hincks. Additionally, from analyses of the 277 GHz detector spectra, we believe that the coupling layer generated additional noise through vibrations in the 2008 season.

The relative calibrations results for individual TODs for the 277 GHz camera have sev-
4.5 Efficiency Computations

Several different visually discernible patterns. These may be categorized roughly into four groups, into which most all of the relative calibration patterns fall. The first type of array of relative calibrations has very scattered amplitudes in columns 0 through 9 and 11 through 20. Figure 4.22a demonstrates an example from this category. The second category of results is characterized by a sparse number of detectors that pass the cutting processes in the either just the lower portion of the array or the entire array. Figure 4.22b demonstrates an example from this category. The third category is characterized by the bottom columns and top columns each exhibiting a relatively constant calibration and with not many detectors being cut. Figure 4.22c demonstrates an example from this category. Finally, the last category has relative calibrations all below one for the bottom portion of the array, while the top portion is nearer to one. Figure 4.22d demonstrates an example from this category. Even the calibrations that fall within one of these categories of visually discernible patterns are not consistent. Figure 4.23 shows a few examples of the difference of a calibration derived from a single TOD to that derived from the mean of all 31 TODs tested for these calculations.

At present, no single set of relative calibrations has been chosen due to the poor results from the flat-fielding tests done. This will need to be completed before any maps of the CMB can be accurately made. For large signal sources, however, A. Hincks has succeeded in demonstrating that the signal from a bright galaxy cluster may be seen in a map using the Cottingham Method described in Hincks et al. [31] and Hincks [30].

4.5 Efficiency Computations

One application of the calibration techniques described thus far is to determine the efficiency of the ACT telescope to observations of planets. This study also serves as a reasonable test of the bias step and IV curve calibration approaches. The approach to testing the efficiency is straightforward once the array responses to power are calculated in terms of $dP(\text{Electrical pW})/dI(\text{DAC})$. For each Saturn observation of the 2008 Season,
Figure 4.22: Relative detector calibrations computed for individual TODs for the 277 GHz camera. The plots show the amplitudes of the fits to a median TOD computed using all detectors. The four different categories of visual patterns for possible flat-fielding results are demonstrated in the four panels. These patterns are described in Section 4.4.3. The plot titles include the computer time stamp (ctime) for when the data were taken.
4.5 Efficiency Computations

(a) 277 GHz Flat-Fielding Category 1 Difference From Mean
(b) 277 GHz Flat-Fielding Category 2 Difference From Mean
(c) 277 GHz Flat-Fielding Category 3 Difference From Mean
(d) 277 GHz Flat-Fielding Category 4 Difference From Mean

Figure 4.23: Differences between relative detector calibrations computed for individual TODs for the 277 GHz camera and the mean over 31 TODs. The four different categories of visual patterns for possible flat-fielding results are demonstrated in the four panels. These patterns are described in Section 4.4.3 and plotted in Figure 4.22. The upper detectors in panels (b) and (c) are cut based on a restriction that the relative calibration be less than 2. The plot titles include the computer time stamp (ctime) for when the data were taken.
Adam Hincks used a simple gaussian fitting routine to determine the maximum amplitude in DAC counts measured for each detector in the MBAC camera. This fitting routine is necessary because the planet does not cross the center of every pixel’s beam when the telescope scans across the sky. The calculation determines the best estimate for the maximum amplitude of each detector’s response to the passing planet. Matthew Hasselfield is currently implementing a similar procedure in the Moby analysis pipeline. Figures 4.24a, 4.26a, and 4.28a show an example set of amplitudes for each of the three arrays. The amplitudes include a relative flat-fielding calibration computed by Adam Hincks specifically for the planet observations. These DAC amplitudes are then multiplied by the individual detector responsivities as computed with each of the IV curve and bias step methods in order to compute the values of electrical pW responses to planet observations. Figures 4.24 through 4.29 include the detector electrical power responses to Saturn for the three arrays. The final step of the efficiency calculation uses the expected power of Saturn received above the atmosphere, taking into account the effective antenna temperature of the planet, $T_{\text{Saturn}}$, its solid angle, $\Omega_{\text{Saturn}}$, the telescope beam size, $\Omega_b$, and bandwidth, $\Delta \nu$, for each of the three detector arrays. The expected power is computed as:

$$S_{\text{Saturn}}(W) = 2k_B T_{\text{Saturn}} \Omega_{\text{Saturn}} \Delta \nu / \Omega_b.$$  \hspace{1cm} (4.26)

The expected powers from Saturn, computed using this formula, are 2.55, 4.35, and 6.06 pW for the 148 GHz, 218 GHz, and 277 GHz arrays, respectively. The efficiency calculated is then simply:

$$\text{Efficiency} = \frac{\text{Observed Electrical Response (pW)}}{\text{Expected Sky Power (pW)}}.$$  \hspace{1cm} (4.27)

Note that this definition of efficiency includes the loss in power due to atmospheric opacity, and the calculations treat the opacity as a constant throughout time.

Figures 4.24 through 4.29 show the resulting efficiencies calculated for all three arrays.
corresponding to the input responsivities and power changes previously referenced. For the 148 GHz and 218 GHz cameras, the efficiencies calculated are approximately $\sim 0.2$ and $\sim 0.3$, on average. These efficiencies are roughly consistent with expectations based on the camera and telescope design. Additionally, the efficiency calculations for these arrays are consistent between the bias step and IV Curve responsivity calculation methods. For the 277 GHz camera, the top and bottom sections of the array also show agreement, but the middle set of rows is less consistent between the two calibration methods.

For all the Saturn observations analyzed by A. Hincks, the efficiencies of the three arrays were computed in this same manner. Using all of these computations, histograms were generated including the efficiency of all detectors over all Saturn observations. These are shown in Figures 4.30 and 4.31. The two different calibrations methods show general agreement for the 148 GHz and 218 GHz arrays in both these distributions and when comparing the individual Saturn observation plots. This provides a good demonstration of the general effectiveness of the bias step calibration method in producing similar results to the IV Curve method for these two arrays, and even the results for the 277 GHz array show a common peak value between the two methods. Unfortunately, individual detectors results still are not precisely consistent throughout the three arrays.

4.6 Final Calibration Method and Results

For the 2008 season, only the 148 GHz and 218 GHz camera data are currently being converted into sky maps for power spectrum and secondary anisotropy measurements. This is partially due to the difficulties in calibrating the 277 GHz camera that have been demonstrated throughout this chapter. The current implementation of the calibration for the 2008 season map-making for the other two arrays uses only three steps. The first step is the time-transfer calibration and conversion from measured DAC counts to changes in detector power. For the current analysis, this calibration uses the corrected IV Curve measurements of the detector responsivity. The average night-to-night responsivity change to
Figure 4.24: 148 GHz plots for the calculation of the camera efficiency. Panel 4.24a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.24c), and efficiencies calculated using the IV Curve method are shown. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken.
4.6 Final Calibration Method and Results

Figure 4.25: 148 GHz plots for the calculation of the camera efficiency. Panel 4.25a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.25c), and efficiencies calculated using the bias step method are shown. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken.
Figure 4.26: 218 GHz plots for the calculation of the camera efficiency. Panel 4.26a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.26c), and efficiencies calculated using the IV Curve method are shown. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken. Bias line 2 (see Section 2.2.3) appears to show a systematically larger response to the planet.
4.6 Final Calibration Method and Results

Figure 4.27: 218 GHz plots for the calculation of the camera efficiency. Panel 4.27a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.27c), and efficiencies calculated using the bias step method are shown. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken. Bias line 2 (see Section 2.2.3) appears to show a systematically larger response to the planet.
Figure 4.28: 277 GHz plots for the calculation of the camera efficiency. Panel 4.28a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.28c), and efficiencies calculated using the IV Curve method are shown. The TOD chosen for this analysis resulted in a relatively high number of working detectors for the gaussian fitting routine. In general, there were only a small number of detectors for which these fits produced an output amplitude for this camera due to a higher noise level in the instrument. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken.
4.6 Final Calibration Method and Results

Figure 4.29: 277 GHz plots for the calculation of the camera efficiency. Panel 4.29a contains the Saturn amplitudes in DAC counts generated by Adam Hincks for one TOD. The responsivities, computed camera response changes in detector power (4.29c), and efficiencies calculated using the bias step method are shown. The TOD chosen for this analysis resulted in a relatively high number of working detectors for the gaussian fitting routine. In general, there were only a small number of detectors for which these fits produced an output amplitude for this camera due to a higher noise level in the instrument. Panel (a) has units of DAC counts, panels (b) and (c) have units of pW/DAC and pW, respectively, and panel (d) is a unit-less ratio. The plot titles include the computer time stamp (ctime) for when the data were taken.
Figure 4.30: The computed efficiencies for all detectors accumulated over all Saturn observations analyzed. These efficiencies were computed using the IV Curve calibration method.
Figure 4.31: The computed efficiencies for all detectors accumulated over all Saturn observations analyzed. These efficiencies were computed using the bias step time-transfer calibration method.
be removed by this calibration was measured using the bias step analysis method. This variation was found to be 3.0%, 5.3%, and 9.1% for the 148 GHz, 218 GHz, and 277 GHz cameras, respectively. The responsivity change during each night was also averaged and found to be 1.0%, 1.8%, and 2.9% for the 148 GHz, 218 GHz, and 277 GHz cameras, respectively. This variation is measured using the three bias steps taken per night, which cover the beginning, middle, and end of the ∼8 – 13 hr observing nights. This variation is not currently being removed, due to the choice of the IV Curve testing method.

The second step of the calibration uses the atmospheric flat-fields to adjust the relative detector calibrations. The relative calibration adjustment is on the order of 20% for the 148 GHz and 218 GHz arrays. The relative RMS for the flat-fielding calibrations applied by this step is 1% for the 148 GHz and 218 GHz cameras.

4.6.1 Absolute Calibration to Uranus

The final step of the calibration is a conversion to units of sky temperature. This absolute calibration to units of \( \mu K \) is accomplished through analysis of Uranus observations. This analysis has been developed and thoroughly described by E. Switzer in Switzer [75]. Initial analyses used Saturn as the primary calibrator, but Uranus has been chosen for the current map-making pipeline. The brightness temperature over the frequency bands for our experiment is expected to be smoother for Uranus than Saturn. The brightness temperature is approximately 100 K for Uranus. The absolute calibrations measure the telescope peak response to Uranus and compare it to a full model for its brightness temperature for several independent observations during the 2008 season. The brightness temperature is adjusted for the relative ratio of the telescope beam’s solid angle and Uranus’s solid angle. This calibration produces an error of 1% for the 148 GHz and 218 GHz cameras, and 6% for the 277 GHz camera.
4.6 Final Calibration Method and Results

4.6.2 Conclusion

The implementation of the 2008 calibration appears to be largely successful in our map analyses thus far. The final pieces of the calibrations for the 2008 season, including new flat-fielding analyses for the 277 GHz array, are currently being developed within the collaboration. The calibration routines for the 2009 season are also currently being developed as extensions of the 2008 calibration methods. The multiple tests of the bias step analysis method shown in this chapter provide some interesting avenues for future exploration. Specifically, the populations of detectors that show systematic disagreement between the IV Curve and bias step analyses will be more carefully studied in the future. Thanks to the general agreement of the bias step and IV Curve methods shown in this chapter, the bias step analyses are already being used more frequently for systems testing in the 2009 season than they were in the 2008 season.
Chapter 5

Point Sources in the ACT Survey

The ACT experiment observes at frequencies spanning the high frequency tail of radio source flux spectra and the low frequency tail of infrared (IR) point source spectra. The bands used provide a unique opportunity to measure both these populations within the ACT fields, where previous experiments have mainly covered the span of frequency space just below or well above our bands. This chapter will begin with a description of the basic properties of the point sources types expected for the ACT observations in Section 5.1. In Section 5.2 I will present the current prominent areas of research in millimeter studies of point sources as an introduction to the motivation and primary goals for characterizing these sources as observed in the ACT maps. In Section 5.3, I will present an overview of the current state of research regarding both main source type populations through an examination of the results of several recent surveys. Section 5.4 will describe tests of the methods used for detection and photometry in the ACT simulated sky maps. Section 5.5 will present findings of the population of sources observed in the ACT 148 GHz and 218 GHz maps with conclusions concerning the distribution of spectral indices and counts of both radio and IR sources extracted from the maps. Finally, Section 5.6 will explore some other considerations for improvements on the methods used for this study and demonstrate some brief results of tests conducted by other members of the ACT collaboration.
5.1 Point Source Types

The ACT bands explore both radio and IR point source populations through millimeter observations. Radio sources include a broad range of source types. The vast majority of radio sources are galaxies containing radio-loud Active Galactic Nuclei (AGN). Radio-loud sources are generally accepted to be those where the AGN includes a relativistic particle jet in addition to a significant accretion disk. Within this broad category of sources are several distinct sub-categories. These include quasars, blazars and ordinary radio galaxies. Blazars specifically include all BL Lacertae type objects and Optically Violent Variable (OVV) quasars. The astrophysical model that distinguishes the three main categories of radio-loud AGN is characterized primarily by the relative angle of the jet to the observer [7]. If viewed along the axis of the jet, a Blazar is observed. When the jet is perpendicular to the line of sight, an ordinary radio galaxy is seen. For intermediate viewing angles, the sources appear as quasars. IR sources more simply consist primarily of dusty galaxies re-emitting absorbed starlight. Figure 5.1 compares the spectral range at which these IR sources have previously been examined with the spectral range of interest for CMB observations. The image indicates that the dusty galaxy emission overlaps with the spectral range of the CMB, and thus it is expected that these galaxies will be seen in the higher frequency CMB observations. This figure covers the frequency range of the Cosmic Infrared Background (CIB), which is a relic radiation similar to the CMB. The CIB was predicted and commonly accepted to be the radiation emitted by the initial formation of stars and galaxies. This radiation has been absorbed and re-emitted by dust and redshifted by cosmic expansion into the infrared spectrum [29].

5.1.1 Radio Source Radiation Mechanism

The radiation mechanism which commonly powers radio point sources is synchrotron radiation. The active nuclei of radio galaxies contain strong magnetic fields which affect the direction of motion of electrons moving through them. The electrons gyrate about the
Figure 5.1: Comparison of the CMB and Cosmic Infrared Background (CIB) spectral range. Dusty IR galaxies will be observed in CMB measurements, thanks to the overlap of the spectral ranges. Shown are CIB theoretical spectra (solid, long dashed and dotted lines) in relation to the CMB spectrum (small dashed line). Also included are data points from several surveys of the CIB and the Cosmic Optical Background. Open squares are from the Diffuse Infrared Background Experiment (DIRBE) [28], the red line measurements are from the COBE Far Infrared Absolute Spectrophotometer (FIRAS) [21], and the solid squares are from Lagache et al. [45] and Dwek and Arendt [19]. Section 5.3.3 discusses recent results regarding the source of the CIB, as observed by the Balloon-borne Large-Aperture Submillimeter Telescope. Image adapted from: Guiderdoni [27] by the kind permission of the ASP Conference Series.
5.1 Point Source Types

magnetic fields because of the Lorentz Force, \( F = q(\mathbf{v} \times \mathbf{B}) \), where \( \mathbf{B} \) is the magnetic field and \( \mathbf{v} \) is the velocity of the electrons. The electrons move at relativistic speeds thanks to acceleration by the extreme gravitational forces of the central black hole. The radiation emitted by the Lorentz Force acceleration process on these relativistic electrons is known as beamed synchrotron radiation. The beaming is specifically caused by the relativistic motion of the electrons, which causes an aberration in the distribution of the emitted radiation. The effect is further described in several reference texts, including Longair [47] and Rybicki and Lightman [66].

The magnetic field strength in these radio galaxies that is necessary to produce the average observed radiation is on the order of \( B \sim 10^{-5} \) G. Additionally, the required electron velocities correspond to a Lorentz factor of \( \gamma \approx 1000 \). To better expand on the characteristics of radio point sources, it is useful to describe them in terms of their flux, \( S \), at a given frequency, \( \nu \). For all point sources, the spectral index, \( \alpha \), is used as a primary form of source characterization. The spectral index \( \alpha \) is formally defined for this thesis by \( S(\nu) \propto \nu^\alpha \) although some texts include a negative sign for the exponent (and other texts will use \( \beta \) with the negative sign). Generally speaking, a radio source can be placed into one of two primary categories based on its spectral index. This distinction is dependent on the amount of synchrotron radiation that is re-absorbed by other relativistic electrons in the source. This process is known as self-absorption. For sources without significant self-absorption, a spectral index of \( \alpha \sim -0.7 - 0.8 \) is normally observed. This corresponds to a simple sum of the output radiation from the distribution of particles in the AGN system. However, for sources that are likely to contain a significant amount of self-absorption, the spectral output is observed to be relatively flat, with an index \( \alpha \sim 0 \). In less abstract terms, the extended portions of a radio source, particularly ones with prominent jets, have little self-absorption while the core regions have significant absorption. Which of these regions dominates the total flux of the source will determine its primary spectral characteristics. One final characteristic of the theoretical spectrum of these sources is a high-energy rolloff in power. Above some high frequency cutoff, the spectrum will decline more steeply due
Point Sources in the ACT Survey

to differential energy losses. The particles lose energy through synchrotron radiation, inverse Compton scattering, bremsstrahlung, adiabatic expansion and ionization. The description above closely follows the presentation of radio galaxy emission in Verschuur and Kellermann [82].

5.1.2 IR Source Radiation

The IR sources observed in the millimeter wavelength regime primarily consist of individual highly dusty galaxies. Recently, the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST) has demonstrated that these individual galaxies are the source of all of the cosmic IR background radiation observed in submillimeter and optical surveys [16].

To further describe these sources, we include several of their properties as presented in Guiderdoni [27]. In these sources, the dust absorbs ultraviolet and optical light and then re-radiates with a broad spectral energy distribution. The heating source for the absorbed energy can come in one of several forms. The most common of these is a large young stellar population, and these source types are known as starburst galaxies. Another possible energy source, which is more likely associated with fainter IR sources, is the average radiation emitted by an old stellar population. The brightest sources are thought to be powered by an AGN as in a radio source, but for these objects, the dust must be sufficient to obscure or dominate the radio emission to be considered a solely IR source.

Much of the current understanding of the IR sources observed at millimeter wavelengths comes from studying local IR source galaxies. These include the family of luminous and ultra-luminous IR galaxies (LIRGs and ULIRGs) as well as local spirals. The population of sources that makes up the CIB and the primary sources observed in CMB experiments most likely contain many highly redshifted sources similar to the local LIRG and ULIRG source types [27]. This likelihood is substantiated by examining how the spectrum of such a source would appear if it were at a variety of redshifts as in Figure 5.2. This
5.1 Point Source Types

Figure 5.2: A Luminous IR Galaxy spectra as observed at multiple redshifts. The redshift increases from the top to bottom curve. This demonstrates the insensitivity of the flux to increasing redshift in the millimeter regime. Image Credit: Guiderdoni [27] by the kind permission of the ASP Conference Series.

The figure indicates that the intensity of a point source in the millimeter wavelength regime is largely unaffected by redshift. This is caused by the wavelength shift in the spectral peak due to redshifting, combined with the decrease in luminosity due to the increased distance [27]. The slope of the spectra of these sources at rest frame wavelengths above 100 $\mu$m is such that these combined effects change the flux in this region very little. Local observations of dusty IR galaxies have found that these sources have spectral indices consistent with $\alpha = 2.6 \pm 0.3$ [43]. For comparison, blackbody emission at low frequencies is characterized by a spectrum with $\alpha \approx 2$. 
5.2 Project Motivation and Goals

Many recent experiments have observed both Radio and IR point sources at frequencies below and well above the ACT bands, and these observations have several key motivations in common.

5.2.1 Spectral Indices

The primary goal of many of the point sources studies conducted in the CMB regime is to extract the spectral index distribution of the population of observed sources. For many experiments, these indices may be extracted self consistently thanks to these instruments having several bands of observations. For experiments with one band, complimentary observations from other instruments are correlated to detections and indices are extracted through the comparison of flux between the catalogs. Several motivations for carefully studying the spectral index distribution exist. One important goal of many studies is to differentiate the types of sources and determine the relative contribution of each type to the total flux observed by the experiment. Specifically, the relative contributions caused by flat and negative spectral index radio sources and IR point sources is useful for calibrating the correct amount of modeled power to subtract from CMB power spectrum estimates. For any survey, there will be a low flux cutoff for source detections, but sources below this cutoff will still contribute a contaminating power to CMB flux measurements. The contribution of each source type must be both modeled independently for its relative contribution to the observed CMB power spectrum and also calibrated to the appropriate level for the instrument’s wavebands and sensitivity. One example of this contamination is that for the WMAP experiment a 5% error in the determination of the point source contributions can create a $0.15\sigma$ change in the measured value of $n_s$ [87].
5.2 Project Motivation and Goals

5.2.2 Source Characteristics

Although a great deal is understood about radio point sources from previous experiments, there are still spectral characteristics that require additional observations. The most important of these spectral regions is the aforementioned high frequency cutoff caused by energy losses. This portion of the source spectra is known to have a much steeper falloff than the ordinary $\alpha \sim -0.75$ average falloff for an extended radio source. If an experiment probes the appropriate combination of redshift and frequency range to include this tail of the radio source spectra, the roll-off must be taken into account in order to appropriately characterize, model, and remove the source contamination from CMB observations. Another source characteristic that requires continued study is point source variability. This is especially important for Blazars, as these object types are often specifically categorized by their high level of variability. To truly understand the flux contribution of source populations to CMB observations, properly averaged statistics over multiple years of observation would be most useful. If a survey is of sufficient length and uses proper weighting in map-making, extracted source fluxes can be used to approximately remove the effects of even variable source contamination. The flux estimates are restricted in their usefulness to the time period and frequencies in which they were measured, however. The variability of the sources is generally not measured sufficiently to determine future flux levels, and the variability may be different for different observing wavelengths. The length of observing time needed to properly extract the variable source contamination will also vary greatly depending on the different source populations probed by the experiment.

5.2.3 Cluster Observations

An important goal of several modern CMB experiments is the detection and characterization of galaxy clusters through measurements of their tSZ signature. Both detection and characterization of clusters are subject to significant interference from coincident point sources. If a point source’s properties are well understood, it can be removed in
map-making processes and the cluster characteristics may be better estimated. Additionally, if statistically useful numbers of cluster detections are desired, as are necessary for using these detections to determine cosmological parameters, point sources contributions to maps must be carefully modeled and subtracted prior to analysis. Radio and IR point sources will naturally contribute to all detector bands, increasing the number of false cluster detections at frequencies above the SZ null and decreasing the number of detections below the null.

5.2.4 Additional Motivations

Individual point sources may contain elements of several different canonical types, as previously mentioned. These mixed source types are interesting focuses of study both for developing statistics concerning their populations and for exploring evolutionary models of the source types. An example case of interest is the study of IR sources powered by an AGN. The spectra of these sources depends on the evolution of both the non-thermal and dust emission source components [60]. Even in simpler dusty IR source galaxies, the evolution of the dust will generate shifts in the luminosity and spectra of sources. For a demonstration of this concept, see Guiderdoni [27]. This evolution is best studied through surveys of sources that explore down to low flux values, and subsequently, wide ranges of redshift.

One consequence of performing a deep survey of sources is that it allows for the removal of a significant portion of the Poisson distribution of the sources on the sky [80]. Sources also are known to exhibit clustering in addition to Poisson distribution, and this can produce an effect on the measured power spectrum of source contamination for CMB observations in particular. Measuring and modeling this clustering only becomes important at the level when a significant portion of the Poisson distribution can be properly removed from CMB maps.
5.3 Recent Survey Results for Point Sources

5.2.5 Goals of This Research

There were several goals for the preliminary point source studies described in Sections 5.4 and 5.5. The main goal of the work was to explore the information about spectral indices of observed sources in the ACT 148 GHz and 218 GHz maps. To attain this goal, several subsidiary goals were achieved. The first of these included the testing of different methods of source detection and optimization of photometry within the context of the SExtractor analysis program (available from Bertin [12]). Second, methods for comparison of catalogs were developed. Next, a system was developed for exploring source catalogs from complimentary experiments with coincident source detections. Finally, a system for extracting the spectral indices using various subsets of the available information from the ACT maps and external observations was developed. This was needed, particularly because of the lack of availability of 218 GHz camera maps during the period of initial study. The map analysis methods and catalog comparison routines were all explored using simulations generated by Neelima Seghal, Paul Bode, Sudeep Das, Carlos Hernandez-Monteagudo, Kevin Huffenberger, Yen-Ting Lin, Jeremiah P. Ostriker, and Hy Trac [68].

5.3 Recent Survey Results for Point Sources

Before describing the study conducted for the ACT observations, it is useful to describe the current state of research for point source observations to provide a context for the final results. Many recent experiments have probed the radio and IR source populations either as independent explorations or as a portion of general survey mapping and analysis. Of these, I have chosen to present a subset of the results from the Wilkinson Microwave Anisotropy Probe (WMAP), the Arcminute Cosmology Bolometer Array Receiver (ACBAR), the Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST), and the Atacama Pathfinder Experiment Sunyaev-Zeldovich (APEX-SZ) surveys in the following
Figure 5.3: The spectral indices of the point sources in the WMAP 5-Year catalog. The histogram demonstrates that a typical source detected in the 5-year maps has a nearly flat spectrum. The spread of the distribution is enlarged by measurement errors, and so the underlying distribution of spectral indices is implied to have a smaller spread. See Section 5.3.1 for further details concerning the spectral indices of the WMAP point sources. Image courtesy of the WMAP science team: Wright et al. [87]

sections.

5.3.1 WMAP Point Source Results

The recent release of the WMAP 5-year point source catalog results in Wright et al. [87] provides a substantial contribution to the current state of research for sources in the 23 GHz to 94 GHz spectral regime. The WMAP 5-year results incorporate an all-sky survey in 5 wavebands centered at 23, 33, 41, 61, and 94 GHz. Using the 5-year maps, 390 point sources have been detected down to a 2 Jy source flux minimum. The minimum Signal to Noise Ratio (SNR) for detection was set to 4.7 for these detections. The 5-year observations are comprised of primarily radio point sources with spectral indices centered at $\alpha = -0.09$. This is shown in Figure 5.3. Given the observed spectral indices, radio sources dominated by central self-absorption or with complicated features that produce equivalently flat spectra appear to be preferentially observed.
5.3 Recent Survey Results for Point Sources

In addition to the large number of detections in the maps, the 5-year WMAP point source discussion includes the results of a multifrequency and high resolution study of the first-year point source catalog originally presented in Trushkin [81]. The study has been used to more accurately determine the source types and spectral classifications of the first year detections. The study found optical identifications for 203 out of the 208 sources detected in the first year WMAP results. Of the 203 sources studied, Trushkin [81] found that $\sim 69\%$ were quasars, $\sim 21\%$ were standard radio galaxies, and $\sim 9\%$ were blazars. The spectral indices of the individual sources studied show that 40% of the sources optically detected have a flat or inverted spectra whereas only 8% and 7% have a falling spectra or combined spectral types, respectively.

WMAP has also been one of few experiments capable of measuring the variability of a collection of sources. The 5-year observation duration for recent WMAP results has allowed an exploration of the variability of their source catalog, and many of their detected sources exhibit a significant percentage of variability [87]. They have specifically reported a 23% rms variability in the Q band flux for the 25 brightest sources they have observed in this band [87].

5.3.2 ACBAR Point Source Results

The ACBAR survey results have recently been presented in Reichardt et al. [61], and the useful point source results are reproduced here. The survey consists of $683\, \text{deg}^2$ of sky coverage. The survey was conducted over a period of 5 years using a $5\, \text{'}$ resolution beam at an observing frequency of 150 GHz. In this survey, 37 sources were detected out of a possible 1601 known sources from the Parkes-MIT-NRAO (PMN) survey catalog. By using these source observations combined with information from the PMN catalog, the team demonstrated an interesting result. The flux ratio from 150 GHz to 4.85 GHz (the PMN catalog observation frequency) was found to be significantly flux dependent. This ratio, $(S_{150}/S_{4.85})$, increases dramatically with increasing PMN flux. Using this information, the
effective band-power contribution from relatively dim radio sources was calculated. These
dim sources were computed to have a spectral index of \( \alpha = -0.67 \). This result points
to the probability that less luminous sources tend to fit the model of extended diffuse
synchrotron sources, while the brighter sources, as shown by WMAP, correspond to more
complicated structures.

5.3.3 BLAST Results

The recent release of BLAST results presented in Devlin et al. [16] has had a pro-
found effect on the understanding of the CIB and IR point sources. The study was con-
ducted with observations of the BLAST instrument in three bands centered at 250, 350,
and 500 \( \mu m \) (1200, 860, and 600 GHz, respectively). Directly, the measurements included
\( \sim 500 \) sources with \( > 5\sigma \) detection level, but the more interesting result utilized a stacking
flux measurement method. In this stacking method, the mean flux determined by BLAST
measurements at the locations of point sources in the Far-Infrared Deep Extragalactic
Legacy (FIDEL) survey catalog is used to produce a reasonable approximation to flux
values for sources well below the SNR threshold for detections using the BLAST obser-
vations alone. The FIDEL observations are conducted at 24 \( \mu m \) (12500 GHz) and have
detected mid-infrared emission from hundreds of thousands of galaxies [18]. Using this
analysis, the study shows that flux from these point sources accounts for \( 75 - 100\% \) of
the far-infrared background (FIRB) measured by other IR experiments as shown in Figure
5.1.

5.3.4 APEX-SZ Results

The APEX-SZ survey consists of a 0.8 deg\(^2\), 150 GHz sky survey conducted with 1\(^{\prime}\)
resolution that was designed to accurately measure the high angular multipole region,
from \( 3000 < \ell < 10000 \), of the CMB power spectrum [62]. The uniquely interesting result
of this survey and analysis presented in Reichardt et al. [62] is that at these high multi-
5.4 Point Source Detection and Photometry Methods

poles, the power spectrum is expected to be dominated by secondary effects, including sub-millimeter bright, dusty galaxies (IR point sources) [62]. The study compares BLAST point source observations conducted at 600 GHz to the APEX-SZ point source power likelihood function to compute spectral index information [62]. The resulting spectral index is $\alpha = 2.64^{+0.4}_{-0.2}$, which is in agreement with measurements from nearby galaxy data as quoted in Section 5.1.2 [62]. This result for the spectral indices of the dusty IR sources will be particularly important for removal of contamination in the ACT CMB power spectrum measurements, as the observing frequency is very close to our lowest frequency waveband, 148 GHz.

5.4 Point Source Detection and Photometry Methods

In order to accomplish the primary goal of spectral index extraction from the ACT maps, several lower level tests of source detection, photometry and catalog comparison needed to be completed. The first portion of the research involved developing a detection and photometry pipeline using SExtractor. SExtractor is capable of a large number of complicated operations useful for source extraction, and for the purposes of this project, only a fraction of the available options were used or tested. Section 5.4.1 will describe the basic setup and testing tools of the SExtractor analysis software used for source detection. Section 5.4.2 will describe tests of filtering types and sizes for source detection on a small section of the ACT simulated sky maps. The filtering routines are used in detection of sources only, as they would affect the amplitudes detected in photometry steps. Section 5.4.3 will describe tests of photometry options and a computation of the optimal aperture for photometry utilizing the ACT simulations. Section 5.4.4 will briefly describe the restrictions placed on source identification when comparing different sets of catalogs. The next Section, 5.5, will describe the application of these methods to determining spectral indices using the ACT 2008 season maps.
5.4.1 SExtractor Setup and Options

The SExtractor program includes options for a very large number of setup parameters for how detection of sources and photometry are performed. Additionally, the program has a great deal of flexibility in astrometry and photometry output options. For the majority of the configuration parameters, the default values were used in the tests conducted. For many of these parameters, examination of the number of detections and flux outputs were conducted with varying parameter options, and no change in output was seen. The parameters which significantly affected the output results are described in the next few paragraphs.

For source detection, the parameter DETECT.THRESH defines the most important quantity, the SNR above which a pixel should be considered as a candidate source. The SNR is computed by measuring each pixel value and comparing it to the standard deviation of the map background. This couples with DETECT.MINAREA, which defines the minimum number of adjacent pixels that must be above the detection threshold in order to mark a source as detected in the output catalog. All sources which are detected and pass further checks, including deblending and cleaning routines, then have photometry performed using the detected source locations. The deblending and cleaning routines attempt to separate point sources whose signals overlap one another and to remove detections due to artifacts caused by very bright sources, respectively. For my initial test of SExtractor using simulations, it was easiest to use very high ($5\sigma$) values of SNR cutoff for detection, but with increased testing, a SNR cutoff of $2\sigma$ and a minimum area of 4 pixels selected a sufficient number of sources without picking up any false detections and while using several filter types (apart from edge effects). For the purposes of photometry testing, finding the optimal SNR cutoff is not necessary. Additionally, the optimal cutoff will vary with the detection filter chosen, so choosing a higher, but fixed, value when testing filters for detection is important. Section 5.4.2 will explain those tests in more detail.

The SExtractor configuration options for weight map input and background estimation
5.4 Point Source Detection and Photometry Methods

can have impacts on the quantity and accuracy of the photometry of detections. If a weight map is available for a given input map, care must be taken to specify the appropriate weight map type in the SExtractor input. When available, weight maps can significantly reduce the number of false detections at map edges. Background estimation helps to distinguish false detections from true detections and also can be used to estimate the true flux of point sources. SExtractor allows the local background for point sources to be measured and subtracted from the map during photometry, so that sources in unusually positive or negative regions will not lose or gain flux due to surrounding effects. SExtractor, when tested on several simulation maps, was found to be remarkably robust to changes in parameters for the background estimation and subtraction routines. Detection rates and photometry calculations are only significantly impacted if the routines are not used, or the parameters are set to be wildly inappropriate for the input map.

5.4.2 Tests of Filtering for Detection

For detection routines, a filter may be applied to a map before source detection is attempted. The primary purpose of filtering is to smooth out noise peaks and to effectively increase the SNR of map objects corresponding to point sources. The SExtractor package includes several default filters, including gaussian, mexican hat and top hat profile types with FWHM values ranging from 1.5 to 5.0 pixels. Using a small section of a simulated map, the number of detections for each of these filters with fixed values for the threshold and source area were tested. The results are shown in Table 5.1. For these tests, a threshold of $1\sigma$ and minimum area of 4 pixels were used. These values, as described before, interact with the filter choice, and for proper filtering, a lower value of threshold may be chosen without introducing significant numbers of false detections. Also for these tests, the maps used have some edge artifacts that would not normally cause difficulty in map analysis, as these areas would be downweighted by proper implementation of a weight map. At the time of the test described, no weight map was available for this simulation.
Using Table 5.1, a best choice of filter for the ACT output maps was made. The selection balanced the criteria of limiting the number of bad detections made while providing a reasonably large number of good detections relative to other filter choices. This is a somewhat subjective selection. Given the dramatically large number of false detections for all but the mexican hat filter types, the choice is a bit easier. The 5.0 pixel FWHM mexican hat filter provides the largest number of correct detections without a number of false detections that is an order of magnitude higher than correct detections. A final reminder is that the filtered maps are not used in photometry, as this would systematically alter the flux of the point sources observed.

5.4.3 Tests of Photometry Options and Parameters

In order to determine point source fluxes, the photometry options available through SExtractor were explored. The SExtractor program is capable of generating a very wide variety of output flux types, with different methods of integration or calculation of the desired flux. Before discussing the output catalog flux types, however, a brief description of the configuration parameters that affect all flux counts is warranted. The choice of background handling routines used or not used can have a profound effect on the calculated or reported flux values. For all flux outputs, SExtractor can subtract or add a value corresponding to the difference of the local image background computed from an annulus around the point source from the global median background value. The calculated fluxes have a low correlation to the size of the background mesh or filter chosen, when these sizes are set reasonably at neither very large or small values. For the initial tests of photometry, a small signal-only output simulated sky map generated by Matt Hilton was explored. This map had no corresponding weight map available. For most input simulations, all map points are simulated to have the same weight. The output simulated sky map, however, is generated by converting an input simulated sky map to time-ordered data and then running the map-making pipeline on the simulated data.
### 5.4 Point Source Detection and Photometry Methods

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Table 5.1: Results of SEExtrator filter tests. For each of the filters that are included with the SEExtrator analysis package, the number of good detections and total detections are shown for applying that filter during photometry on a small simulated sky map. Good detections are determined by elongation (major axis length divided by minor axis) $< 5.0$, FWHM $> 0.1$, and at least one match to the location of an input point source from the simulation input Radio and IR catalogs. As can be seen in the table, several of the filters do a poor job of screening, producing many false detections.
To determine the best choice among the photometry options available in the SExtractor package, several options were tested and compared. The SExtractor manual Bertin [11] and “SExtractor for Dummies” Holwerda [38] together provide a fairly thorough description of the various types of flux calculations available. Of these options, the primary estimates tested were FLUX.AUTO, FLUX_ISO, and FLUX_APER. FLUX_APER requires an input diameter to define a hard circle surrounding each point. The source flux is computed using a simple integration of the intensity within this circle, and adjusted for the background offset. FLUX_AUTO was chosen as this is intended to be the best estimate to the flux for a source that SExtractor can compute automatically. FLUX_AUTO was used with default values for the Kron_fact and min_radius options of 2.5 and 3, respectively. These values define the size of the ellipse used to compute the source flux. In simple terms, the Kron_fact value is a multiplier of a computed size for the source over which the flux is integrated, while min_radius forces the algorithm to use no less than a minimum size for the integration ellipse. For further details of the algorithm, see Bertin [11]. Finally, FLUX_ISO is defined as the integrated flux in all pixels above the detection threshold value, and so varies greatly with the adjustment of this value. This is not an ideal measurement, as this becomes entangled with the detection algorithm chosen. The entanglement is due to the way that filtering causing changes in the desired detection threshold. Better filter choice allows lower thresholds to be set.

For the initial test of photometry conducted on a simulated sky map generated by Matt Hilton, the primary goal was to compare the outputs of various SExtractor photometry options to the input radio source catalog. The simulated sky map for these tests was an early product of our analysis pipeline. To compare the catalogs, a conversion from the simulation map units of $\mu K$ to units of Janskies must be made. This conversion uses the Rayleigh-Jeans approximation for unresolved point sources:

$$S(\nu) \approx \frac{2k_B \nu^2 \Omega_B T}{c^2},$$

(5.1)
5.4 Point Source Detection and Photometry Methods

where $\nu$ is the frequency of the camera band center, $\Omega_B$ is the solid angle of the beam, and $T$ is the integrated temperature over the map of the source in units of Kelvin. The Rayleigh-Jeans approximation requires that $h\nu << kT$, which holds for the point sources observed at the frequencies of the ACT experiment. For the 148 GHz simulated sky maps on which these photometry tests were conducted, the values are $\nu = 148.0 \text{ GHz}$ and $\Omega_B = 218.2 \text{ nsr}$. An additional factor of 1.65 must be included to convert from the map units of $\Delta(T)_{\text{CMB}}$ to units of $\Delta(T)_{\text{RJ}}$ ($\Delta(T)_{\text{CMB}} = 1.65 \Delta(T)_{\text{RJ}}$) in order to use this formula. This factor corrects for the change in intensity from a change in the CMB temperature compared to the change in intensity from a change in temperature for a Rayleigh-Jeans source.

A catalog of sources was generated including the results of all of the photometry types discussed above. For this test, a coarse set of fixed aperture sizes were chosen for the FLUX_APER diameter settings. Using a detection and analysis threshold of $1 \sigma$, 35 detections were made. These, however, are not screened for edge effects and also include IR point sources input to the map, for which an input catalog was not originally available. From the set of 35 sources, 18 were found to match the input catalog when using a roughly chosen coincidence size of $\pm 1.8'$. Figures 5.4 and 5.5 show the results of this test for two randomly chosen point sources in this set. As can be seen in the figures, neither FLUX_ISO or FLUX_AUTO reproduce the input flux well for this choice of configuration parameters, and the trend of overestimation holds for all sources analyzed. As can also be seen on the figures, however, an estimate for the optimal choice of aperture size when using FLUX_APER may be generated by interpolating between the data points at the apertures chosen and matching to the input flux. This analysis was conducted using each of the 18 point sources, and the results are shown in Figure 5.6. The median optimal aperture computed from this sample and coarse aperture diameter choice is $\approx 1.3$ pixels. The spread in these data is large, however, and for further testing, a finer distribution of aperture sizes and larger number of sources was needed to provide a better estimate of the appropriate aperture. Finally, a plot of the best aperture for each of the 18 sources
Figure 5.4: SExtractor calculated fluxes are shown for a radio point source in an early simulated ACT data map generated by Matt Hilton. The blue curve indicates the flux determined within a fixed aperture diameter of the indicated size. This example is typical of the 18 sources detected by SExtractor and matched to the input catalog for the simulation. Both the FLUX_AUTO and FLUX_ISO options overestimate the flux of most of the point sources significantly.

compared to their input flux is shown in Figure 5.7. This plot shows that there is no correlation between the best aperture for flux reconstruction and the input flux.

A similar aperture test was also repeated on a much larger simulation map in order to explore a larger sample size and test more recent mapping developments. Tobias Marriage commented that the beam convolution in this round of simulated sky maps may have been incorrect, and so the aperture results for the test are omitted here. The larger maps used, however, provided very good tests of the SExtractor options for source detections. These maps have an area roughly two times that of the 2008 season data maps. The detection and analysis thresholds were adjusted to $2\sigma$ from $1\sigma$ for this test. The results of this application of SExtractor included 338 total detections. Using comparison with the input catalogs, only two of the detected sources were not matched to a catalog input, with
Figure 5.5: Another example of SExtractor calculated fluxes for a radio point source in an early
simulated ACT data map. This is included to show what occurs when the aperture chosen begins
to collect poor background data. The SExtractor configuration used attempts to remove the back-
ground before performing photometry, but this example shows that the algorithm would fail with
apertures that are too large. By examining where the input flux crosses the FLUX_APER outputs,
the proper aperture can be seen to be just less than 2 pixels in diameter for this source.
Figure 5.6: The distribution of the computed aperture diameters for the 18 point sources detected and matched to the input catalog. The computed aperture is the pixel diameter used with FLUX_APER that best reconstructs the input flux to the map.
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Figure 5.7: The computed aperture diameters for the 18 point sources detected and matched to the input flux catalog, compared to their input fluxes. This demonstrates that there is no correlation of optimal aperture size to the simulation input source flux.
Point Sources in the ACT Survey

196 IR and 140 Radio sources measured.

Aperture Tests on Improved Simulations

Given that the simulated sky maps analyzed for the large-map aperture tests may have had improper beam convolutions, the tests were repeated on several newer input simulations of the Southern observation strip. These maps are designed to be inputs used to test the ACT map-making pipelines. The maps analyzed in this second round of tests have our current best estimate for the telescope beam convolved with the maps after the simulations are generated. These simulations included separate maps of only IR point sources, only radio point sources, and a full simulation of a sky map (skymap) including CMB, point sources, and secondary anisotropies. Each of these maps was produced with units of Jy/Sr, unlike the previous simulations analyzed. For the comparison of computed fluxes to the input catalogs, the total flux found with each method was multiplied by the telescope beam solid angle of 218.2 nsr in order to convert to Jy.

The majority of the SExtractor configuration parameter choices was not changed for this test from the tests on the early simulations provided by Matt Hilton. The most notable change between the two configurations was a finer choice of apertures, chosen to more carefully explore the phase space near a pixel diameter of one. The second important change was an adjustment of the detection and analysis thresholds to $2\sigma$ from $1\sigma$.

For the IR-only point source maps compared with the IR source input catalog, the optimal aperture diameter found was 1.20 pixels. For the radio-only point source maps compared with the radio source input catalog, the optimal aperture size found was 1.23 pixels. The skymap detected sources were checked against each of the two input catalogs separately. Again, this map included both types of point sources and the CMB with secondary effects. The average aperture found to reproduce the input flux was 1.22 pixels for the radio sources and 1.26 pixels for the IR sources for the skymap simulation. Figures 5.8 and 5.9 show the histograms of the interpolated aperture diameters for each of these
5.4 Point Source Detection and Photometry Methods

(a) IR Source Map Matched Flux Apertures
(b) Radio Source Map Matched Flux Apertures

Figure 5.8: These distributions show the pixel diameter aperture sizes that should be used by SExtractor analysis to best reproduce the input flux for the newest set of source only simulations. The first histogram is the set of computed apertures for an IR source simulated sky map. The second histogram includes the apertures determined for a radio source simulated sky map.

tests.

The calculated apertures for these four tests are very similar to the 1.3 pixel aperture found using the simulated sky maps provided by Matthew Hilton. A useful test of these results is a comparison to the measured FWHM of the 148 GHz beam. In the analysis conducted by Adam Hincks using specially generated 2008 season maps, the beam profile was measured to have a FWHM of $1.344 \pm 1.406'$ [31]. The simulated sky maps used to determine the optimal apertures of 1.20 to 1.26 pixels use a cylindrical equal area projection. This creates a slight change in pixel size over the map. This was not taken into account when computing the optimal apertures, and may have reduced the aperture variability had it been included. On average, the pixels have a size of $\sim 0.5'$. The best fit circular aperture diameter is thus $\sim 0.6'$. This measurement does not match the measured beam profile from our data maps very well. Specifically, the aperture over which the flux for a point source is completely collected should be slightly larger than the FWHM of the telescope beam. Given the discrepancy between expected beam shape in the maps and the best determined aperture for flux determinations, a better method for photometry for future calculations is recommended.
Figure 5.9: These distributions show the pixel diameter aperture sizes that should be used by SExtractor analysis to best reproduce the input flux for the newest set of source only simulations. The first histogram is the set of apertures for all IR input sources, computed using the skymap simulation. The second histogram includes the apertures determined for all radio sources in the skymap simulation. The skymap simulation includes both types of sources and the CMB.

Unfortunately, no simulations with beam-convolved point sources existed for the 218 GHz or 277 GHz camera bands at the time of this analysis. For fixed aperture photometry using the 218 GHz maps discussed in Section 5.5, the best aperture computed for the 148 GHz maps was scaled by the ratio of the measured beam FWHM values for the two cameras.

5.4.4 Catalog Comparisons and Notes on Astrometry

For several steps of the analysis, including the photometry tests explained in the previous section, comparisons between catalogs computed through different methods were needed. These steps included the initial determination of false detections and accurate photometry through comparisons of the SExtracted catalog and input catalog for simulations. Additionally, in the following Section, 5.5, the compiled catalog of sources from other experiments was compared to the final SExtractor-generated catalogs in order to determine the spectral indices in two ways. The first method used only external data, and the second method compared the external data to the 148 GHz fluxes. Using Rayleigh’s
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criterion for distinguishing point sources, the beam width of the arrays, FWHM = 1.4’ and 1.0’ for the 148 GHz and 218 GHz bands, respectively, and the maximum pixel size of the output maps from the ACT pipeline, 0.84’ for both bands, one can compute the minimum pixel separation of point sources for unambiguous detection. The minimum detection separations using these maximum FWHM measurements are 1.7 and 1.2 pixels for the two arrays.

These minimum separations for detection provide a reasonable guideline for the precision with which a source location may be determined, however, position determination for sources which are not closely spaced may in general be achieved with much smaller errors. Newer versions of SExtractor address the issue of position error with the output options ERRX2 and ERRY2, which are equal to the variances in the calculations of the X_IMAGE and Y_IMAGE barycenter position results. For reference, the barycenter is computed as:

\[
\text{Barycenter} = X = \frac{\sum I_i x_i}{\sum I_i},
\]

where \(x_i\) and \(I_i\) are the position of a pixel in the map, and the intensity of the pixel. For an output simulation, a median over the square root of ERRX2 and ERRY2 for all detected sources would provide a reasonable estimate to the 1 \(\sigma\) error in position calculation. This result would then be used to set the maximum acceptable distance between putatively identical sources in the two catalogs being compared.

Practically, the catalog searches are implemented by allowing the right ascension and declination coordinates to vary by up to the FWHM of the beam in arcminutes divided by the conversion of 0.84’ per pixel. This forms a square region, as opposed to a method which matches points within a disk. This method was chosen for computational simplicity and speed. If any source in the comparison catalog falls within the square region, it will be accepted. This was chosen because the advanced features of SExtractor were not available in the version installed on our primary pipeline computers. Additionally, when several sources were matched in the comparison catalog, an algorithm is used to deter-
Figure 5.10: A section of the first large simulated sky map used for aperture tests. The green circles indicate input point sources from both the IR and radio source catalogs, with circle radius increasing with increasing input flux. The red diamonds indicate the positions of the detected sources using the SExtractor analysis. The catalog comparison routines successfully identified 336 input catalog matches out of the 338 detections made with the SExtractor analysis.

mine the nearest source to the detected source. This nearest source is chosen for any comparisons. As described in Section 5.4.3, this approach was used with a large input simulation catalog and the SExtractor output catalog for a $-55^\circ$ declination simulation strip. As reported earlier, 336 sources of 338 detections were successfully matched to the input catalog. A section of the map used for this comparison is shown in Figure 5.10 with detected sources and a flux-limited selection of the input catalog sources indicated.
5.5 Study Results

5.5.1 Initial Spectral Indices Within the ACT Data

Using the results of the tests described above, a catalog of sources and flux estimates was generated for the 148 GHz and 218 GHz 2008 season maps. The 218 GHz maps unfortunately were not as fully developed as those tested for the 148 GHz camera. SExtractor was again used for source detection. For both bands, the minimum area of a detection was held at 4 pixels. A detection threshold of $3\sigma$ was chosen for the 148 GHz band map to balance between the desire to reduce false detections and still detect a large number of point sources. With this threshold, 1774 point sources were detected. The threshold for the 218 GHz map was set to $2\sigma$, as the map does not have many clear sources. To reduce the number of false edge detections, the value was raised to $3\sigma$, and still 6480 sources were detected at this threshold. For the 148 GHz map analysis, a fixed aperture size of 1.23 pixels was used for photometry, in accordance with the results of the simulated sky map analysis. For the 218 GHz map detections, a 0.88 pixel aperture size was used. This was calculated by scaling the 148 GHz aperture by the ratio of the measured beams for the 148 GHz and 218 GHz cameras.

Due to the rough nature of the map edges and the underdeveloped pipeline for the 218 GHz maps, cuts on the source Elongations and FWHM as determined by SExtractor astrometry were performed when comparing the catalogs. The SExtractor Elongation corresponds to the ratio of the major axis to the minor axis when fitting the sources to an ellipse, as opposed to assuming all sources are circularly symmetric. These restrictions were set to FWHM $> 0.01$ pixels, FWHM $< 6$ pixels and Elongation $< 5.0$ for the 148 GHz results. The upper limit for the FWHM was raised to 15 for the 218 GHz results in order to ensure that no actual sources were unnecessarily cut. The sets of cuts significantly reduce the number of bad source detections due to edge effects. The accepted region for cross-detected sources was also cut in the catalog comparison step to help avoid the edges of both maps and also to exclude a contaminated region of the 148 GHz map.
Point Sources in the ACT Survey

The resulting set of cross-detections was checked for false detections by eye, and all cross-detections were valid. Unfortunately, only four sources were found to match in the two catalogs. Table 5.2 indicates the positions and computed spectral indices of these four point sources using the SExtractor analysis and catalog comparison structure. The spectral indices found for the four sources are all far more negative than expected for any of the known point source types. This is likely to indicate that the point source fluxes were underestimated for the 218 GHz maps. One likely cause for underestimating the flux is that the photometry techniques used were not sophisticated enough to properly integrate the total flux that should be attributed to the point sources. This may have been due to a choice of too small an aperture, as a best guess was used. The integration is likely to have been largely affected by the large noise level of the current 218 GHz maps. The noise level would be expected to scatter the computed fluxes both above and below their actual values. Given the small sample size, however, it is possible that these four sources all had more negative deviations than positive over the regions where their photometry was computed. One last possibility is that the maps used for the analysis were produced incorrectly. The 218 GHz maps are still in a very early developmental stage, and so the map-making routine may not be correctly attributing the appropriate amount of power to the sources.

A second calculation of the spectral indices for these four sources was used to check that the choice of fixed aperture photometry was not the only cause for the low spectral indices. For this second calculation, the SExtractor photometry FLUX_AUTO option was used to determine the fluxes of the sources in both maps. From these fluxes, the spectral indices were recalculated, and the results are shown in Table 5.2. At least one of the point sources appears to have a spectral index consistent with a radio source using this choice of photometry. This may indicate that both the choice of fixed aperture photometry and the current quality of the 218 GHz data maps are likely to be systematically skewing the computed fluxes and spectral indices.
5.5 Study Results

<table>
<thead>
<tr>
<th>RA</th>
<th>DEC</th>
<th>$\alpha$ From FLUX_APER</th>
<th>$\alpha$ From FLUX_AUTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>359.48</td>
<td>-53.18</td>
<td>-2.89</td>
<td>-2.14</td>
</tr>
<tr>
<td>348.95</td>
<td>-50.31</td>
<td>-2.44</td>
<td>-0.68</td>
</tr>
<tr>
<td>43.38</td>
<td>-54.70</td>
<td>-3.06</td>
<td>-2.85</td>
</tr>
<tr>
<td>32.70</td>
<td>-51.02</td>
<td>-2.77</td>
<td>-2.80</td>
</tr>
</tbody>
</table>

Table 5.2: Source locations and spectral indices for four sources detected in both the 148 GHz and 218 GHz preliminary maps. Detections were cut at a threshold of $3\sigma$ and $3\sigma$, and the fixed aperture photometry (FLUX_AUTO) used diameters of 1.23 and 0.88 pixels for the 148 GHz and 218 GHz band maps, respectively. The spectral indices computed using fixed aperture photometry are all far more negative than expected for radio or IR point source types. The FLUX_AUTO SExtractor photometry option was used to compute the spectral indices for fourth column. The spectral index for the second point source computed with the automatic photometry option is consistent with that expected for a radio point source.

5.5.2 Spectral Indices Using the ACT 148 GHz Best Point Source Catalogs and External Survey Catalogs

In parallel with the studies of SExtractor photometry and analysis conducted and presented above, several other ACT collaboration members have been working on developing catalogs from both simulation and data maps as they are produced. In order to learn more about the point sources in the ACT maps, the following study was completed using the source catalog generated by Jean-Baptiste Juin. Jean-Baptiste Juin has compiled a catalog of point sources using the currently best available 148 GHz camera maps for the ACT collaboration. His analysis pipeline uses SExtractor for the initial point source detection. He has developed an approximation to a matched filter for the 148 GHz maps, and applies to this to the maps before performing the detections. A matched filter is designed to maximize the SNR of the sources in the filtered maps. Section 5.6 will discuss more about matched filters. The photometry for this catalog utilizes a Python pipeline to replace available SExtractor photometry options. The photometry is computed using a fit to either a 2-D Gaussian or Airy profile. For future catalogs, the collaboration may choose to change this to a fit to the measured beam profile for each camera.

In order to determine the spectral indices for these point sources, a second set of observations at a different frequency was required. Due to the currently underdeveloped...
nature of the 218 GHz maps, observations from other instruments were selected to be used with the 148 GHz detections. Yen-Ting Ling has previously compiled a wide selection of point source observations from surveys at both radio and IR wavelengths for the ACT collaboration. This catalog includes data from the AT20G (Australia Telescope 20 GHz, Ricci et al. [64], Massardi et al. [52]), PMN (Parkes-MIT-NRAO, Wright et al. [86]), and FIRAS PSCz (COBE Far Infrared Absolute Spectrophotometer Point Source Catalog Redshift Survey Saunders et al. [67]) catalogs. The AT20G catalog data includes observations at 20, 8.6, 4.8 and .8 GHz source fluxes. The PSCz catalog includes 12, 25, 60, and 100 $\mu$m source fluxes. The PMN catalog includes only 4.85 GHz observations.

Jean-Baptiste Juin’s full catalog of 148 GHz ACT point sources was compared to the catalogs for each frequency in all of the surveys listed. Only one ACT source matched the PSCz observations, and the spectral indices between the ACT observation and the four PSCz fluxes were computed. These indices are 0.56, 0.77, 1.72, and 2.41 for the 12, 25, 60, and 100 $\mu$m wavelengths, respectively. A spectral index was computed using only the four PSCz fluxes and found to be $-2.18$. The comparisons with the ACT flux indicate that this single unusual source may have a spectral index similar to an IR point source, as would be expected given that the source was detected in an IR survey. In contrast, the highly negative spectral index computed, using only the PSCz measurements, may indicate that the source is a radio source. This steep spectrum might indicate that the PSCz observations sampled the high frequency roll-off of the spectrum for the radio source.

The AT20G catalog matched 12 of the ACT point sources. The spectral indices were again computed using the difference in flux between the ACT observations and each of the different frequencies in the AT20G catalog. Figure 5.11 shows the distribution of the computed spectral indices using only the 20 GHz and ACT 148 GHz fluxes. The spectral indices appear to be consistent with a distribution of radio point sources, and fall within a similar range to those seen by the WMAP experiment. Spectral indices using the 20, 8.6 and 4.8 GHz fluxes from the AT20G catalog were computed for each of the ACT sources as well. Figure 5.12 compares the spectral indices using the ACT to AT20G flux
5.5 Study Results

Figure 5.11: Spectral indices are shown for the 12 cross-detections between the ACT 148 GHz band maps and the AT20G 20 GHz survey. The indices are computed by comparing the flux observed in the ACT 148 GHz band with the flux observed in the AT20G 20 GHz survey. The spectral indices appear to be consistent with a distribution of radio point sources.

differences to the indices computed using only AT20G data. The ACT to AT20G indices are nearly all lower than the AT20G indices. Until final catalogs and maps are generated for the ACT experiment, no conclusion may be properly drawn from these results. Again, however, the spectral indices computed using ACT data appear to agree with a radio source distribution.

The comparison of the ACT 148 GHz catalog to the PMN source catalog generated a significant number of matches. The spectral indices computed using the difference in flux between the two catalogs are shown in Figure 5.13. This distribution is very similar to the WMAP spectral indices, but is shifted toward lower spectral indices. This shift may indicate that the ACT observes a wider spread of radio source types, including those dominated by both diffuse and compact features.
Figure 5.12: Comparison of the spectral indices computed using only AT20G survey detections with cross-detections to the ACT 148 GHz band catalog. The y-axis indices are computed by comparing the flux observed in the ACT 148 GHz band with the flux observed in each of the AT20G frequencies. The x-axis is computed by considering only the fluxes observed in the AT20G observations at 20, 8.6 and 4.8 GHz. The indices computed using the ACT observations are nearly all lower than the AT20G indices, but further ACT map analysis will need to be conducted before a conclusion is drawn regarding this result. Another interesting result is that the indices derived from comparison to the 20 GHz observations are consistently the lowest, while those derived from the 0.8 GHz observations are commonly the highest for each source.
5.5 Study Results

Figure 5.13: Spectral indices are shown for cross-detections between the ACT 148 GHz band maps and the PMN 4.85 GHz survey. The indices are computed by comparing the flux observed in the ACT 148 GHz band with the flux observed in the PMN survey. The spectral indices again appear to be consistent with a distribution of radio point sources. This distribution is very similar to the spectral indices found in the WMAP experiment, but is shifted toward lower spectral indices.
5.6 Improved Methods and Future Work

Although the SExtractor analysis package is both powerful and fairly flexible, to obtain optimal source characterization, several improvements will likely be implemented in the process of final catalog generation for the ACT 2008 season maps. The first of these will be the implementation of optimal matched filtering for source detection and astrometry. A matched filter is designed to maximize the SNR of the sources in the filtered maps. An introduction to this concept is demonstrated in Vio et al. [83]. The key needs to construct such a filter are knowledge of the exact functional form for the point source response of our telescope and the spectrum of the image background. The first of these has been computed by Adam Hincks, but the latter will require a careful analysis of our final output maps before it may be constructed. The second significant improvement to catalog generation will be the continued improvement of the map-making pipeline. Once better maps for the 218 GHz band are generated, far more sources should be separable from background noise and computed fluxes should have much less error. Additionally, other collaboration members are continuing to advance the source detection and photometry pipelines used to make source catalogs. The catalogs being produced by Jean-Baptiste Juin and used in Section 5.5.2 already have more detections and use a more rigorous approach to photometry, compared to the catalog used for the results in Section 5.5.1. Spectral indices using only ACT data should be computable with these improvements, and then the distribution from ACT-only detections will be compared to known radio and IR source distributions. Once both the 218 GHz and the 277 GHz maps are generated, more IR sources are likely to be detected, as the flux of these sources is expected to increase as $\sim \nu^{2.6}$ over our frequency bands.
5.6 Improved Methods and Future Work
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