Probing The Cosmic Microwave Background Radiation With Actpol: A Millimeter-Wavelength, Polarization-Sensitive Receiver For The Atacama Cosmology Telescope

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Abstract
In this dissertation manuscript, we document the design, development, characterization, and scientific application of next-generation millimeter wavelength imaging technologies, conducted under the auspices of a NASA Space Technology Research Fellowship (NSTRF-11) grant, based at the University of Pennsylvania and completed under the advisement of Professor Mark J. Devlin. NASA's Science Mission Directorate, supported by recommendations from the National Research Council (NRC) Decadal Survey, has placed the development of mission-enabling technologies for future-generation, seminal orbital platforms probing the nature of the early universe and cosmic inflation at the forefront of directives in space technology research. To work toward the rapid achievement of these directives, we highlight considerations for the design and integration of ACTPol, a new receiver for the Atacama Cosmology Telescope (ACT), capable of making millimeter-wavelength, polarization-sensitive observations of the Cosmic Microwave Background (CMB) at arcminute angular scales. ACT is a six-meter telescope located in northern Chile, dedicated to enhancing our understanding of the structure and evolution of the early universe by direct measurement of the CMB. We will focus first on the manner by which the integrated millimeter-wavelength imaging technologies of ACTPol with critical upgrades deployed to the ACT telescope superstructure and site, will enable the instrument to address a myriad of high-priority topics in experimental cosmology. We will then consider the design of the first ACTPol 150 GHz detector array package, which, along with a second 150 GHz array package and a multichroic array package with simultaneous 90 GHz and 150 GHz sensitivity, and associated optomechanical subsystems, comprises the ACTPol focal plane and, ultimately, receiver. Each of these detector array packages reside behind a set of normal-incidence, high-purity silicon reimaging optics with a novel anti-reflective coating geometry, the development flow of which will be detailed. As a root design system, the 150 GHz polarimeter array package consists of 1044 transition-edge sensor (TES) bolometers used to measure the response of 522 feedhorn-coupled polarimeters, which enable characterization of the linear orthogonal polarization of incident CMB radiation. The polarimeters are arranged in three hexagonal and three semi-hexagonal silicon wafer stacks, mechanically coupled to an octakaidecagonal, monolithic corrugated silicon feedhorn array (~140 mm diameter). Readout of the TES polarimeters is achieved using time-division SQUID multiplexing (TDM). The three polarimeter array packages comprising the ACTPol focal plane, and associated optical and cryomechanical elements of the fully integrated ACTPol receiver are cooled via a custom-designed, field-deployable dilution refrigerator (DR) providing a 100 mK bath temperature to the detectors, which have a target Tc of 150 mK. Given the unique cryomechanical constraints associated with this large-scale monolithic superconducting focal plane, we address the design considerations necessary for integration with the optical and cryogenic elements of the ACTPol receiver. The ACTPol receiver deployment and early operational protocol development are highlighted, and receiver laboratory and on-site operational optical, cryogenic, and detector performance characterization is considered. ACTPol early scientific operational results are then detailed, including CMB polarization measurements between l=200 and l=9000, measurements of galaxy clusters via the Sunyaev-Zel’ dovich effect, and the first set of maps and associated analysis of ACTPol first season galactic field observations. Consideration is also given to work underway toward the realization of Advanced ACTPol, a next-generation receiver for ACT, with the enhanced capability to measure large-angular-scale regimes to probe inflationary cosmology. Finally, an outlook is provided in which lessons-learned from the development of a distributed portfolio of ACTPol and Advanced...
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Benjamin Louis Schmitt

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ABSTRACT

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Benjamin Louis Schmitt
Mark J. Devlin

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Preface

Sea-birds are asleep,
the world forgets to weep,
sea murmurs her soft slumber-song
on the shadowy sand
of this elfin land;

I, the Mother mild,
hush thee, O my child,
forget the voices wild!
Hush thee, O my child,
hush thee

Isles in elfin light
dream, the rocks and caves,
lull’d by whispering waves,
veil their marbles
veil their marbles bright,
foam glimmers faintly, faintly white
upon the shelly sand
of this elfin land.

from Edward Elgar’s “Sea Pictures: Sea Slumber Song”

The development of ACTPol, a polarization-sensitive, millimeter-wavelength receiver for the Atacama Cosmology Telescope, which serves as the focus of dissertation, encompassed
not only the development of core science and technology objectives to enable the success of the project, but also the ability to join a spirit of exploration and adventure that are core to the pursuit of modern experimental cosmology research. Completion of the doctoral research central to this dissertation required travel to national laboratories, conferences, engineering subcontractors, data analysis supercomputing centers, and deployment sites, some located in extreme environments on all four continents of the Atlantic basin. To achieve the core science and technology development goals described herein, travel was completed to the Rocky Mountains of Boulder, Colorado to develop advanced millimeter-wavelength polarimeters along with teams at NIST, to Greenbelt, Maryland to complete subsystem validation testing at NASA’s Goddard Space Flight Center, to the high-altitude Atacama Cosmology Telescope site for receiver deployment and operations in the Atacama Desert of Northern Chile, to Durban, South Africa to complete initial data analysis of the ACTPol galactic plane data set, and across Canada, and European capitals to present key science and technology development results while engaging with the broader experimental cosmology community. Invariably, pursuit of these science and technology objectives across such a large span of the globe led to memorable side adventures and experiences ranging from self-drive safaris in the KwaZulu-Natal region of South Africa, to expeditions to climb to the summit of Cerro Toco and other Atacama stratovolcanoes in Chile, to sorting through legal issues associated with an “expired visa in Calama, Chile and on the Chile-Bolivia border in the Bolivian altiplanico of the Atacama Desert, to a hike across the high-altitude Chile-Argentina desert border to retrieve a new visa (witnessing llama skeletons, scorpions, and active mine fields along the way), to a respite from the visa experience near Cape Horn, including dog sledding across Tierra del Fuego and navigation on the Beagle Channel.

Of course, if these experiences have a single thread outside of their science and technology motivation, it is that none of these adventures were accomplished alone. Indeed, it was the vast network of colleagues and friends, all driven by the same passion for science, adventure, and exploration that were critical for this work, and should be recognized before
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experience in support of inertial confinement fusion research on the laboratory’s OMEGA laser system. Few researchers have the patience to mentor an eager physics student beginning as a junior in High School, but Dr. Marshall offered me a truly unique opportunity to get a head-start in hands-on, cutting-edge physics research that led me to study physics and astronomy at the University of Rochester and remain in his x-ray diagnostics development laboratory throughout my entire undergraduate career. I know I would not be the scientist or person I am today without that transformational opportunity, and for that I am incredibly thankful.

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Part I

Introduction
Chapter 1

Physical Implications of the Cosmic Microwave Background Radiation

Sea-sound, like violins,
to slumber woos and wins,
I murmur my soft slumber-song,
    my slumber-song,
leave woes, and wails, and sins,

Ocean’s shadowy might
breathes good-night,
    good-night...
leave woes, and wails, and sins,

Good-night...  Good-night...
    Good-night...
    Good-night...
Cosmology is the first of the natural sciences to be studied by humanity. Fundamental questions related to the origins, development, and characteristics of the Universe at its largest scales can be found throughout the ethnographic record, beginning with our earliest human ancestors, and underpinning the scientific, cultural, and religious pursuits of every civilization through to the present. Philosophers, scholars, and ordinary people across the centuries have gazed skyward and asked versions of the questions “how did the Universe begin?,” “what is the nature and extent of time and space?,” and “how has the Universe evolved to reach its present state?” That attempts to answer these questions have driven some of the greatest scientific advancements in history should not give one pause. These are questions that are central to the human experience and spirit of discovery. The field of cosmology attempts to answer these questions, and in the process, posits new and heretofore unimaginable theories based on empirical evidence obtained through the characterization of the Universe itself.

It is this pursuit of experimentally verifiable results, which can confirm or challenge contemporary theoretical models describing the origin, composition, dynamics, and physical properties of the observable Universe that is the underlying motivation for this dissertation. The development of cosmology as a precision experimental science in the past century has built upon centuries of observational techniques designed to better characterize our place in the Universe. Certainly, astronomical observation has been central to the confirmation or evolution of our most fundamental understanding of the Universe, spanning from the simple naked-eye observing of antiquity, to the development of the first optical telescopes of late-Renaissance Europe that were improved for astronomical observation by
Galileo, to the development of sextants and other instrumentation allowing for improved maritime navigation utilizing observations of stellar objects, to the precision ground- and later satellite-based optical telescopes developed throughout the twentieth century. All of these instruments have a common trait - each enable the observation of astrophysical systems and phenomenon at optical wavelengths of the electromagnetic spectrum, between roughly 390 and 700 nanometers in wavelength. Until the advent of photographic plates, and later, digital recording via, e.g., charge-coupled device (CCDs) detectors, the sole detector used in any of the aforementioned instruments developed for astronomical observation was the human eye, confining probes of astronomy and cosmology to optical wavelength regimes.

Of course, over the past century, our understanding of the extent and nature of the Universe was broadened significantly as new technologies were developed and corresponding discoveries made, with the advent of technologies enabling observations outside of the visible band of the electromagnetic spectrum. It was this era of critical development in imaging systems operating over multiple wavelength-regimes with increasing precision and sensitivity, that enabled historically unprecedented and rapid advances in our understanding of not only astrophysical phenomenon occurring in our own ‘local’ galactic neighborhood, but also unlocked our ability to directly probe characteristics of the observable Universe at greater and greater extra-galactic distances, ultimately leading to the so-called ‘era of precision cosmology,’ in which, for example, the direct measurement of the oldest observable light in the Universe, the Cosmic Microwave Background, has allowed us to probe the nature of the Universe in its most nascent form. In this pursuit of experimentally verified data throughout the current era of precision cosmology, we are thereby able to constrain theoretical models to increasingly high precision that describe our cosmic origins, the growth of structure in the Universe at its largest scales, to better understand the observed dynamics and composition of the contemporary Universe, and, ultimately, to predict the ultimate fate of the Universe.
The primary aim of this dissertation is the description of the design, development, integration, and validation of a suite of next-generation critical space technologies that comprise ACTPol, a millimeter-wavelength, polarization-sensitive receiver for the Atacama Cosmology Telescope, operating at arcminute-angular scales with arcminute angular resolution. The principal science driver of the ACTPol receiver operating on the Atacama Cosmology Telescope is to probe with high-precision the fundamental characteristics of the Cosmic Microwave Background manifested through observations of both the temperature and polarization anisotropies of the CMB. Ultimately, this dissertation will present ACTPol-enabled CMB mapping results in both temperature and polarization and their associated power spectra, early surveys of galaxy clusters detected via the Sunyaev-Zel’dovich (SZ) effect, and presented for the first time in this work, mapping, power spectra, and polarization analysis results of a field of the galactic plane observed with ACTPol analyzed in tandem with corresponding intensity and polarization results obtained by the Planck satellite for the same observable region allowing for the characterization of foregrounds sourced from galactic dust emission, as well as, i.e., providing a characterization of the galactic magnetic field, of use to the broader galactic astronomy community. Taken together, the development of advanced cryogenics, high-purity silicon optics with novel metamaterial anti-reflective coatings, and millimeter-wavelength polarimeters operating with sensitivity at both 90 GHz and 150 GHz comprising ACTPol, along with analysis of cosmology from CMB temperature and polarization mapping, SZ cluster surveys, and foreground characterization, will enable both future-generation ground- and satellite-based experimental cosmology platforms to probe the earliest epoch of the observable universe, including the pursuit of observations of the so-called B-mode CMB polarization predicted from inflationary models of the primordial Universe. The Chapter, which follows, will provide a brief overview of the nature of our understanding of the contemporary standard cosmological model, selected overviews of the physical processes leading to primary and secondary temperature and polarization anisotropies of the CMB, a review of key cosmology results provided from the operation of
ACTPol’s predecessor receiver on ACT, called MBAC, and closes with a review of the primary science drivers and predicted cosmological constraints that will be determined through the development and operation of the ACTPol receiver. As we will find by the close of this dissertation, the development of ACTPol not only represents the development of a vital standalone experimental cosmology platform that will advance our knowledge of the properties of the CMB, but also represents a critical pathfinder experiment that, viewed broadly, will enable next-generation probes of cosmological inflationary models and validation (or not) of other core predictions of modern theoretical cosmology. In this manner, ACTPol resides in the broadest continuum of instruments developed throughout history to advance the insatiable human drive for an answer to the most fundamental questions of the nature of the Universe in which we live.

1.1 Cosmic Origins: The Cosmological Distance Scale

The study of cosmology is at its broadest definition a field of science that attempts to characterize and constrain some of the most fundamental properties of the observable universe at a variety of scales. These properties principally include theoretical predictions and measurements that advance our understanding of the age, size, composition, and evolutionary dynamics of the observable Universe. Before the evolution of modern cosmology in the past century, models of the Universe evolved from those proposed by the classical astronomers of Greek antiquity, such as Pythagoras, Aristotle, and Ptolemy, to the Copernican and Galilean models of the Universe, taking into account observations of astronomical bodies observable primarily at visible wavelengths, like stars, planets, and galaxies. A key parameter of these observations that continued to advance in the early-twentieth century was the constraint of distances to increasingly distant astronomical objects with increasing precision. For example, as taught in any elementary astronomy course, the distance to a nearby star can be easily calculated by measuring its parallax angle, or the angle subtending the apparent change of position of the nearby star with respect to more distant astronomical
objects (e.g. more distant stars or galaxies) measured six-months apart from one another (or 180 degrees elongated on Earth’s orbit) from the same position on Earth. The relation between distance (in parsecs) to the nearby star, and parallax angle (in arcminutes), is thus given by Equation 1.1, for distance \(d_{\text{star}}\) and parallax angle \(p_\theta\). For reference, one parsec is equal to 3.26 light years (the distance that a photon can travel in a year, or roughly 9.46 \(\times\) 10\(^{12}\) kilometers), or 2.06 \(\times\) 10\(^5\) astronomical units (the distance between the Earth and the Sun, or roughly 1.496 \(\times\) 10\(^8\) kilometers). Of course, while the measurement of parallax angle can be a useful elementary tool for distance estimation of nearby astrophysical objects, say within a few hundred parsecs, other methods can allow for parallax-independent distance estimation out to larger scales. Given that the Milky Way galaxy in which we reside is roughly 100,000 light years in diameter (or roughly 30,660 parsecs), the utility of the parallax angle method is clearly limited for measuring distances to objects located further afield within our own galaxy, notwithstanding extragalactic structures of cosmological import.

\[
d_{\text{star}} = \frac{1}{p_\theta} \tag{1.1}
\]

One such relation utilizes what is known as the distance modulus, or the difference between the apparent magnitude and absolute magnitude of a given object, where distance modulus \(\mu\) goes as \(\mu = M_{\text{app}} - M_{\text{abs}}\). As a reminder, the apparent magnitude of a given stellar object is based off of the magnitude scale of astrophysical objects, definitions of which were first laid out by the Greek astronomer Hipparchus, and based on the perceived magnitude of a given astrophysical object viewed from Earth’s surface. Absolute magnitude, however, is defined as the apparent magnitude that a given astrophysical object would have were it located at a distance of 10 parsecs from Earth. With these definitions in mind, we then find that the relation between these values gives us the distance modulus \(\mu\), which is thereby related to luminosity distance, \(d_L\), to a given object as seen in Equation 1.2. Likewise, the luminosity distance to a given object can be experimentally determined for
an object of known luminosity $L$ and measured flux $f_{\text{obs}}$ related to the inverse square law, given in Equation 1.3.

$$\mu = M_{\text{app}} - M_{\text{abs}} = (5) \log_{10}(d_L) - 5$$

$$d_L = \left(\frac{L}{4\pi f_{\text{obs}}}\right)^{1/2}$$

Of course, for these relations to be useful, objects with known absolute magnitudes or luminosities are required for the distance determination to a given object. Fortunately, the discovery of a number of stellar objects that exhibit regular, well-characterized luminosities both within and outside of our Milky Way allowed for the cosmological distance scale to be probed and ultimately extended during the twentieth century, with increasing accuracy. These objects which exhibit predictable and well-understood light curves, often referred to as ‘standard candles,’ include Cepheid variable stars, which exhibit an extremely regular periodicity in their observed brightness curve that are related to their absolute luminosity, and Type 1a Supernovae, which also exhibit characteristic brightness curves related to their absolute luminosity. For the purposes of distance determination, Cepheid Variables are generally effective for the measurement of distance to objects located within roughly 25 megaparsecs (Mpc) form Earth, while Type 1a Supernovae continue to be effective tools out to a few gigaparsec (Gpc) from Earth. The use of Cepheid variables as standard candles had a tremendous impact on the course of our understanding of the Universe in the early twentieth century. In 1925, Astronomer Edwin Hubble used observations of Cepheid variables in Messier Objects, M31 (the Andromeda Galaxy) and M33 (the Triangulum Galaxy) to great effect, constraining their distances to show that indeed these objects were extragalactic (Hubble’s measurement estimated their distances to be roughly 0.93 Mpc from Earth), rather than nearby ‘nebulae’ confined to the Milky Way as originally postulated (Hubble 1925). Thus, this discovery led to the experimental realization that the extent of
the Universe was not confined to objects in our own galaxy, but led to the understanding that the Universe was comprised of a multitude of galaxies in addition to our own. The use of Cepheids continued to prove useful tools for Hubble to build on his work of characterizing distances to galaxies outside of our own Milky Way, ultimately unveiling the first empirical method for understanding not only the scale, but also dynamics of our Universe.

While the distance relations given earlier are useful tools for measuring distances to objects in the astronomical neighborhood of Earth, given the vast distances between objects (e.g. galaxies, galaxy clusters, the Cosmic Microwave Background, etc.) on the cosmological scale, experimental cosmologists often parameterize distance to objects of cosmological interest in terms of their redshift, rather than kilometer, light year, or parsec as we have used to describe astronomical distances thus far. By the early-Twentieth century, the measurement of the atomic absorption lines, within what would be later understood as distant galaxies, by Slipher and others revealed that through in the measurement of objects on extragalactic scales, absorption lines exhibit a wavelength that is longer or shorter than would be expected from the measurement of analogous atomic absorption lines characterized in atomic physics laboratories on Earth (Partridge 1995; Slipher 1917). This observed lengthening and shortening of wavelength was determined to be the result of these galaxies exhibiting Doppler shifting effects, where galaxies exhibiting a shortening of wavelength were described as exhibiting “blueshift” resulting from a negative recessional velocity from Earth (e.g. galaxies moving toward Earth), while those exhibiting a lengthening of wavelength were described as exhibiting “redshift” resulting from a positive recessional velocity from earth (e.g. galaxies moving away from Earth). Equation 1.4 gives the mathematical definition of redshift, denoted as \( z \), where \( \lambda_{\text{obs}} \) is the wavelength from an observed spectral measurement, \( \lambda_{\text{lab}} \) is the corresponding expected wavelength if measured in an atomic physics laboratory on Earth, \( v_c \) is the recessional velocity of the galaxy, and \( c \) is the speed of light.
Ultimately, in 1929 by combining his measurements of luminosity distance to Cepheid variables in an observed sample of 24 galaxies (at the time, these objects were still described as ‘nebulae’) with radial velocities provided by Slipher’s earlier measurements of redshifts of the same objects, Hubble was able to discover a relationship between the distance from Earth of a given object, and its recessional velocity. In particular, Hubble’s results provided for the understanding of a linear relationship between distances to galaxies and their recessional velocities - the greater the distance measured to a given observed galaxy, the greater its recessional velocity (Hubble 1929). Figure 1.1 provides results presented in Hubble’s landmark 1929 paper, in which a linear relationship is described between recessional velocity (determined by redshift) and distances (determined by observations of Cepheid variables) measured to distant ‘nebulae,’ later determined to be other galaxies. This allowed for the expression of Hubble’s Law, given in Equation 1.5, where $H_0$ is called Hubble’s constant. Slipher had in his catalog of redshifts already demonstrated that a majority of galaxies he had measured had a positive recessional velocity, and coupled with the distance results of Hubble and others, it was shown that aside from a relatively small number of galaxies demonstrating peculiar velocities approaching the Milky Way (e.g. demonstrating blueshift), most galaxies measured at greater distances were indeed moving away from the Milky Way. This discovery thus provided the first empirical evidence of an expanding Universe, or more generally, ushering in an era for the precise characterization of the dynamics of cosmological history, with the Universe shown as non-static for the first time. Combining these measurements with concepts of Einstein’s field equations from his general theory of relativity, or General Relativity, and taking into account the cosmological principle, in which the Universe at its largest scales is both homogeneous and isotropic (discussed further later in this Chapter), we then predict that, correcting for galactic peculiar velocities, the
dominant mechanism responsible for the observed redshifts of distant galaxies is the expansion of space in the Universe itself, in which galaxies are moving away from one another as space undergoes expansion. Galaxies for which peculiar velocities are effectively trivial and exhibit motion only due to this expansion is described to be a system undergoing Hubble flow. This first experimental verification of an expanding Universe also had obvious implications for what would become known as the Big Bang model of the Universe, which was first postulated by one of Hubble’s contemporaries, Georges Lemaitre. In this case, if the Universe is expanding in a homogeneous and isotropic manner, then it follows that at earlier and earlier times in the evolution of the Universe, galaxies that are currently observed as moving apart given the expansion of space would thus be closer and closer together until they converged in a cosmological singularity from which the Big Bang originated (Lemaitre, 1931).

\[ z = \frac{d_LH_0}{c} \quad (1.5) \]

From Hubble’s work, a value of what would become known as the Hubble Constant was presented to be 500 km s\(^{-1}\) Mpc\(^{-1}\) (Hubble 1929). This calculated value would ultimately prove to be an order of magnitude too large owing to distance underestimation by Hubble, but would be improved on in ensuing decades using increasingly accurate distance measurements of Cepheid Variables. As we noted earlier, however the usefulness of Cepheids is limited to galaxies within roughly 25 Mpc from Earth, so the detection and increasingly accurate estimation of distances to Type 1a Supernovae was vital to extending our measurement of \( H_0 \) using galactic data sets out to roughly a few Gpc. The study and measurements of Type 1a Supernovae released by Perlmutter and Riess in 1998 led to further refinement of the measurement of \( H_0 \), while also providing evidence for an accelerating expansion of the Universe leading to the 2011 Nobel Prize for Physics (Perlmutter et al. 1999; Riess et al. 1998). More recently, estimates of Baryonic Acoustic Oscillation in the Cosmic Microwave Background, have also led to an accurate determination of the value
Figure 1.1: Results presented in Hubble's seminal 1929 paper, in which a linear relationship is described between recessional velocity (determined by redshift) and distances (determined by observations of Cepheid variables) measured to distant ‘nebulae,’ later determined to be other galaxies. From this work, a value of what would become known as the Hubble Constant was presented to be $500 \text{ km s}^{-1}\text{ Mpc}^{-1}$. In the ensuing decades following Hubble’s work, using Cepheid Variables and Type 1a Supernovae, as well as estimates of Baryonic Acoustic Oscillation in the Cosmic Microwave Background, have led to a more accurate determination of the value of the Hubble Constant of about $70 \text{ km s}^{-1}\text{ Mpc}^{-1}$, though recent results from experiments conducting measurements using a variety of methods from the Cosmological Distance Scale continue to refine estimates of the exact value of the Hubble Constant (Hubble 1929).
of the Hubble Constant, though recent results from experiments conducting measurements using a variety of these methods from the cosmological distance scale continue to refine estimates of the exact value of the Hubble Constant, with a range of results near 70 km s\(^{-1}\) Mpc\(^{-1}\). Most recent results include the measurement of \(H_0\) by the Planck mission, yielding a result of roughly 67.8 km s\(^{-1}\) Mpc\(^{-1}\), and by the Hubble Space Telescope, yielding a result of roughly 73.2 km s\(^{-1}\) Mpc\(^{-1}\) (Planck Collaboration et al. 2016; Riess et al. 2016). The implications of the constraint of the Hubble constant can also provide useful information regarding an approximation for the age of the Universe, at least to first order by taking into account a linear expansion of the Universe. In this case, Hubble time, denoted as \(T_H\) can be defined as in Equation 1.6, where \(v_{rec} = H_0d_L\), and yields an approximation for the age of the Universe, or more precisely, time since the Big Bang. Using Hubble’s 1929 result, this would correspond to a Universe where \(T_H = 1.96\) Gyr, which clearly illustrates the issues with this initial estimate of the Hubble Constant, since the age of the Earth is itself roughly 4.5 Gyr. The estimated Hubble time corresponding to current measurements of \(H_0\) of roughly 70 km s\(^{-1}\) Mpc\(^{-1}\), would correspond to a Universe where \(T_H = 13.97\) Gyr, which is much closer to the actual age of the Universe, of roughly 13.8 Gyr. Clearly, the importance of experimentally obtained cosmological observations is made clear, and indicates the manner by which twentieth century studies of the cosmological distance scale has been able to dramatically advance our understanding of, as we have observed in this section, the size, age, and evolutionary dynamics of the Universe in which we live (Dodelson 2003; Partridge 1995; Ryden 2003).

\[
T_H = \frac{d_L}{v_{rec}} = \frac{1}{H_0} \quad (1.6)
\]

1.2 The Standard Cosmological Model

As we saw in the previous section, the combination of experimentally obtained measurements by Hubble and others with concepts set forth in General Relativity by Einstein, have
been able to begin to describe the size, age, and evolutionary dynamics of the Universe, however thus far we have not considered also the composition of the Universe, which, with the other characteristics, can help form our best possible description of the Universe, or more precisely, define a standard cosmological model.

1.2.1 The Cosmological Principle and the Robertson-Walker Metric

Let us begin by considering simple three-dimensional spherical geometry in euclidean space, defined through the coordinates $r$, $\theta$, and $\phi$. Then the equation describing the metric for the displacement between two given points in this system is given in Equation 1.7.

$$\delta s^2 = \delta r^2 + r^2 \delta \theta^2 + r^2 \sin^2(\theta) \delta \phi^2$$  \hspace{1cm} (1.7)

Furthermore, including a fourth-dimension, time, to this metric, then for a Universe in which mass and gravity are excluded, from special relativity we have Equation 1.8. This equation is the metric more commonly called the metric of Minkowski space, described by Hermann Minkowski in his 1909 text *Raum und Zeit* (Minkowski 1909).

$$\delta s^2 = -c^2 \delta t^2 + \delta r^2 + r^2 \delta \theta^2 + r^2 \sin^2(\theta) \delta \phi^2$$  \hspace{1cm} (1.8)

However, as we attempt to define a metric to best describe the standard model of cosmology for a Universe in which matter and gravity exist and General Relativity is correspondingly considered, we must take this a bit further. In the previous section, we described empirical evidence for an expanding Universe based on measurements of distance and redshift (recessional velocity) for astronomical objects on various scales. We can then define a scale factor, $a$ for the time-dependent expansion of space within the Universe, given in Equation 1.9 (Partridge 1995).

$$a(t) = \frac{1}{z(t) + 1}$$  \hspace{1cm} (1.9)
With these tools in hand, we now find ourselves able to describe a metric that would best describe an expanding Universe, in which $r, \theta,$ and $\phi$ are now considered comoving coordinates for fixed points within the expanding system. In particular, to describe such a Universe, which also takes into account the aforementioned cosmological principle, in which the Universe is, at its largest scales, both homogeneous and isotropic, then we can yield the metric for such a Universe similarly to that first defined by Howard Robertson and Arthur Walker in the late-1920s and early-1930s. We must recall that such a characterization of the Universe as isotropic and homogeneous is indeed appropriate only for the largest scales, or roughly at scales greater than a few hundred Mpc. This includes isotropic and homogeneous expansion of the Universe, since measured at large scales by, i.e. the Planck mission, the Universe does not appear to be expanding in a preferential direction and can thus be well characterized by the scale factor defined earlier (Ryden 2003). However, at scales smaller than this, say, on the scale of our own Milky Way galaxy, there are blatant inhomogenities in the distribution of mass (e.g. distribution of mass in the galactic center compared to its spiral arms) and there are also clearly preferred directions in the mass distribution that leads to its characterization as a non-isotropic system. Likewise, as the constituent objects comprising the Milky Way galaxy are gravitationally bound, we also do not observe evidence of an expanding Universe as we do for more distant objects, e.g., via the measurement of the recessional velocities of distant galaxies as we saw in the previous section. It is therefore appropriate to use the Robertson-Walker metric to describe our expanding, isotropic, and homogeneous Universe. The Robertson-Walker metric is given in Equation 1.10, for speed of light $c$, scale factor $a(t)$, and comoving coordinates $r, \theta,$ and $\phi$ (Robertson 1929). The final variable in the Robertson-Walker metric, $\kappa$, is a constant that describes the spatial curvature of the Universe and can take one of three possible variables $\kappa = -1, 0, 1$. This value thus provides for three possible geometries of the Universe at large scale, both euclidean and non-euclidean. If $\kappa = 0$ then the Universe is considered flat, so that a triangle comprised of three points in this Universe described by comoving coordinates will
have interior angles that sum to 180°, or in other words, following the properties of euclidean geometry. Conversely, if \( \kappa = 1 \) then the Universe would have a positive curvature in which a triangle comprised of three points in this Universe described by comoving coordinates will have interior angles that sum greater than 180°, and if \( \kappa = -1 \) then the Universe would have a negative curvature where the sum of the interior angles would be less than 180°, and therefore the Universe would not follow a euclidean geometry (Ryden 2003). Thus, \( \kappa \) is therefore an important cosmological parameter to describe the spatial curvature of the Universe.

\[
\delta s^2 = -c^2 \delta t^2 + a(t)^2 \left[ \frac{\delta r^2}{(1 - \kappa r^2)} + r^2 \delta \theta^2 + r^2 \sin^2(\theta) \delta \phi^2 \right]
\]

1.2.2 General Relativity and the Friedmann Equations, and ΛCDM Cosmology

With an appropriate metric now defined for the description of a homogeneous and isotropic Universe undergoing expansion under the same homogeneous and isotropic conditions, let us now return to mathematics of Einstein’s theory of General Relativity, first published in his seminal landmark 1916 paper Die Grundlage der allgemeinen Relativitätstheorie or The Foundations of the Theory of General Relativity (Einstein 1916). In this work, Einstein presented his field equations, for which the Einstein tensor, \( G_{\mu\nu} \), is defined in Equation 1.11 as:

\[
\left( \frac{8\pi}{c^4} \right) G T_{\mu\nu} = G_{\mu\nu} = \Lambda g_{\mu\nu} + R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R_s
\]

In this equation, \( c \) is the speed of light, \( G \) is Newton’s gravitational constant from classical mechanics, \( T_{\mu\nu} \) is the energy-momentum tensor, \( R_{\mu\nu} \) is the metric-dependent Ricci tensor, \( g_{\mu\nu} \) is the tensor describing the metric (in our case we assume this represents the Robertson-Walker metric), and \( R_s \) is the Ricci scalar. The additional term, \( \Lambda \) was included by Einstein as a cosmological constant to describe a Universe containing matter that was
static (e.g. with space neither expanding or contracting due to gravitational effects), as was the general theory in this pre-Hubble result period (Dodelson 2003; Gron 2007). Theoretical work to better characterize the evolutionary dynamics of the Universe continued in the decade following the publication of Einstein’s field equations, culminating in the 1922 publication of a set of equations based on Einstein’s theory of General Relativity for an expanding Universe by Soviet physicist Alexandar Friedmann. These equations, derived from Einstein’s field equations are represented in Equations 1.12, 1.13, and 1.14 (the first two of which are commonly referred to as the “Friedmann Equations”), and were first published in Friedmann’s 1922 Über die Krümmung des Raumes, or Concerning the Curvature of Space (Friedmann 1922; Ryden 2003).

\[
\left( \frac{\dot{a}}{a} \right)^2 = \left( \frac{8\pi G \rho}{3c^2} \right) - \left( \frac{k c^2}{a^2} \right) + \left( \frac{\Lambda}{3} \right) \tag{1.12}
\]

\[
\left( \frac{\ddot{a}}{a} \right) = - \left( \frac{4\pi G \rho}{3c^2} \right) - \left( \frac{4\pi G P}{c^2} \right) + \left( \frac{\Lambda}{3} \right) \tag{1.13}
\]

\[
\dot{\rho} + 3 \rho \left( \frac{\dot{a}}{a} \right) + 3 P \left( \frac{\dot{a}}{a} \right) = 0 \tag{1.14}
\]

In these equations, we again have from earlier $a$ as our scale factor, $G$ as Newton’s gravitational constant from classical mechanics, $c$ is the speed of light, cosmological constant $\Lambda$, the constant $k$ describing the spatial curvature of the Universe, and where here, $\rho$ represents energy density, and $P$ pressure. Additionally, we also have included in the Friedmann equations the definition for the so-called time-dependent Hubble parameter, given in Equation 1.15, which describes the rate of change of the scale factor and provides the value for the Hubble constant at a given comoving time in the evolution of the Universe, where we have from earlier $H_0$ representing the value of the Hubble parameter measured for the contemporary Universe.
Additionally, the relation between energy density $\rho$ and pressure $P$ is given by the equation of state for a Universe consisting of an ideal fluid in Equation 1.16, where the constant $w$ is described in physical cosmology as the equation of state parameter and for a Universe comprised only of relativistic photons the radiation pressure goes as, $P = (\rho c^2)/3$ so that $w = 1/3$ in this case (Ryden 2003). Furthermore, the energy density for which the spatial curvature of the Universe is flat, e.g. $\kappa = 0$ is called the critical density, denoted as $\rho_{\text{crit}}$, is defined as found in Equation 1.17, and depends on the Hubble constant. We can also define a useful cosmological parameter, called the density parameter $\Omega(t)$, given in Equation 1.18 as the ratio of the measured energy density in the Universe and the critical density defined in Equation 1.17, where similar to our convention for the Hubble parameter and constant, we express the contemporary value of the density parameter as $\Omega_0$.

$$H(t) = \left(\frac{\dot{a}(t)}{a(t)}\right) \quad (1.15)$$

$$w = \left(\frac{P}{\rho c^2}\right) \quad (1.16)$$

$$\rho_{\text{crit}} = \left(\frac{3H_0^2}{8\pi G}\right) \quad (1.17)$$

$$\Omega_0 = \left(\frac{\rho}{\rho_{\text{crit}}}\right) \quad (1.18)$$

### 1.2.3 ΛCDM Cosmology

Consideration of these definitions is key since the constraint of their values has a significant impact on the ultimate characterization of the Universe that can fulfill our search for a standard cosmological model. First, since the critical density of the Universe $\rho_{\text{crit}}$ is directly related to its potential spatial curvature $\kappa$, we can see that the measurement of $\Omega_0$ is therefore of critical importance - if $\Omega_0 = 1$ then the Universe is manifested within a
euclidean, flat geometry, whereas if $\Omega_0 > 1$ or $\Omega_0 < 1$ a non-euclidean geometric regime for the Universe would be possible, with positive and negative curvatures, respectively. Likewise, the constraint of $w$ is equally fundamental. We found earlier that a Universe comprised of only relativistic photons would result in a radiation pressure corresponding to a value where the equation of state parameter, $w = 1/3$. However, the existence of other relativistic particles in our Universe, namely neutrinos, requires us to consider $w = 1/3$ to correspond to a Universe that is filled with only relativistic particles, not just photons. Of course, our Universe is not filled solely with relativistic particles and radiation, but also contains nonrelativistic particles, such as baryonic and dark matter, for which we would expect $w = 0$. Furthermore, for a Universe undergoing accelerating expansion, such as demonstrated in our description of the work of Perlmutter and Riess in the previous section, but without a cosmological constant $\Lambda$, we would require the left-hand side of Equation 1.13 to be positive, so that for this to happen, it would be necessary that $w < -1/3$, whereas with a cosmological constant we would need $w = -1$ (Perlmutter et al. 1999; Riess et al. 1998; Ryden 2003). Additionally, returning to the first Friedmann Equation, represented in Equation 1.12 we can readily see that for an expanding Universe we would expect the $(\dot{a}/a)$ term to be larger than the $(8\pi G \rho)/(3c^2)$ term. Thus, for a flat Universe in with $\kappa = 0$, then the cosmological constant term would therefore be required in the first Friedmann equation to balance the equation for an expanding Universe in which flatness is maintained.

With these options in mind, we clearly see that the resulting possible models of the Universe are myriad, and can take into account Universes dominated by matter, dominated by radiation, with various spatial curvatures, various energy densities, and the possibility of an included cosmological constant. For the purposes of this discussion, we will jump directly to the current best estimate of the Universe in which we reside, based on constraint of this parameter space by observational and experimental cosmology platforms over the past two decades. This model of the Universe is called the $\Lambda$ Cold Dark Matter or $\Lambda$CDM model, and represents the current standard cosmological model, which has been borne out by
constraints placed on the various cosmological parameters discussed in this section through
the mapping and characterization of the Cosmic Microwave Background (to be formally
introduced in the next section), as well as methods to probe the cosmological distance scale
mentioned in the previous section, including measurements of Type 1a Supernovae. In the
ΛCDM model, the Universe has a flat spatial curvature and is described as originating in
a hot Big Bang - possibly followed by a rapid inflationary period - preceding the surface of
last scattering from which the Cosmic Microwave Background originated followed by the
evolution of an expanding Universe which is now in an epoch of accelerating expansion.
In ΛCDM cosmology, this accelerating expansion observed in the contemporary Universe is
described as being driven by the presence of the so-called “dark energy,” which is associated
with the presence of the cosmological constant, Λ. Furthermore, in the ΛCDM regime,
the presence of non-relativistic dark matter dominating the matter energy density (over
the contribution of baryonic matter) of the Universe is predicted. Therefore, the energy
density components of the ΛCDM model consist of matter (baryonic and cold dark matter
contributions), radiation (relativistic photons and neutrinos), and dark energy, as well as
that associated with the spatial curvature of the Universe in the possible case that deviation
from a flat Universe is found, though is likely trivial. Therefore, we can for the ΛCDM model
define the total density parameter for the Universe as a sum of its constituent components
observed today, defined in Equations 1.19, 1.20, 1.21, 1.22, as represented in Equation 1.23,
where Ω₀ = 1 if the Universe is flat, and the subscripts RAD, M, Ω, and κ correspond to
radiation, matter, the cosmological constant, and spatial curvature, respectively.

\[ \Omega_{\text{RAD}} = \left( \frac{\rho_{\text{RAD}}}{\rho_{\text{crit}}} \right) \]  (1.19)

\[ \Omega_{\text{M}} = \left( \frac{\rho_{\text{M}}}{\rho_{\text{crit}}} \right) \]  (1.20)

\[ \Omega_{\Omega} = \left( \frac{\rho_{\Omega}}{\rho_{\text{crit}}} \right) \]  (1.21)
\( \Omega_{\kappa_0} = \left( \frac{\rho_{\kappa_0}}{\rho_{\text{crit}}} \right) = \left( \frac{-\kappa}{H_0^2} \right) \) \hfill (1.22)

\[ \Omega_0 = \Omega_{RAD_0} + \Omega_{M_0} + \Omega_{\Lambda_0} + \Omega_{\kappa_0} \] \hfill (1.23)

In \( \Lambda \)CDM model, we find that the Universe has undergone three distinct epochs in terms of its constituent energy density, in which the Universe was first radiation dominated, then matter dominated, and is now dark energy dominated, where the energy density of radiation scales as \( 1/a^4 \), energy density of matter scales as \( 1/a^3 \), energy density due to a non-flat curvature scales as \( 1/a^2 \), and the presence of a cosmological constant associated with dark energy scales as \( 1/a \) (Dodelson 2003). Therefore, we can thus re-express the first Friedmann equation defined in Equation 1.12 in terms of the Hubble parameter, Hubble constant, the scale factor, and the various density parameter components, which is written simply in Equation 1.24.

\[ H = (H_0) \left( \Omega_{RAD_0}(z + 1)^4 + \Omega_{M_0}(z + 1)^3 + \Omega_{\Lambda_0} + \Omega_{\kappa_0}(z + 1)^2 \right)^{1/2} \] \hfill (1.24)

Over the decade prior to the development of ACTPol, a wide array of experimental cosmology platforms mapping the Cosmic Microwave Background gathered data in remarkable concordance with the \( \Lambda \)CDM model of the Universe, which has led to this model being the leading candidate to form the basis of a Standard Cosmological Model, in which extensions to this model, such as the aforementioned inflationary period following the Big Bang are now being probed while \( \Lambda \)CDM cosmology continues to be tested through constraint of cosmological parameters. These experiments include the WMAP satellite mission and the ground-based Millimeter Bolometer Array Camera, or MBAC, which was the predecessor instrument to ACTPol on the Atacama Cosmology Telescope dedicated to measuring the temperature anisotropies of the Cosmic Microwave Background. For example,
results from WMAP’s final nine-year data set are in good agreement with ΛCDM cosmology, in which for CMB data from WMAP combined with CMB data resulting from ACT+MBAC and from the South Pole Telescope surveys, the energy density parameters went as \( \Omega_M = 0.273 \pm 0.049 \), \( \Omega_\Lambda = 0.728 \pm 0.038 \), \( \Omega_\kappa = -0.001 \pm 0.012 \), so that the measurement of \( \Omega_0 = 1.001 \pm 0.012 \). Furthermore, these results constrained the Hubble constant to \( H_0 = 71.2 \pm 6.5 \text{ km/s/Mpc} \), the age of the Universe to \( t_0 = 13.71 \pm 0.65 \text{ Gyr} \), and, assuming a constant equation of state and a flat Universe, measured the equation of state parameter to \( w = -1.07^{+0.38}_{-0.41} \) and furthermore combining the CMB results with BAO, \( H_0 \) and SNe data, yielded, \( w = -1.084 \pm 0.063 \) (Hinshaw et al. 2013).

In other words, the constraint of cosmological parameters by the WMAP mission supports ΛCDM cosmology as a standard cosmological model, in which the Universe has an energy density dominated by dark energy, e.g. composed of roughly 72.8% dark energy, 27.3% matter (in which WMAP’s nine-year results showed that roughly 85% of the matter energy density is sourced from cold dark matter and 15% from baryonic matter) and a very small contribution from relativistic species (e.g. photons and neutrinos), and with a cosmological constant associated with dark energy and a flat spatial curvature (Hinshaw et al. 2013). Thus, we have observed in this section that constraint of cosmological parameters from experimental cosmology observational platforms mapping, the Cosmic Microwave Background is fundamental to our ability to confirm from a wide parameter space our standard cosmological model, ΛCDM cosmology, and through these measurements continue to answer important questions about the age, geometry, composition, and evolutionary dynamics of the Universe in which we live. In the section, which follows, we will define the physical properties of the Cosmic Microwave Background and discuss the manner by which measurement of its observable properties, namely the temperature and polarization anisotropies of the CMB, can allow for further constraint of relevant cosmological parameters that can both further confirm ΛCDM cosmology as the appropriately-defined standard cosmological model (which we will use as our standard cosmological model for the remainder
of this manuscript), as well as probe extensions of $\Lambda$CDM cosmology, such as a primordial inflationary period of the Universe.

1.3 The Cosmic Microwave Background (CMB) Radiation

1.3.1 Prediction, Detection, and Confirmation of Hot Big Bang Cosmology

Thus far, we have utilized the foundations of theoretical cosmology, e.g. General Relativity, Einstein’s field equations, the Friedmann equations, etc., to describe a standard cosmological model, namely $\Lambda$CDM cosmology, which has been supported by our ability to observe and measure with methods and instruments of increasing sensitivities, astrophysical phenomenon of fundamental importance to our Understanding of the physical dynamics of the Universe. To this end, one of the most important physical discoveries over the past half-century, which has enhanced our fundamental understanding of the Universe, has been the prediction and detection of the Cosmic Microwave Background (CMB) radiation. The prediction of a model of physical cosmology in which the Universe originated in a hot Big Bang was introduced by George Gamow’s studies in 1946 that built on Lemaitre’s work of the previous decade (Gamow 1946). From this, physicists Ralph Alpher and Robert Herman, in a 1948 paper simply entitled *Evolution of the Universe* in which they were “checking the results” presented in Gamow’s hot Big Bang predictions, predicted in 1948 for the first time that the Universe must have an ambient temperature, and themselves predicted a background temperature for the present Universe of 5°K, thus introducing the concept of a Cosmic Microwave Background resulting from a Universe with a cosmology originating in a hot Big Bang for the first time (Alpher and Herman 1948). It was then not for nearly two decades that this detection of a Cosmic Microwave Background as relic radiation confirming a hot Big Bang model of the Universe was experimentally discovered. The empirical discovery of the CMB was in fact not the result of an experimental cosmology
platform designed specifically for the measurement of the CMB, but rather by a 20 foot horn reflector antenna operating at a wavelength of 7.35 cm located at Bell Labs. During measurements of the sky using this instrument by Arno Penzias and Robert Wilson at Bell Labs in 1964, following correction for systematic effects, an excess background noise temperature from the sky of $3.5^\circ$K was measured, in which Penzias and Wilson reported that the noise temperature was isotropic for all areas of the sky measured, unpolarized, and “free from seasonal variations” (Penzias and Wilson 1965). This serendipitous discovery provided confirmation of the presence of a Cosmic Microwave Background sourced from a hot Big Bang, and set off a decades of research leading to the era of precision cosmology, in which, as we will see, the development of receivers of increasing temperature and polarization sensitivity confirmed the results of Penzias and Wilson, while also correcting some of their earlier results that were limited by the performance of their instrument - namely providing evidence of CMB polarization and of small anisotropies in the temperature and polarization of this background radiation.

Since its observational confirmation, measurement of the CMB with increasing precision has been the foremost transformational element in the study of physical cosmology, as well as providing broad scientific impact across a myriad of scientific areas, from particle physics to astronomy. Within the past two decades, in particular, key advances in receiver technologies operating on telescope facilities dedicated to observational cosmology at a wide range of angular scales (from entire sky to arcminute resolution), have resulted in cosmic-variance limited measurements of the temperature anisotropies of the CMB, as well as significant progress in the measurement of the CMB polarization anisotropies (BICEP2 Collaboration et al. 2014). As mentioned earlier, these measurements have improved constraints on cosmological parameters in continued confirmation of ΛCDM cosmology, and allowed for the precise characterization of the spatial curvature of the Universe, energy density components, nature of the baryonic matter, sum of neutrino masses, primordial helium abundance, as well as probes of the mysterious dark energy. Additionally, mapping of the CMB at small
angular scales as been proven to serve as an effective detection mechanism for galaxy clusters via the Sunyaev-Zel'dovich effect (SZE), interpretation of which has provided insight to the nature of the dark energy, in addition to key advances in the characterization of astrophysical phenomenon via x-ray, infrared, and optical follow-up observations of confirmed SZE clusters (Carlstrom et al. 2002). In spite of this remarkable scientific yield, the CMB still has much to tell us, primarily in the measurement of its polarization anisotropies.

1.3.2 Decoupling Matter and Radiation in the Primordial Universe

When referring to the CMB, we describe a relic light produced 380,000 years after the Universe began, where the existence of the CMB provides compelling evidence of hot Big Bang cosmology, as described in the previous section. As we saw earlier in this Chapter, the energy density of the early Universe was radiation dominated. In the period before the formation of the CMB, the Universe was comprised of a hot, opaque, dense primordial plasma consisting of coupled photons and baryons, in particular a plasma comprised principally of free electrons, ionized hydrogen, and photons. When we describe this environment as consisting of coupled baryons and photons, we are referring to the characteristic of this period in which the Universe had a sufficiently high enough temperature and density such that photons and electrons continue to scatter and remain in thermal equilibrium to each other given that the high-density of the Universe in this primordial period did not allow for a sufficiently long mean-free path for photon decoupling. As the Universe expanded, however, it cooled to a temperature of roughly 3000°K allowing for a period of recombination, defined as the period in which the ionized primordial plasma was able to combine into neutral atoms such that the number density of neutral atoms in the Universe was able to begin to exceed the number density of ions. In this period, the number density of free electrons clearly also began to decrease given the recombination of electrons and ions in the primordial Universe into neutral atoms. As the number density of free electrons dropped, so too did the rate of scattering events between photons and free electrons until the expansion
of the Universe allowed for photons to decouple from free electrons and cease scattering (defined as the time when the rate of photon scattering dropped below the value of the Hubble parameter dictating the rate of expansion of the Universe at that primordial stage in the evolution of the Universe) (Carroll and Ostlie 2007; Ryden 2003).

This final set of scattering events is commonly referred to as the ‘surface of last scattering,’ though as it took place over the course of roughly 115,000 years during which expansion, decoupling, and recombination took place it can be thought of geometrically more as a spherical shell than a spherical surface. When we observe the CMB, it is the photons from this surface of last scattering that we are measuring, where observationally, the CMB is optimally observed in the millimeter wavelength regime, as it has a characteristic thermal blackbody spectrum that peaks in the millimeter (in a frequency window of roughly 150 GHz), and exhibits a blackbody temperature of 2.725{eq}^{\circ}\text{K} (Hinshaw et al. 2013). That the detected current temperature of this background radiation has decreased significantly from its temperature at the surface of last scattering in the primordial Universe is expected for an expanding Universe in which CMB photons would be redshifted over the expansion history of the Universe. The equation for an ideal thermal blackbody spectrum is given in Equation 1.25, where we define \(A\) as \(A = (hc)/(\lambda kT)\), for the speed of light \(c\), Boltzmann constant \(k\), thermal temperature \(T\), Planck constant \(h\), frequency \(\nu\), and wavelength \(\lambda\). We will discuss in the next Chapter (and present the result as a figure) the 1990s measurement by the COBE satellite, which demonstrated that measurement of the CMB does indeed reveal a nearly ideal blackbody spectrum (and confirmed many times over by experiments following COBE), with great temperature homogeneity, displaying temperature variations at the \(10^{-5}\) level (we will discuss the source and nature of the CMB temperature and polarization anisotropies in the next subsection), so that the CMB does lead to a confirmation of hot Big Bang cosmology given its broad homogeneity and isotropy on large scales and its characteristic blackbody spectrum. For experimental cosmologists, the CMB is typically observed between roughly 60 GHz and 150 GHz owing to foreground emission from four
main sources: synchrotron, dust, free-free, and anomalous emission. Of these effects, synchrotron emission dominates at lower frequencies while dust emission dominates at higher frequencies, thus setting the window for optimal CMB experimental observation. The discussion of optimal CMB observing frequency windows, and contributions from foreground emission sources are discussed in greater detail in the presentation of ACTPol galactic field polarization analysis, presented for this first time later in this manuscript.

\[ B_\nu = \left( \frac{2\pi h}{c^2} \right) \left( \frac{\nu^3}{e^A - 1} \right) \]  

(1.25)

1.4 CMB Anisotropy

As we mentioned in the previous section, while the measurement of the CMB shows an incredible level of homogeneity and isotropy across all sky mapping, both small temperature and polarization anisotropies indeed are manifest across measurements of the CMB, and the characterization of these anisotropies is fundamental to the proper characterization of CMB for use as a tool to probe both the nature of the primordial Universe and its evolutionary dynamics, and are vital to constraint characteristics central to the ΛCDM model.

1.4.1 Temperature Anisotropy of the CMB

In particular, according to ΛCDM cosmology, quantum mechanical density fluctuations in the primordial Universe resulted in the formation of random over- and under-densities in the primordial plasma, which were stretched to large scales during inflation (we will discuss inflation and implications for its measurements in more detail later). These density fluctuations created acoustic oscillations in the aforementioned primordial plasma (consisting of coupled baryons and photons) given that the energy density of this plasma was subdominant to the energy density of dark matter in the early Universe, thus creating differential
gravitational potentials between overdense and underdense regions in which the dark matter induced a velocity in the still-coupled baryons and photons. The induced gravitational effect of the dark matter on the primordial plasma allowed for the coupled baryon and photon plasma to be compressed under gravitational effects resulting in an increase of its local pressure, which eventually would allow for the coupled baryon and photon plasma to expand and thus resulted in an oscillatory acoustic dynamic until decoupling at the surface of last scattering. In this mechanism, areas of maximum overdensity are associated with temperature maxima, while areas of maximum underdensity are associated with temperature minima, with those areas where the process was exhibiting motion between maxima would undergo red- or blueshifting. While this source of anisotropy from acoustic oscillations is characteristics at smaller scales, at larger scales the so-called Sachs-Wolfe effect is dominant, in which a photon traversing an overdense region must escape a larger gravitational potential than those traversing an underdense region, leading to loss and gain of energy, and therefore comparative higher and lower temperatures, respectively (Carroll and Ostlie 2007; Dodelson 2003; Ryden 2003).

We can define the simple measurement of the mean temperature of the CMB over any given data set, say from the WMAP 9-year data set discussed earlier, in which \( T_{\text{avgCMB}} \) was measured to be 2.72548°K, through Equation 1.26 (Hinshaw et al. 2013). Furthermore, we can then define a general expression for the temperature fluctuation measured for a given point on the sky, \( T(\theta, \phi) \) compared to the average temperature integrated over the entire measured field (e.g. a given observing field or the entire sky), according to Equation 1.27.

\[
T_{\text{avgCMB}} = \left( \frac{1}{4\pi} \right) T(\theta, \phi) \sin(\theta) d\theta d\phi \quad (1.26)
\]

\[
\left( \frac{\delta T(\theta, \phi)}{T} \right) = \left( \frac{T(\theta, \phi) - T_{\text{avgCMB}}}{T_{\text{avgCMB}}} \right) \quad (1.27)
\]

Given that we observe the CMB emanating from the surface of last scattering, we are observing the CMB thus emanating from a spherical shell, so that we can then define the
temperature anisotropies of the CMB in terms of a decomposition into spherical harmonics, which we given in Equation 1.28, for spherical harmonic $Y^\ell_m$, where we define $\ell$ as $(180^\circ)/(\theta)$, and referred to as a the angular multipole moment (which will appear as a convention throughout the remainder of this manuscript). We can then define the associated CMB temperature power spectrum in terms of $[(\ell)(\ell+1)(C_\ell)]/(2\pi)$, where we define $C_\ell$ as follows in Equation 1.29 (Carroll and Ostlie 2007; Dodelson 2003; Ryden 2003). It should be noted at this time, that if we recall our discussion of redshift from earlier in the Chapter, we would expect, an indeed do measure, an overall redshift/blueshift dynamic in all-sky maps of the CMB, often referred to as the CMB dipole anisotropy, given our peculiar motion moving within our galactic reference frame, although this effect is well-characterized and can thus be removed from CMB temperature mapping data as a systematic effect, thus providing us with the proper CMB temperature power spectrum within which we can probe $\Lambda$CDM cosmology in a variety of ways, in which, for example, the nature of the baryonic matter and dark matter can be probed by comparison of the various harmonic peaks in the power spectrum. In the penultimate section of this Chapter, we provide a view of a CMB temperature anisotropy map and associated temperature power spectrum taken by the first-generation receiver on the Atacama Cosmology Telescope, MBAC.

\[
\left( \frac{\delta T(\theta, \phi)}{T} \right) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y^\ell_m(\theta, \phi)
\]

\[
C_\ell = \left( \frac{1}{(2\ell + 1)} \right) \sum_{-\ell}^{\ell} |a_{\ell m}|^2
\]

1.4.2 Polarization Anisotropy of the CMB

In the previous section, we discussed the physical dynamics of the primordial Universe that imprinted temperature anisotropies on the Cosmic Microwave Background as decoupling took place at the surface of last scattering, associated with acoustic oscillatory behavior
and the Sachs-Wolfe effect in areas of over- and underdensity in the early Universe. It turns out that the dynamics of these mechanisms leading to CMB temperature anisotropy also lead to a polarization signal to be manifest in measurements of the CMB. In particular, the primary mechanism resulting in the polarization of the CMB temperature signal is Thompson scattering of CMB photons off of free electrons at the surface of last scattering, resulting in linear polarization of CMB temperature radiation. In order to source the linear polarization of the CMB, we require that the incident radiation have quadrupolar anisotropy (Hu and White 1997). That quadrupolar anisotropy arises in incident radiation at the surface of last scattering is specifically due to the mechanisms described for the development of CMB temperature anisotropies from oscillatory motion into and out of over- and underdense in the previous section in which photons will either gain or lose energy depending on the region from which they are sourced. An additional source of quadrupolar anisotropy is associated with anisotropies created by compression or expansion within the primordial plasma due to gravitational waves (in which a passing gravitational wave would compress the plasma more in one direction than another), which would be expected in an inflationary cosmology regime. Thus, this leads to radiation of quadrupolar anisotropy incident on free electrons from these two sources at the surface of last scattering. The Thompson scattering of such a quadrupolar radiation field is given in Figure 1.2, in which we define hotter or more intense unpolarized radiation (colored in blue to represent more intense blue shifted regions) and cooler or less intense unpolarized radiation (colored in red to represent less intense red shifted regions) incident on a free electron. Thus, following scattering off of the free electron we are left with resultant polarized radiation that is linearly polarized along the line of sight according to the incident radiation intensities (Carroll and Ostlie 2007; Hu and White 1997; Newburgh 2010).

Viewed broadly, the characterization of CMB temperature and polarization anisotropies require knowledge of three quantities for any given observed point on the sky. These three quantities are: the observed temperature of the CMB blackbody spectrum T, the degree
Figure 1.2: The Thompson scattering of a CMB field. The CMB field is quadrupolar, and here which we define hotter or more intense unpolarized radiation (colored in blue to represent more intense blue shifted regions) and cooler or less intense unpolarized radiation (colored in red to represent less intense red shifted regions) incident on a free electron. Thus, following scattering off of the free electron we are left with resultant polarized radiation that is linearly polarized along the line of sight according to the incident radiation intensities (Hu and White 1997)
of polarization, or polarization intensity $P$, and the angle between the direction of polarization and a given coordinate system on the sky, denoted as $\alpha$. $P$ and $\alpha$ are traditionally parametrized in terms of the Stokes Parameters, $Q$ and $U$, defined in Equations 1.30 and 1.31 as:

$$Q = P \cos(2\alpha)$$  (1.30)  

$$U = P \sin(2\alpha)$$  (1.31)  

It should be pointed out here that Stokes $Q$ and $U$ vectors are elongated from each other by $45^\circ$, which is important for our later discussion of the design of the ACTPol polarimeter array package, which is designed with polarimeters aligned at $0^\circ$ and $45^\circ$ for coverage of Stokes $Q$ and $U$. These definitions do not quite tell the full story, however, since we can also decompose polarized radiation with Stokes $V$ parameter (though in this case, since the Stokes $V$ has circular polarization and thus cannot be sourced from a quadrupolar radiation field undergoing Thompson scattering), so we can define this decomposition of CMB radiation in terms of its intensity and polarization more formally, according to (Kamionkowski et al. 1997), in which for radiation propagating along the $z$-axis, we can decompose its electric fields into $E_x$ and $E_y$ and then yield the corresponding time-averaged Stokes Parameters $P$, $Q$, $U$, $V$ corresponding to amplitudes $a_x$ and $a_y$ according to Equations 1.32, 1.33, 1.34, 1.35, 1.36, and 1.37 (Kamionkowski et al. 1997).

$$E_x = a_x \cos[\omega_0 t - \theta_x(t)]$$  (1.32)  

$$E_y = a_y \cos[\omega_0 t - \theta_y(t)]$$  (1.33)  

$$P = \langle a_x^2 \rangle + \langle a_y^2 \rangle$$  (1.34)
\[ Q = \langle a^2_x \rangle - \langle a^2_y \rangle \]  
\[ U = \langle 2a_x a_y \cos(\theta_x - \theta_y) \rangle \]  
\[ V = \langle 2a_x a_y \sin(\theta_x - \theta_y) \rangle \]

Similar to our treatment of the temperature anisotropies in the previous section, given that we observe the CMB emanating from the surface of last scattering, we are observing the CMB thus emanating from a spherical shell, so that we can then define the CMB polarization in terms of a decomposition into spherical harmonics for the relevant Stokes parameters for CMB polarization, namely Stokes Q and U as we have discussed. As described in (Zaldarriaga and Seljak 1997), the all-sky expansion in spherical harmonics for CMB polarization must have a spin-weighted basis, so that the expansions in spherical harmonics go as in Equation 1.38 and 1.39.

\[ (Q + iU)(\theta, \phi) = \sum_{\ell m} a_{2,\ell m} Y_{2,\ell m}(\theta, \phi) \]  
\[ (Q - iU)(\theta, \phi) = \sum_{\ell m} a_{-2,\ell m} Y_{-2,\ell m}(\theta, \phi) \]

When an instrument like ACTPol makes a polarization-sensitive map of a given field of the CMB, we measure the Stokes Q and U polarization on the sky and then decompose them into two linear orthogonal bases, which have: (i) curl-free E-mode polarization, which arises from plasma accelerating into and out of overdense regions of the early Universe; and (ii) divergence-free B-modes, which, if directly detected, would provide evidence of gravitational waves propagating through space and a verification of inflationary cosmology. We can express the expansion for E-mode and B-mode signal according to Equation 1.40 and 1.41 as described by (Zaldarriaga and Seljak 1997).
\[ E(\theta, \phi) = -\frac{1}{2} \left( \delta^2(Q + iU) + \delta^2(Q - iU) \right) = \sum_{\ell m} \left( \frac{\ell + 2)!}{(\ell - 2)!} \right)^{1/2} a_{E,\ell m} Y_{\ell m}(\theta, \phi) \quad (1.40) \]

\[ B(\theta, \phi) = \frac{i}{2} \left( \delta^2(Q + iU) - \delta^2(Q - iU) \right) = \sum_{\ell m} \left( \frac{\ell + 2)!}{(\ell - 2)!} \right)^{1/2} a_{B,\ell m} Y_{\ell m}(\theta, \phi) \quad (1.41) \]

With the mathematical expansion for E- and B-modes now in hand, we can jump to their associated power spectra similar to the previous section. As described by Kaminkowski in (Kamionkowski 2002), the two-point statistics of a combined CMB temperature and polarization map is described by six power spectra, given in Equation 6.3.

\[ C_{KL}^{\ell}, \text{for } K, L = T, E, B \quad (1.42) \]

However given constraints of parity invariance, \( C_{\ell}^{TB} \) and \( C_{\ell}^{EB} \) are trivial, leaving four relevant power spectra to describe CMB maps in temperature and polarization: \( C_{\ell}^{TT}, C_{\ell}^{TE}, C_{\ell}^{EE}, \) and \( C_{\ell}^{BB} \) (Kamionkowski 2002). The corresponding non-trivial power spectra definitions for \( C_{\ell}^{TT}, C_{\ell}^{TE}, C_{\ell}^{EE}, \) and \( C_{\ell}^{BB} \), then go as defined in Equations 1.43, 1.44, 1.45, 1.46 as defined by (Zaldarriaga and Seljak 1997).

\[ C_{\ell}^{TT} = \frac{1}{(2\ell + 1)} \sum_m \langle a_{T,\ell m}^* a_{T,\ell m} \rangle \quad (1.43) \]

\[ C_{\ell}^{TE} = \frac{1}{(2\ell + 1)} \sum_m \langle a_{T,\ell m}^* a_{E,\ell m} \rangle \quad (1.44) \]

\[ C_{\ell}^{TT} = \frac{1}{(2\ell + 1)} \sum_m \langle a_{E,\ell m}^* a_{E,\ell m} \rangle \quad (1.45) \]

\[ C_{\ell}^{BB} = \frac{1}{(2\ell + 1)} \sum_m \langle a_{B,\ell m}^* a_{B,\ell m} \rangle \quad (1.46) \]
For the purposes of this manuscript, we shall simplify notation for $C_{\ell}^{TT}$, $C_{\ell}^{TE}$, $C_{\ell}^{EE}$, and $C_{\ell}^{BB}$, to TT, TE, EE, and BB, respectively. Figure 1.4 provides a visual representation of the sort of polarization geometry characteristic of E- and B-mode polarization. In particular, the top left inset shows a simulated CMB temperature map with both E- and B-modes represented in a linear combination across the field, with the corresponding decomposed E- and B-mode polarization maps shown for the right insets. The lower left inset shows curl-free E-modes in which E-mode polarization consists of tangential vectors around more intense, or warmer, regions of the CMB (designated in red), and radial vectors around less intense, or cooler, regions of the CMB (designated in blue). Furthermore, the divergence-free B-mode polarization is shown, which shows counter-clockwise vectors around more intense, warmer regions of the CMB, and clockwise vectors for less intense, cooler regions of the CMB.

Whereas previous experimental cosmology platforms such as MBAC were able to better constrain characteristics of the primary temperature anisotropy, or TT, power spectrum of the CMB to good agreement with $\Lambda$CDM cosmology models (as did the early temperature results from the Planck mission), next generation, polarization-sensitive instruments like ACTPol would then be able to further probe the other three characteristic power spectra for temperature and polarization maps of the CMB, the temperature-polarization cross power spectrum, TE, and the so-called E-mode, and B-mode power spectra, EE and BB, respectively. Figure 1.3 represents the theoretical predictions of the TT, TE, EE, and BB power spectra, in which the significant drop in intensity for the polarization signals expected for both EE and BB power spectra set the principal technological challenge requiring CMB polarimeters operating with appropriate sensitivities to effectively measure these spectra.

Finally, as described in detail in (Hu and White 1997) and following the physical description earlier in this section, we find that while scalar perturbations associated with acoustic oscillations produce solely E-mode polarization, tensor perturbations associated with gravitational waves, which are necessary for an inflationary period of the primordial Universe can produce both E-mode and B-mode polarization. Thus, the measurement of the tensor-to-
Figure 1.3: The theoretical predictions of the TT, TE, EE, and BB power spectra, in which the significant drop in intensity for the polarization signals expected for both EE and BB power spectra set the principal technological challenge requiring CMB polarimeters operating with appropriate sensitivities to effectively measure these spectra. (Hu and White 1997)
scalar ratio, denoted as $r$ remains at the forefront of CMB polarization studies, and requires the measurement of the BB power spectrum, which, as yet, has been undetected, though measurements of the TT, TE, and EE power spectra have been made and results for the ACTPol instrument will be presented later in this work, along with a description of the implications of inflationary cosmology and some of the next-generation instruments that seek to confirm this model through the measurement of B-modes. If confirmed, inflationary cosmology would extend our understanding of $\Lambda$CDM cosmology and would help to explain the measured spatial curvature of the Universe as well as to explain how quantum mechanical density fluctuations in the primordial Universe could be stretched to large scales during inflation, preserving apparent thermal equilibrium between areas of the CMB that should not be in causal contact, which is often described as the so-called horizon problem (Carroll and Ostlie 2007). It should also be noted that the CMB temperature and polarization anisotropies described in this section are not the only anisotropic features that experimental cosmology platforms observing the Cosmic Microwave Background measure, since what we are describing here are ideal CMB temperature and polarization signals detected without interaction with any structure throughout the expansion history of the Universe, so-called primary anisotropies. There are also secondary anisotropies, associated with small-angular scale measurements of the CMB, that describe effects on temperature and polarization signal following interaction with structures in the Universe, including gravitational lensing of CMB temperature signal, and E-mode polarization that is induced to B-mode polarization from gravitational lensing from large scale structure. In the next section, we will briefly describe another such source of secondary anisotropy, describing the Sunyaev-Zel’dovich effect resulting from the interaction of CMB radiation with ionized gas in galaxy clusters.

1.5 The Sunyaev-Zel’dovich (SZ) Effect

Galaxy clusters are the largest virialized structures in the Universe, and can act as important cosmological probes. Additionally, the observation and characterization of galaxy clusters
Figure 1.4: A visual representation of the sort of polarization geometry characteristic of E- and B-mode polarization. In particular, the top left inset shows a simulated CMB temperature map with both E- and B-modes represented in a linear combination across the field, with the corresponding decomposed E- and B-mode polarization maps shown for the right insets. The lower left inset shows curl-free E-modes in which E-mode polarization consists of tangential vectors around more intense, or warmer, regions of the CMB (designated in red), and radial vectors around less intense, or cooler, regions of the CMB (designated in blue). Furthermore, the divergence-free B-mode polarization is shown, which shows counter-clockwise vectors around more intense, warmer regions of the CMB, and clockwise vectors for less intense, cooler regions of the CMB (Hu and White 1997).
are fundamentally important to physics more broadly, exhibiting physical phenomenon, e.g. shocks and cold fronts, that are of crucial importance to other areas of physics and the characterization of astrophysical dynamics. Galaxy clusters form from the collapse of dark matter halos, and range in mass from $10^{14}$ to $10^{15}$ solar masses. Connecting this with our earlier discussion, the largest overdensities formed in the primordial Universe in fact lead to gravitational potential wells in which galaxy clusters form, and in general support the growth of the large scale structure of the Universe. Thus measurements of galaxy clusters can also be useful probes of the manner by which the growth of structure, and thus the evolutionary dynamics of the Universe can be probed.

Galaxy clusters were observed throughout the CMB fields of ACT+MBAC and will also be detected in ACTPol CMB fields, via the Sunyaev-Zel’довich effect (Sunyaev and Zeldovich 1972). The Sunyaev-Zel’dovich effect occurs when low-energy photons from the CMB inverse Compton scatter when interacting with a cloud of high-energy electrons, such as those comprising hot, ionized gasses existing in intracluster medium of galaxy clusters. As a result of this process, CMB photons become blue-shifted through the Sunyaev-Zel’dovich effect, and, more pertinent to ACTPol, in the observable band of frequencies (90 GHz and 150 GHz channels), a decrement is observed in the CMB intensity allowing for surveys of galaxy clusters to be acquired from ACTPol CMB maps. The relations that govern both this frequency shift due to the Sunyaev-Zel’dovich effect, as well as the temperature deviation from average CMB temperature signal (decrement in ACTPol CMB signal) and its associated frequency dependence $f(x)$ definition, are given in Equation 1.47, 1.48, and 1.47. In these equations, we have the Boltzmann constant $k$, electron mass $m_e$, speed of light $c$ (where $m_e c^2$ is the electron rest mass energy), electron temperature $T_e$, Thompson scattering cross-section $\sigma_T$, Compton $y$-parameter $y$, electron number density $n_e$, and the relativistic correction for the frequency dependence is given by $\delta_{SZE}$ (Carlstrom et al. 2002):

$$\left(\frac{\Delta \nu_{\text{avg}}}{\nu}\right) = (4) \left(\frac{k T_e}{m_e c^2}\right) \delta_{\text{SZE}} \tag{1.47}$$
\[
\frac{\Delta T_{\text{SZE}}}{T_{\text{CMB}}} = f(x) y = f(x) \int \left( \frac{n_e k T_e \sigma_T}{m_e c^2} \right) d\ell
\]  
(1.48)

\[
f(x) = \left( x \left( \frac{e^x + 1}{e^x - 1} \right) - 4 \right) \left( 1 + \delta_{\text{SZE}}(x, T_e) \right)
\]  
(1.49)

Figure 1.5 provides an illustration of the Sunyaev-Zel’dovich effect along with the expected shift in frequency of the CMB blackbody spectrum induced by the Sunyaev-Zel’dovich effect. We also see here that the number counts of Sunyaev-Zel’dovich galaxy clusters are sensitive to various cosmological models, including $\Lambda$CDM, therefore galaxy cluster survey and detection is fundamental for the constraint and verification of cosmological models. Observation of Sunyaev-Zel’dovich galaxy clusters also allows for further constraints to test $\sigma(8)$, which defines the linear mass fluctuations of the Universe on the scale of 8 Mpc/h which is used to constrain the mass density of the Universe, and the equation of state parameter $w$, and enable a better understanding of the nature of dark matter and dark energy densities (White et al. 1993). Like its predecessor instrument, MBAC, ACTPol will be an effective Sunyaev-Zel’dovich galaxy cluster survey instrument and will again employ a multi-stage approach to Sunyaev-Zel’dovich measurements, by: detecting Sunyaev-Zel’dovich galaxy clusters in CMB surveys, determining cluster redshifts via optical follow-up, use x-ray, optical, and Sunyaev-Zel’dovich data to determine the mass selection function, calculating the number distribution, finally allowing for further constraint of $\sigma(8)$ and $w$.

1.6 Toward Direct Probes of the CMB in Temperature and Polarization with a Next-Generation ACT Receiver: ACT-Pol

The predecessor receiver to ACTPol, MBAC, the operations of which will be briefly described in the next Chapter, was able to succeed in making temperature-sensitive maps
Figure 1.5: An illustration of the Sunyaev-Zel’dovich effect and impact on galaxy cluster number count constraints on ΛCDM cosmology. The Sunyaev-Zel’dovich effect occurs when low-energy photons from the CMB inverse Compton scatter when interacting with a cloud of high-energy electrons, such as those comprising hot, ionized gasses existing in intracluster medium of galaxy clusters. As a result of this process, CMB photons become blue-shifted through the Sunyaev-Zel’dovich effect, and, more pertinent to ACTPol, in the observable band of frequencies (90 GHz and 150 GHz channels), a decrement is observed in the CMB intensity allowing for surveys of galaxy clusters to be acquired from ACTPol CMB maps. We also see here that the number counts of Sunyaev-Zel’dovich galaxy clusters are sensitive to various cosmological models, including ΛCDM, therefore galaxy cluster survey and detection is fundamental for the constraint and verification of cosmological models. Observation of Sunyaev-Zel’dovich galaxy clusters also allows for further constraints to test σ(8), which defines the linear mass fluctuations of the Universe on the scale of 8 Mpc/h which is used to constrain the mass density of the Universe, and the equation of state parameter w, and enable a better understanding of the nature of dark matter and dark energy densities.
of the Cosmic Microwave Background, as well as serve as an effective platform for galaxy cluster surveys detected via the Sunyaev-Zel’dovich effect. Figure 1.6 presents two representative results from the full operation of MBAC on the Atacama Cosmology Telescope: the CMB temperature anisotropy power spectrum measured using the full ACT+MBAC dataset, as well as a sample of galaxy clusters detected in the full set of ACT+MBAC data via the Sunyaev-Zel’dovich effect (Hasselfield et al. 2013a; Sievers et al. 2013). MBAC was able to effectively constrain the TT power spectrum at small angular scales across all of its operational frequency channels, and was ultimately able to detect 68 galaxy clusters via the Sunyaev-Zel’dovich effect, 19 of which were original discoveries of previously undetected clusters. The clusters shown in the lower panel represent the 10 SZ cluster detections of highest signal-to-noise ratio, in which the grayscale runs from -350 \( \mu K \) to 100 \( \mu K \), from black to white, respectively.

The aim of this dissertation is to develop a next-generation receiver, ACTPol, with improved sensitivity in both temperature and polarization which will allow for constraints to be placed on cosmological parameters discussed throughout this Chapter, and ultimately, test the characteristics of our standard cosmological model, \( \Lambda \)CDM cosmology. Ultimately, primary ACTPol observational surveys will measure intrinsic CMB temperature and polarization anisotropies, probing \( \Lambda \)CDM cosmology through constraint of the TT, EE, and BB (via gravitational lensing) power spectra. First, ACTPol will measure the TT power spectra across observed fields for multipole \( 200 < \ell < 9000 \) with increased sensitivity over its predecessor instrument, MBAC. Second, ACTPol will measure the TE and EE power spectra across observed fields to roughly \( \ell < 3000 \). Finally, ACTPol will attempt to constrain the BB power spectrum generated by gravitational lensing. Previous generation EE power spectrum measurements have been able to constrain \( \Lambda \)CDM cosmology predictions to good agreement on large-angular scales, though operating at small-angular scales, ACTPol, will be able to probe further down the Silk damping tail at higher \( \ell \) than those experiments, given that at smaller angular scales, as achievable by ACTPol, the polarization fraction...
arising from foregrounds at higher ℓ is lower for the EE power spectrum than at larger-angular scales. Finally, throughout the operational lifetime of the ACTPol instrument, taking into account the projected ACTPol Deep, ACTPol Wide, and ACTPol Ultra-Wide surveys operationally described in the later Chapters, roughly 1000 Sunyaev-Zel'dovich effect detected galaxy clusters are expected by the close of ACTPol operations.

1.7 Summary

The dissertation manuscript, which follows, is partitioned into three distinct sections. The first section provides details regarding the critical space technology development that was associated with the development of the ACT site and optomechanical superstructure for ACTPol operations, as well as the development and performance of the ACTPol receiver, describing both the design and development of its constituent subsystems, systems, and integrated space technologies, as well as its performance results. This section is followed by a look at the first two seasons of ACTPol operations and the development of operational protocols and logistics that enabled the highest-possible operational efficiency of CMB science operations for ACT+ACTPol. We also describe the early CMB temperature and polarization mapping results from the first season of ACTPol operations, initial results from ACTPol two-season Sunyaev-Zel’dovich cluster surveys from the ACTPol data set from these two seasons, and finally describe the characterization of the ACTPol season one galactic field data set in both temperature and polarization sensitivity, and through a joint-analysis with analogous polarization data from the Planck satellite, perform a polarization analysis of this dataset which will set the groundwork for the future characterization of foregrounds in future-generation CMB polarization-sensitive imagers. The results for the ACTPol season one galactic field temperature and polarization analysis are presented for the first time in this work. The final section provides an outlook for future-generation experimental cosmology platforms that will continue to probe the CMB in temperature and polarization (including ACTPol’s successor instrument, Advanced ACTPol), setting the
Figure 1.6: Two representative results from the full operation of MBAC on the Atacama Cosmology Telescope: the CMB temperature anisotropy power spectrum measured using the full ACT+MBAC dataset (above), as well as a sample of galaxy clusters detected in the full set of ACT+MBAC data via the Sunyaev-Zel’dovich effect (below) (Hasselfield et al. 2013a; Sievers et al. 2013). MBAC was able to effectively constrain the TT power spectrum at small angular scales across all of its operational frequency channels, and was ultimately able to detect 68 galaxy clusters via the Sunyaev-Zel’dovich effect, 19 of which were original discoveries of previously undetected clusters. The clusters shown in the lower panel represent the 10 SZ cluster detections of highest signal-to-noise ratio, in which the grayscale runs from -350 $\mu$K to 100 $\mu$K, from black to white, respectively.
stage for future-generation instruments able to effectively probe the epoch of inflation. As we will see, not only has the development of ACTPol allowed for competitive mapping of the CMB in both temperature and polarization in good agreement with ΛCDM cosmology, thus demonstrating an effective integration of experimental space technologies as a standalone CMB science platform, but the technology and science development represented in this work also qualify ACTPol as an effective pathfinder experiment for technologies that will contribute to the success of future inflationary probe platforms.
Part II

Instrumentation Development for the Atacama Cosmology Telescope
Chapter 2

The Atacama Cosmology Telescope

Closely let me hold thy hand,
storms are sweeping sea and land;
love alone will stand.

Closely cling, for waves beat fast,
foam-flakes cloud the hurrying blast;
love alone will last.

Kiss my lips, and softly say:
“Joy, sea-swept, may fade to-day;
Love alone will stay.”

from Edward Elgar’s “Sea Pictures: In Haven (Capri)”

The Republic of Chile, a nation of 17.5 million citizens representing just 0.25% of the global population, may from the outset seem a surprising candidate to host over 40% of global astronomical infrastructure as of 2015 - a number that is projected to increase to
over 70% of worldwide investment across the field by 2020, with over two billion dollars in projected commitments from the U.S. National Science Foundation alone by that time, in real terms. Rugged terrain, vast regions of characteristically sparse population and infrastructure along its 6,435 km coastal extent, and, until recent decades, a turbulent political history might be seen as factors to dissuade multinational investment and partnership in support of long-lead-time astrophysics and experimental cosmology platforms.

The reality, however, is a country which has taken the preeminent global role as a leader in fostering astronomical research given inputs that are equal part environmental, cultural, and geopolitical. Moreover, the example of contemporary Chilean leadership to act as the global center of astronomical scientific activity is a key illustration of the fundamental role that international scientific relationships play to support robust bilateral and multilateral diplomatic relationships. Such relationship-building is initiated at first by individual scientists, institutions, and supranational science and technology organizations, ultimately resulting in international diplomacy in traditional terms. As we will observe, the narrative of multilateral collaboration in Chilean astronomy is one firmly rooted in the unique role that scientists and technologists have had, both historically and in the contemporary era, to foster international engagement via shared scientific truths. This so-called “scientific diplomacy” has been fundamental in the foundation of increased solidarity between existing allies, and has provided leadership to thaw discourse between even the coldest geostrategic adversaries - often yielding successful results inaccessible to political diplomats of monodisciplinary background (CIA 2015; Hammer 2015).

In this chapter, we consider the role of the Atacama Cosmology Telescope and its three generations of deployed receiver technologies within this hegemony of scientific engagement and research. Section 2.1 provides a brief account of the development of astronomical observations in Chile utilizing a purely historiographic approach. The Section continues by considering the factors that led to the later development of experimental cosmology in the northern Atacama Desert region, which began in the early 1990s after the transition to
modern Chilean democracy. Section 2.2 provides a brief look at the geographic, atmospheric, and logistical conditions that led predecessor experiments and early site testing campaigns to establish a permanent presence on the location of the current ACT facility, before racing forward to characterize the site-selection criteria that facilitated the development of the ACT project itself, including precipitable water vapor (PWV) and atmospheric observing frequency window conditions for optimal measurement of the Cosmic Microwave Background (CMB) from Cerro Toco.

Section 2.4 describes the inception of the ACT collaboration over its three operational generations (MBAC era, ACTPol era, and Advanced ACTPol era), and highlights U.S. domestic federal support for the project from both the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA), as well as bilateral partnership with and support from the Chilean Comisión Nacional de Investigación Científica y Tecnológica (CONICYT). Section 2.5 briefly discusses the fabrication and integration of the ACT telescope superstructure and initial site infrastructure construction, which led to first-generation ACT operations with the Millimeter Bolometer Array Camera (MBAC), the site infrastructure and operational logistics for which are detailed throughout Section 2.6. Section 2.7 provides a focused characterization of the ACT warm optical off-axis Gregorian design requirements, and the manner by which these considerations resulted in the ultimate segmented primary and secondary mirror design, telescope and ground screen superstructural construction. Additionally, this section provides an overview of the two principal methods of primary, secondary, and receiver critical alignment using a previous-generation laser-tracking alignment system, and the development of a next-generation integrated photogrammetry alignment strategy.

Section 2.8 provides an overview of the site infrastructure and logistics system upgrades that were custom-designed to foster efficient ACTPol operations, including design summaries for the four principal integrated assemblies of the ACTPol Receiver Alignment Systems (ACTPol RAS), as well as improvements to ACT site access made possible through
the establishment of the Parque Astrónomico de Atacama by CONICYT, on-site receiver integration enabled by the construction of a custom site high bay facility, and the partnership yielding improved polarimeter array package pre-integration characterization and testing at the ALMA Operations Support Facility (ALMA-OSF). Finally, in Section 2.9 a brief description of the overarching strategy for ACT observations is provided.

2.1 Experimental Cosmology in Chile

2.1.1 The Development of Chilean-based Astronomy

Although the Atacama Cosmology Telescope (ACT) firmly resides among the foremost facilities focused on astronomical, and more specifically, experimental cosmology research within the modern era of international cooperation in Chilean-based astronomy, ACT and its contemporaries are hardly the first platforms that have capitalized on the ideal observing conditions experienced in the nation, especially across the Atacama Desert of Northern Chile. An expansively long and thin desert bounded to the east by the imposing Andes mountain range, and to the west by the Chilean Coastal mountain range and vast waters of the Pacific Ocean, the geography and resulting climate of Chile’s Atacama Desert have made it a notable site for astronomical observations for centuries. With ancestry tracing to the early centuries C.E., the Atacameño and (later) Incan peoples indigenous to the Atacama Desert region that would become part of present-day northern Chile recognized the clarity of their nighttime skies through a close integration of astronomy into their own ethnocultural identity. Throughout their history, astronomy had an overarching impact across scientific, cultural, and artistic traditions, the juxtaposition of which was a central element in The ARTacama Project, highlighted in Appendix A. This focus on astronomy as a central ethnocultural signifier would continue through the colonial era and extend into the foundation of the early Chilean republic.
International interest and collaboration in Chilean-based astronomy also has roots pre-dating the modern race toward an Atacama-centric paradigm of globally-connected observational platforms. In terms of bilateral science diplomacy between Chile and the United States, among the earliest contact between the two nations in a scientific capacity came during the visit of American natural scientists and surveyors during stops in Chile by the United States Exploring Expedition, which, led by U.S. Naval Commander James Wilkes, succeeded at circumnavigating the globe between 1838 and 1842, advancing the state-of-the-art in instrumentation for cartographic and astronomical measurements, while simultaneously amassing a collection of specimen that would become the basis for the initial collection of the American Smithsonian Institution (Philbrick 2004).

Following this early mission, in 1849 U.S. Navy Lieutenant James Gilliss was dispatched as the leader of a follow-on expedition sponsored by the fledgling United States Naval Observatory, an institution that itself was developed as a result of contributions made by Wilkes to its predecessor, the U.S. Navy Department of Charts and Instruments. Central to the Gilliss expedition was the objective of determining a suitable location in the Southern Hemisphere for observations of Mars and Venus, a campaign which was to take place concurrent to a coordinated set of observations of these inner planets that would be performed in the Northern Hemisphere, at the Naval Observatory in Washington. Ultimately, Gilliss and his crew would erect two refracting telescopes, the larger of which had a diametrical aperture of 6.5 inches, near the peak of the Santa Lucia hill in central Santiago, Chile’s capitol city. Figure 2.1 includes an illustration sketched by Gilliss himself of the observatory constructed by his crew on Santa Lucia hill.

Upon return to the United States in 1852, after a three year expedition, Gilliss and his crew would finally be able to transport their data back to the Naval Observatory for comparison, integration, and analysis with the observing campaign results simultaneously obtained by their counterparts in the Northern Hemisphere. It should be noted here, that until the final connection of the ACT site into a modern fiber optical internet network currently
**Figure 2.1:** Illustration of observing infrastructure constructed on Santa Lucia hill in Santiago, Chile by U.S. Navy Lieutenant James Gilliss and his crew during the U.S. Naval expedition to the Southern Hemisphere during the years 1849-1852 (Gilliss 1856; Keenan 1991)
undergoing final installation for connection of the ALMA Operations Support Facility to
the worldwide broadband network, bandwidth limitations have required the hand-carrying
of ACT+MBAC and ACT+ACTPol data for processing and analysis in North America
and abroad by ACT site operations team members (albeit now via rapid intercontinent-
ral flights), even nearly two-hundred years following the hand-transported data strategy
of the Gilliss expedition! In addition to yielding a remarkably accurate measurement of
the distance from the Earth to the Sun (referred to an Astronomical Unit, or AU), Gilliss
also was able to diplomatically engage his host nation, securing the transfer of ownership
of the instrumentation and infrastructure that his team had imported and developed on
Santa Lucia hill to the Chilean government, ultimately becoming the base infrastructure
leading to the founding of the Observatorio Astronómico de Chile (OAN) - the National
Astronomical Observatory of Chile. The gesture of scientific solidarity would pay rapid
dividends, as continued collaboration between Chilean OAN scientists and the U.S. Naval
Observatory team would result in further coordinated measurements of solar parallax by
Chilean astronomers on one side, and American on the other, and moreover, seed a culture
of bilateral scientific collaboration and engagement between the United States and Chile,
that remains a robust relationship and a paramount driver in U.S.-Chilean relations to the
present day. (Gilliss 1856; Hammer 2015; Keenan 1991)

In spite of long periods of optimal weather for the optical measurements performed by
Gilliss in pre-industrial Santiago, the expedition leader would also lament that “...late in
the season a sort of dry fog, resembling thin smoke, deprives the atmosphere by day of
something of its transparency, though the nights are all that the astronomical observer can
desire...” and that there were periods during the expedition in which months of cloudy
conditions impeded measurements. (Gilliss 1856) The Chilean astronomers that would
inherit the Gilliss site also noted these conditions (along with the unstable geography of
Santa Lucia hill), leading to the move of OAN to several sites in the Santiago region over
the next century, ultimately resulting in the creation of a new observatory facility based on
Cerro Calán in 1956 (completed in 1962), administered by the Santiago-based Universidad de Chile. (Rutllant 1960)

It was in this era that international consortia from the United States, Europe, and Asia pushed forward to establish partnerships with the Chilean government, OAN, and other Chilean institutions to lead the development of a new generation of astronomical observatories (mostly operating at optical and infrared wavelengths) in the southern Atacama Desert, situated in the region near La Serena and Coquimbo. The marginal distance traveled north to resettle these sites yielded a substantial improvement in seeing, number of clear nights (in the Coquimbo area, there are on average 345 clear nights per year), minimal light pollution, and overall atmospheric stability in an ultra-low humidity environment over previous Santiago-based astronomical platforms. (Embassy 2015) In the decades since the early 1960s, facilities such as the Cerro Tololo Inter-American Observatory (administered by the U.S. National Optical Astronomy Observatory), the Las Campanas Observatory (administered by the Carnegie Institution for Science), the ESO La Silla Observatory (administered by the European Southern Observatory), and more recently, the Gemini South Observatory (administered by a multinational consortium including partners in the United States, Chile, Australia, Brazil, Argentina, and Canada), and as well as the forthcoming U.S.- and Chilean-led Large Synoptic Survey Telescope (LSST), have been successfully operated, with a high-scientific impact in the astronomical and astrophysical sciences, as well as fostering international scientific collaboration and multilateral discourse, through some of the most turbulent decades of Chilean political history. (Carnegie 2015; ESO 2015; Gemini 2015; LSST 2015; NOAO 2015) In spite of the success of the myriad of optical- and infrared-wavelength astrophysical observatory platforms operating in this southern corner of the Atacama, for the ultimate success of millimeter- and submillimeter-wavelength observatories focused on probing larger-scale cosmology and mapping of the Cosmic Microwave Background (CMB), the search for a suitable observing site would lead researchers to higher altitudes in the far north of the Chilean Atacama Desert - a region more rugged and re-
more than had yet been proposed for a permanent research presence worldwide, save for the growth of Antarctic-based cosmological platforms in the past few decades.

2.1.2 The Rise of Atacama-based Experimental Cosmology

Although a myriad of fully-developed experimental cosmology facilities now reside firmly in the Northern Atacama, and have been under development since the emergence of modern Chilean democracy in the early 1990s, the growth of these contemporary platforms owes a degree of credit to astronomical research expeditions to the region a century earlier. Following earlier centuries of astronomical observations by the Atacameño culture, the earliest international expedition for the deployment of telescopic instrumentation in the Northern Atacama was led by Americans from the Harvard College Observatory, founding in 1889 an observing station on a peak in the Bolivian Atacama, following the conclusion of the War of the Pacific just six years earlier. Highlighting the geostrategic importance of a seemingly barren region, this conflict was fought in the Northern Atacama between the nations of Chile, Bolivia, and Peru over motivations including sea access, border disputes, and key economic gains from raw materials present across the region, including mineral and salpeter deposits, the latter of which was used as a military asset in the production of explosives. (Arana 1881) Although the conclusion of the War of the Pacific resulted in the Chilean acquisition of the northern Atacama region, geopolitical gulfs between Chile and Bolivia over the conflict continue to the present day. Most notably, in 2014 Bolivian officials issued legal petitions with the International Court of Justice in The Hague, The Netherlands, arguing that in treaties concluding the conflict over a century-ago, Chile would be obliged to negotiate for Bolivian sovereign access to sections of the ceded Atacama Pacific coastline at a later date. While arbitration in the case is not expected to reach a final conclusion before 2020, and limits the ability of the International Court of Justice to mandate any outcome in the trans-border conflict aside from Chile’s negotiations with Bolivia be conducted “in good faith,” the case underscores further the extent by which the territory of the northern
Atacama remains both an astronomical and geostrategic asset in contemporary discourse. (Blair January 2016)

Ultimately, the astronomical site founded at this location, referred to as “Mt. Harvard”, housed early visual meridian photometric equipment deployed to measure the brightness of stars to sixth magnitude, only observable from the Southern Hemisphere. These measurements were the long-sought-after additions to the compiled catalog of Northern Hemisphere stellar brightness observations that had until 1889 formed the Harvard Photometry, and the impetus to extend this catalog to an early all-sky survey through the foundation of a Southern Station at “Mt. Harvard,” funded with a grant of $238,000. In spite of early contributions made to the brightness catalog from the Bolivian site, the research station at “Mt. Harvard” was abandoned in 1890 after just a year of operation owing to poor observing conditions, and the equipment was relocated further north, where it was re-erected near the Peruvian city of Arequipa. (Duerbeck 2003)

The early days of the Harvard College Observatory Southern Station at Arequipa were turbulent. Although work rapidly continued to yield precise additions to the photometric catalog, within a year of completing the construction of the facility at Arequipa, station director (and brother of the director of the Harvard Observatory) William H. Pickering was relieved of his duties after commissioning a large fraction of remaining grant funds to construct an opulent villa for his personal use, and the use of his team. While operational and funding stability returned in the decades that followed, allowing for operation of a Southern Station situated at Arequipa until 1927, it should be noted that this was not the first site considered to follow the climatic disappointment of “Mt. Harvard.” A notable discovery for the future of Atacama-based cosmology was the favorable observing climate experienced by a detachment of Harvard researchers in 1890 at Pampa Central. Pampa Central is located between the modern Chilean cities of Antofagasta and Calama, and was selected as researchers could leverage existing railroad and salpeter mining infrastructure to set up operations in what would otherwise have been an wholly inaccessible outpost. A six-
week photometric observing campaign was completed on the Pampa Central site providing some of the most precise additions to the photometric catalog due to the low humidity and excellent atmospheric stability conditions of the site - a harbinger of the climate assessment that led to the construction of modern cosmology research facilities in the vicinity a century later. In spite of the superior conditions at Pampa Central, long term settlement of the site was foregone in lieu of the Arequipa station given purely logistical considerations at the time, including the relative inaccessibility of the desert site and the overall lack of safe drinking water. The Southern Station at Arequipa was relocated to Bloemfontein, South Africa in 1927, where it continued to operate until the 1950s, at a site that was originally the intended location of the observational platforms that would be founded as a part of the European Southern Observatory in the southern Atacama Desert of Chile. In spite of this move from South America, taken together, the photometric observations at “Mt. Harvard,” Arequipa, and Pampa Central formed the foundation of Harvard Revised Photometry and the Bright Star Catalog, which are still key reference catalogs for modern astronomical researchers. (Duerbeck 2003)

Other short-term observing operations took place during the early years of the twentieth century in the Northern Atacama, including a three-month campaign for the observation of Mars during its 1907 opposition. In this case, an 18-inch refracting telescope was deployed through a collaboration between American astronomers David P. Todd of Amherst College and Earl C. Slipher of the Lowell Observatory, again leveraging existing mining infrastructure, this time at a mining site just 70km inland from the Chilean coastal city of Iquique, a key Chilean port city to this day, and principal port of entrance for much of the critical infrastructure and materials comprising the large-scale experimental cosmology platforms of the contemporary Northern Atacama. It was at this site that 13,000 images of Mars were recorded - for many years one of the most comprehensive compendia of images of the planet worldwide. (Duerbeck 2003)

Outside of the Harvard College Observatory Southern Station at Arequipa, another
Figure 2.2: Photograph of the Smithsonian Astrophysical Observatory solar observatory station at Cerro Moctezuma, 12 km south of Calama, Chile in the 1920s. The solar observatory station was comprised of a wide array of instrumentation for measurements of solar radiation (using sets of pyrheliometers and pyranometers), solar altitude (using a theodolite), and also included a heliostat coupled to a spectrobolometer (Duerbeck 2003)
long-term astronomical research presence was established in the Northern Atacama at the close of World War I, with the construction of a solar observatory in the copper mining outpost of Calama, Chile in 1918. Developed by the Smithsonian Astrophysical Observatory, the early Calama station was relocated 12 km south to the summit of nearby Cerro Moctezuma, near the present-day El Loa airport and visible from Chilean Route 23, the main highway connecting Calama with the community of San Pedro de Atacama, 100 km southeast. There, observations leading to a characterization of the physical properties of the Sun, including an accurate measurement of the solar constant, were completed by a director and assistant who remained on-site for three year intervals before replacement by a new pair of observers. Like the Pampa Central site to the east, the Smithsonian solar observatory at Cerro Moctezuma benefited from atmospheric observing conditions of extremely stable character. Figure 2.2 includes an early photograph of the Smithsonian Astrophysical Observatory solar observatory station at Cerro Moctezuma in the 1920s, which was comprised of a wide array of instrumentation for measurements of solar radiation (using sets of pyrheliometers and pyranometers), solar altitude (using a theodolite), and also included a heliostat coupled to a spectrobolometer. Solar observing operations continued at Cerro Moctezuma until 1955, at which point the site was decommissioned since mining activities at the nearby Chuquicamata mining facility, a key supplier to the global copper market (one of Chile’s most strategic material exports), had expanded to such a scale that air pollution precipitated the suspension of observing. As we have discussed, in the decades that followed, optical and infrared observing platforms built and operated by multinational consortia were centered principally in the Southern Atacama region, while the Northern Atacama, with the rise of the Chilean military dictatorship, was home to less aspirational institutions than outward looking telescopes, including camps for political prisoners and political executions, some located nearly adjacent to previous astronomical research sites, including at Pampa Central. The plebiscite of October 1988 and the following stable transition to modern Chilean democracy in March 1990 again transformed the Northern Atacama, and just as
was observed following the conclusion of the War of the Pacific, the region was again made accessible to international research partnerships with motives to exploit not the physical or political resources of the region, but the stable skies of the Northern Atacama, which were coupled with timely advances in sensitive detector technologies to open a new era of precision cosmology, with the Northern Atacama as the global center-of-mass for the field. (Duerbeck 2003)

2.2 Development of the ACT Site

2.2.1 The Atacama Desert Region

During the early-and-mid-1980s, Chilean President Augusto Pinochet, who had ruled since 1974 as the leader of an oppressive dictatorial regime responsible for widespread violations of human rights, began to face increasing domestic and international pressure to step down as leader of the country. In response to mounting domestic discourse, the loosening of the Soviet grip over political systems in eastern Europe through movements such as glasnost and perestroika under Mikhail Gorbachev, and a state visit by Pope John Paul II in 1987 calling for free and open elections, a national plebiscite was held on 5 October 1988 resulting in the rejection of the continued unquestioned rule of Pinochet by the Chilean people - a historic ‘No’ vote that resulted in national presidential and parliamentary elections the following year. Thus, in December 1989, just a month after champagne-cork-popping revelers celebrated the opening of the Berlin Wall and a return of democracy in eastern Europe, Chileans went to the polls to elect Patricio Aylwin from the Coalition of Parties for Democracy, as the first democratically elected president of Chile in nearly two decades. Finally, on 11 March 1990, Pinochet, and the repressive military regime he led, officially relinquished power, ushering in a new framework supporting sustained liberal democracy in Chile. Moreover, like similar political transitions happening concurrently a hemisphere away across Europe, this moment marked a reentry of Chile into the open international
community. A new era of political, economic, and, as we will consider here, scientific and technological engagement rapidly followed. (Chile 2015; Weigel 2003)

The political opening of Chile in 1990 might have reinvigorated interest in Atacama-based astronomy in its own right. Programs, including the aforementioned efforts of teams from the Harvard College Observatory, that had been implicitly displaced in the region by political internment camps and human rights abuses across the northern Atacama under Pinochet, might have been slowly re-established after decades of abandonment in the region, however events occurring hundreds of miles above the Earth’s surface would begin a race in the two decades that would follow, establishing at a remarkable pace the northern Atacama Desert as the preeminent global platform for experimental cosmology studies.

Just weeks before the historic December 1989 Chilean elections, on 18 November 1989 the Cosmic Background Explorer, or COBE, was launched from Vandenberg Air Force Base in southern California on top of a Delta 5000 series rocket, after a decade of development at NASA’s Goddard Space Flight Center in Greenbelt, Maryland. Operated from launch until it was decommissioned in December 1993, COBE made direct all-sky observations of the CMB using three onboard instrument packages: the Differential Microwave Radiometer (DMR) aimed at making measurements of any potential temperature anisotropies across the extent of the CMB; the Far-InfraRed Absolute Spectrophotometer (FIRAS) aimed at measuring the power spectrum of the CMB and observe the galactic dust and line emission; and the Diffuse Infrared Background Experiment (DIRBE) aimed at directly characterizing the Cosmic Infrared Background (CIB). The results generated by this suite of instruments comprising COBE and their fundamental impact on the field of cosmology, detailed in the previous Chapter, were revolutionary. Most notably, COBE’s suite of measurements both confirmed the presence of temperature anisotropy across it’s all-sky survey of the CMB, which supported models in which large-scale structures of the contemporary universe were formed in a universe requiring a hot Big Bang modeled origin with gravitational instability, and also showing that the CMB power spectrum very closely follows that of a perfect
blackbody, also providing evidence of the hot Big Bang model. Figure 2.3 illustrates COBE all-sky mapping of the CMB temperature anisotropy including dipole subtraction for the three operational frequencies of the DMR instrument (31.5, 53, and 90 GHz) including all four-years of COBE mission data, while Figure 2.4 illustrates the CMB spectrum measured by COBE, and the manner by which it precisely matched the spectrum of an ideal blackbody showing that 99.7% of the radiant energy present in the universe would need to have been emitted within a year of a hot Big Bang. (GSFC 2008) Indeed, these results from COBE, which resulted in a Nobel Prize for principal investigators George Smoot and John Mather in 2006, transformed a century of work in cosmological theory and early measurement campaigns that began with the aforementioned serendipitous discovery of the CMB by Penzias and Wilson (discussed in the previous Chapter), into a fully-mature experimental science. This rapid scientific revolution, which mirrored the concurrent political revolutions toward modern democracy in Chile and around the world, precipitated a rush to develop instrumentation with ever higher sensitivities on new ground-, balloon-, and satellite-based platforms to better constrain the temperature, and later polarization, anisotropies of the CMB, of which the Northern Atacama would play the leading role for ground-based experimental cosmology research. (GSFC 2008; Smoot 2015)

Of course, as undoubted the transformational scientific impact of a space-borne observational platform like COBE may have been to the worldwide cosmology community, the cost and development time for such seminal projects are prohibitive for rapid deployment and on-sky testing of revolutionary detector technologies and integrated systems on sub-decade timescales. If once-in-a-generation satellite-based platforms see launch and operation roughly once per decade as has been observed in the cosmology community with COBE in the 1990s, the Wilkinson Microwave Anisotropy Probe (WMAP) in the 2000s, and the Planck satellite in the 2010s, then ground and balloon based CMB probes would lead the field in interceding years, themselves serving as fully-integrated, scientifically-impactful observatory pathfinders for future satellite technology deployments. Of course, the absence
Figure 2.3: COBE all-sky mapping of the CMB temperature anisotropy including dipole subtraction for the three operational frequencies of the DMR instrument (31.5, 53, and 90 GHz) including all four-years of COBE mission data (GSFC 2008)
Figure 2.4: CMB spectrum measured by COBE, and the manner by which it precisely matches the spectrum of an ideal blackbody showing that 99.7% of the radiant energy present in the universe would need to have been emitted within a year of a hot Big Bang (GSFC 2008)
of launch-grade technology standards and relatively easier logistical impediments compared to satellite project development, should not imply a far easier road to success. With respect to ground-based observations, throughout the mid-Twentieth century, attempts to design millimeter and submillimeter wavelength observatory technologies of sufficient sensitivity to probe the weak signal associated with CMB temperature anisotropies were often impeded by ionospheric absorption and distortion of this cosmologically-sourced millimeter and submillimeter wavelength radiation. In fact, not only does water vapor in the Earth’s atmosphere offer such distortion of CMB signal, but it radiates within the same millimeter and submillimeter wavelength windows of CMB observation, adding atmospheric noise signal that can dominate and potentially confuse CMB science results. Thus, as the groundbreaking results from COBE excited a worldwide astronomical community intent on expanding these on these measurements to ensure further progress on the field of cosmology from one once dominated by theoretical predictions to a robust experimental discipline, it became increasingly evident that to make any progress to this end from a ground-based site, a location that fit criterion for avoiding atmospheric distortion of millimeter and submillimeter wavelength CMB radiation must be found. In other words, a location at high-altitude with a dry, stable atmospheric climate, which would avoid as much of the distortion associated with atmospheric water vapor at wavelengths relevant to CMB observation, while also remaining relatively accessible for considerations of site logistical development. Hence, in 1994, this quest would lead international researchers to “rediscover” the Northern Atacama just 100 km southwest of the solar observatory abandoned on Cerro Moctezuma several decades earlier, beginning an era of experimental cosmology site development on and around the Chajnantor Plateau, using the then sleepy village of San Pedro de Atacama as a base of operations. (Bhattacharjee 2014; Planck 2015; WMAP 2015)
2.2.1.1 The Chajnantor Plateau and San Pedro de Atacama

The spring of 1994 marked a breakthrough in an ongoing ambitious search to find a location suitable to host what would in the following decades become the largest, and most expensive ground-based submillimeter wavelength interferometer on Earth - the Atacama Large Millimeter Array, or ALMA. (ALMA 2015) The fully-realized ALMA facility was dedicated in 2013, and would eventually lead to groundbreaking scientific operations from 66 antennas of 12-meter primary diameter led by a multinational consortia of already large-scale research consortia, including the U.S. National Radio Astronomy Observatory (NRAO), the European Southern Observatory (ESO), the National Astronomical Observatory of Japan (NAOJ), along with Chilean, Canadian, and Taiwanese minority partners, costing over $1.4 billion in U.S. dollars to complete and operate. But in the early 1990s, with the project requiring a high-altitude, flat, and stable atmospheric site on which to be based, its humble beginnings were led by Chilean astronomer Hernán Quintana, American-based astronomers Paul Vanden Bout, Robert Brown, and Ricardo Giovanelli (of NRAO and Cornell University, respectively), and Angel Otárola of ESO, who utilized maps originally developed by the Chilean military for the deployment of land mines and camps for political prisoners in the Northern Atacama, that led them to the tiny village of San Pedro de Atacama, from where they would lead expeditions to reach the region of the high Chilean Andes just 45 kilometers west in search of a suitable location for a proposed observatory that would become ALMA. (ALMA 2015; Bhattacharjee 2014)

Figure A.2 provides geographic context of the location of the Llano de Chajnantor, or Chajnantor plateau region of the Northern Atacama, which resides at the confluence of the Chilean, Bolivian, and Argentinian borders on the West coast of the South American continent, while Figure A.3 provides topographic detail of the Chajnantor region and surrounding vicinity, including the Chilean village of San Pedro de Atacama. The use of San Pedro de Atacama as a logistical base of operations for Quintana and his team was notable in that this precedent to utilize San Pedro in such a capacity has been followed by all other
Figure 2.5: Geographic context of the location of the Llano de Chajnantor, or Chajnantor Plateau region (including Cerro Toco) of the Northern Atacama Desert region, which resides at the confluence of the Chilean, Bolivian, and Argentinian borders on the West Coast of the South American continent. (Cartographic imagery courtesy Google Maps)
Figure 2.6: Topographic detail of the Chajnantor region and surrounding vicinity, including the Chilean village of San Pedro de Atacama. (Cartographic imagery courtesy Google Maps)
experimental cosmology facilities in the region to the present day, including by the Atacama Cosmology Telescope collaboration. Originally an oasis community of pre-Columbian Atacameño artisans, over the centuries San Pedro de Atacama grew into a strategic outpost and was eventually ceded to Chile by Bolivia following the War of the Pacific. The strategic character of the area continued throughout the Pinochet regime, with military outposts established and mine fields dug between San Pedro and Chile’s national borders with Bolivia and Argentina, some 45 km and 125 km removed to the west, respectively. The San Pedro of the early 1990s was much smaller and less developed than the community one finds today, and driven by the rise of contemporary astronomical facilities and increased tourism (drawing both backpacking and luxury ecotourists alike), the population of the village rose by around 75% from a population of a few thousand in the decade starting in 1992. The village itself is located at an elevation of 2435 meters (7988 feet) above sea level and shares the extremely dry climate that is typical of the region, with just 42 mm of annual precipitation, and very little (if any) precipitation experienced between the Winter months of June and August. Mean temperature and precipitation data for San Pedro de Atacama measured between 1982 and 2012 can be found in Figure 2.7, while Figure 2.8 gives a view of central San Pedro de Atacama from during the first deployment of the ACTPol receiver to the Atacama Cosmology Telescope in 2013. (ALMA 2015; Bhattacharjee 2014; Climate-Data.org 2015; Institute 2015a)

Connecting San Pedro de Atacama with Bolivia and Argentina is the Paso de Jama highway, which was used by Quintana and his team to reach the mining access roads and off road paths that would allow his team to reach the Chajnantor Plateau, which is located at an elevation of roughly 5035 meters (16,519 feet), 45 kilometers to the southeast of San Pedro de Atacama, and 20 kilometers south of the Licancabur volcano. Figure 2.9 gives mean temperature and precipitation data for the Chajnantor plateau between 1982 and 2012, also experiencing near trivial precipitation between June and August of each year. Contributing to the ideal dry and stable environment of the Chajnantor region are unique
Figure 2.7: Mean temperature and precipitation data for San Pedro de Atacama measured between 1982 and 2012. (Climate-Data.org 2015)
Figure 2.8: A view of central San Pedro de Atacama from during the first deployment of the ACTPol receiver to the Atacama Cosmology Telescope in 2013.
Mean temperature and precipitation data the Llano de Chajnantor (Chajnantor Plateau) measured between 1982 and 2012. (Climate-Data.org 2015)

geological and weather conditions intrinsic to the entire Atacama Desert region, protected by the Andes Mountain range from encroachment of the humid airmasses from the Eastern section of the South American continent, a rainshadow desert effect from air transiting the Chilean Coastal Range, and air currents from the Pacific that absorb little humidity from the cold Humboldt ocean current. (ALMA 2015; Bhattacharjee 2014; Climate-Data.org 2015; Garreaud 2010)

These climatic characteristics, coupled with favorable radiometric measurements of the precipitable water vapor, or PWV, of the airmass above the Chajnantor plateau (which will
be discussed further in following sections) led Quintana and his colleagues to recommend the site as best suited to host what would become the ALMA project. Following these initial recommendations, joint site testing was completed by personnel from NRAO, ESO, NAOJ, and Chilean institutions in 1995 and the the signing of an initial memorandum of understanding (MOU) between U.S. and European stakeholders in 1999. These early agreements were quickly followed by a resolution in favor of creation of the ALMA project between U.S., European, and Japanese partners in 2001, the signing of the North American - European ALMA bilateral agreement and subsequent groundbreaking on the Chajnantor plateau in 2003. In addition to the clear logistical challenges with developing a fully-integrated experimental cosmology site at a remote high-altitude location as the Chajnantor Plateau represents, the ALMA consortium needed to further contend with removal of Pinochet-era land mines and unexploded military ordinance and debris, as well as negotiate a rerouting of a proposed oil pipeline interconnector that would have run through the region, placing experimental cosmology in direct dialogue with overarching geostrategic and geopolitical energy resource considerations. With the successful negotiation of these logistical hurdles, a decade of site and instrumentation development led to the official dedication of the ALMA project in March 2013, just days after the ACTPol receiver at its first level of deployment arrived on the nearby Atacama Cosmology Telescope site. Figure 2.10 provides a view of the Chajnantor plateau from during the first deployment of the ACTPol receiver to the Atacama Cosmology Telescope in 2013. While not the scientific or technology development focus of this dissertation, the integral logistical role that the newly-dedicated ALMA facilities would hold for Atacama Cosmology Telescope operations through a critical partnership developed during the initial and subsequent deployments of the ACTPol receiver between 2013 and 2015 will be briefly discussed later in this Chapter, and its obvious pathfinding work in the region is notable for the development of the myriad of experimental cosmology facilities in the Chajnantor region, including those leading to the development of the Atacama Cosmology Telescope on nearby Cerro Toco. (ALMA 2015; Bhattacharjee 2014)
Figure 2.10: A view of the Chajnantor plateau from during the first deployment of the ACTPol receiver to the Atacama Cosmology Telescope in 2013.
2.2.1.2 Cerro Toco

Located at the northeastern extent of the Chajnantor plateau is Cerro Toco, an extinct stratovolcano which, at its summit, reaches an elevation of 5604 meters, or 18,386 feet. In terms of context, this elevation places the summit of Cerro Toco well above both of the principal base camps of Mount Everest of the Himalayan range of Central Asia (the Northern Everest base camp resides at an elevation of 5364 meters in Tibet, while the Southern Everest base camp is at an elevation of 5150 meters in Nepal). Cerro Toco is one of over 400 volcanic structures formed by geophysical processes of continental tectonic activity around the Pacific Ocean, from the Andes Mountain range of South America, to the fault lines of the North American Pacific coast, and on to a myriad of plate tectonic and volcanic mechanisms in East Asia and Indonesia, forming what is colloquially referred to as the “Ring of Fire.” Figure 2.11 illustrates the view of Cerro Toco as seen from one of several mining access roads near Paso Jama, which have been developed for access to experimental cosmology facilities in the area, while Figure 2.12 provides a view from the summit of Cerro Toco with the Licancabur Volcano in backdrop to the north of Cerro Toco, taken during a climbing expedition undertaken by the Atacama Cosmology Telescope team during PA2 deployment during Austral autumn 2014. (Reynolds 2006; Smithsonian 2015)

Located at latitude 22° 57′ 0″ South and longitude 67° 47′ 0″ West, Cerro Toco was formed as a constituent of the expansive Purico Complex, a pyroclastic shield comprised of dual ignimbrite sheets and a collection of related stratovolcanos, and lava domes during eruptions around 1.3 million years ago. While not immediately apparent from assessment at ground level, satellite imagery reveals the larger-scale geophysical properties of this Andean region, and illustrate an expansive ring fracture of a 10 kilometer by 20 kilometer extent, for which Cerro Toco provides definition. Figure 2.13 provides a view of Cerro Toco within the greater Purico Complex region, with Cerro Toco found in the upper left of the image field, and the Chajnantor Plateau to the lower center of the image field. (Reynolds 2006; Smithsonian 2015)
Figure 2.11: The view of Cerro Toco as seen from one of several mining access roads near Paso Jama, which have been developed for access to experimental cosmology facilities in the area.
Figure 2.12: A view from the summit of Cerro Toco with the Licancabur Volcano in backdrop to the north of Cerro Toco, taken during a climbing expedition undertaken by the Atacama Cosmology Telescope team during PA2 deployment during Austral Autumn 2014.
Figure 2.13: A view of Cerro Toco within the greater Purico Complex region, with Cerro Toco found in the upper left of the image field, and the Chajnantor Plateau to the lower center of the image field. Image courtesy Global Volcanism Program, Smithsonian Institution. (Smithsonian 2015)
Studies from the Smithsonian Institution’s Global Volcanism Program indicate that Cerro Toco is situated directly above a principal vent area the Cajón Ignimbrite, formed from the deposit of earlier pyroclastic flows in the immediate vicinity of the stratovolcano. The geologic composition and morphology of Cerro Toco is significant: large deposits of sulfur found on and around the summit of Cerro Toco led to the development of decades of infrastructure development on Cerro Toco by Chilean sulfur mining operations during the twentieth century. The abandonment of both unpaved access roads, and rudimentary mining structures by the early 1990s allowed experimental cosmologists of the era (including the aforementioned teams from ALMA) to access and survey the terrain of Cerro Toco as a potential site for cosmological telescope development. Ultimately, the partially cleared mining areas proved insufficient to meet the areal requirements of an expansive interferometer project, as ALMA would become, though other teams with plans for single-dish experimental cosmology platforms that would arrive on Cerro Toco in the mid 1990s would ultimately exploit and expand the logistics left behind by the Chilean mining industry, and develop a series of telescopes on a small-plateau located on the eastern face of Cerro Toco, with equally stable and dry atmospheric conditions as the Chajnantor Plateau, though located over 100 meters higher in elevation. Figure 2.14 displays an example of an abandoned mining structure near the summit of Cerro Toco, with exposed sulfur deposits visible, as well as a view of the approach to Cerro Toco on a former mining access road, improved for support and access of experimental cosmology operations on Cerro Toco. (Reynolds 2006; Smithsonian 2015)

2.3 ACT Predecessor Experiments and Site Testing

As early infrastructure, design, and site testing activities began to increase in the mid- and late- years of the 1990s for ALMA, and other Chajnantor-based experiments (including the Cosmic Background Imager, or CBI, which operated between 1999 and 2008), so too did interest and activities to establish small-scale experimental cosmology platforms on nearby
Figure 2.14: An example of an abandoned mining structure near the summit of Cerro Toco, with exposed sulfur deposits visible, as well as a view of the approach to Cerro Toco on a former mining access road, improved for support and access of experimental cosmology operations on Cerro Toco.
These experiments would serve as direct predecessor instruments to the development of permanent site infrastructure on Cerro Toco to follow in the succeeding decade, including the Atacama Cosmology Telescope, POLARBEAR, and the Cosmology Large Angular Scale Surveyor (CLASS) experiments. One such experiment that leveraged earlier mining access infrastructure present on the southwestern approach toward the summit of Cerro Toco, paving the way for ACT and others, was the Mobile Anisotropy Telescope on Cerro Toco (MAT/TOCO), often referred to simply as TOCO. The deployment of TOCO to an area a few hundred meters from the present day ACT site was actually the second iteration of the experiment: the receiver instrumentation and operational platform were originally developed in the mid-1990s as a balloon-borne gondola payload experiment known as QMAP. Developed, fabricated, fully-integrated, and operated within two years, the QMAP experiment completed two flights with the objective of mapping the anisotropies of the angular power spectrum of the CMB at arcminute angular scales, first in June 1996 from Palestine, Texas, and again in November 1996 from Fort Sumner, New Mexico, both at an altitude of 30 kilometers. Ultimately, QMAP was able to complete measurements of the temperature anisotropy of the CMB angular power spectrum, in particular in multipole bands between ℓ of 40 and ℓ of 140. Selected QMAP results are represented in Figure 2.15, which illustrates the resultant CMB angular power spectrum as measured by the QMAP experiment during the first flight of the instrument from Palestine, Texas in June 1996 (Devlin et al. 1998; Miller et al. 2002).

In the months that followed the second flight of the QMAP instrument in December 1996, the experiment was recovered, reconfigured, and shipped to Northern Chile for deployment to Cero Toco, where it would operate as the TOCO experiment for two complete seasons, concluding in December 1997 and December 1998, respectively. Building on science operations completed during the QMAP flights, the TOCO experiment operated directly adjacent to the aforementioned abandoned sulphur mining facility on the southwestern face of Cerro Toco, just a few tens of meters from the site, which would ultimately host the
Figure 2.15: CMB angular power spectrum as measured by the balloon-borne QMAP experiment during the first flight of the instrument from Palestine, Texas in June 1996, with analogous results from COBE satellite shown. (Devlin et al. 1998; Miller et al. 2002)
Atacama Cosmology Telescope. Ultimately, TOCO operations were able to extend CMB angular power spectrum measurements at arcminute angular scales using an optical beam fixed in altitude and azimuth, with beam coverage centered on the South Celestial Pole. Figure 2.16 illustrates the resultant angular power spectrum results from TOCO operations in Chile, with comparable results to contemporary experiments and ΛCDM predictions, with first peak measured at $\ell$ of $216 \pm 14$. Following TOCO operations, another temporary experimental cosmology platform also leveraged existing logistical and observational conditions of the Cerro Toco location, the Millimeter INTerferometer, or MINT. MINT, which was fielded for first season operations in 2001, operated a compact prototype interferometer platform dedicated to observations of the CMB with 145 GHz sensitivity. In doing so, MINT leveraging the 9 K median nighttime atmospheric temperature of the site and verified further the positive quality of 145 GHz operations from Cerro Toco. Taken together, both the TOCO and MINT experiments were clearly not only instrumental at pushing forward the state of the art in CMB observational science in the early 2000s, but perhaps most important, provided a baseline logistical basis of protocol for operating from Cerro Toco, while demonstrating that the site was indeed feasible for more ambitious, future-generation experimental cosmology platforms for direct observation of the CMB (Fowler et al. 2005; Miller et al. 2002).

2.3.1 Site Selection Criteria

As illustrated in the previous sections, early-generation, northern-Atacama based experimental cosmology platforms were able to effectively characterize the Cosmic Microwave Background from both Chajnantor altiplanic and adjacent sites, including from the southwestern face of the stratovolcano, Cerro Toco. In particular, selection this region of the Atacama desert to probe the CMB is driven by a number of factors, both with respect to operational logistics and scientific feasibility of observations from these sites themselves. As we will see later in this Chapter, logistically, the Chajnantor plateau offers benefits
Figure 2.16: CMB angular power spectrum results measured by the Mobile Anisotropy Telescope on Cerro Toco (MAT/TOCO), comparable to contemporary experimental results and ΛCDM predictions (Miller et al. 2002).
not found in other sites worldwide. In spite of its rugged terrain, and occasional precipitation events impeding access to the site, unlike, e.g. experimental cosmology platforms constructed and operated at the South Pole Station, sites in this region of the Atacama are accessible in a reasonably straightforward manner. Commercial flights can be taken from major international hubs to the Chilean capitol of Santiago, with domestic airlines offering intra-Chilean flights to the city of Calama - capitol of the El Loa province, located in the Chilean Antofagasta Region. San Pedro de Atacama, home to most of the operational base camps for experimental cosmology facilities in the region is a roughly two-hour drive from Calama, and driving from San Pedro de Atacama to the Chajnantor Plateau and nearby sites in and around Cerro Toco and Cerro Chajnantor can range from 45-90 minutes. While small-scale all-terrain trucks are principally used for personnel transport to the sites, with only marginally greater logistical difficulty (depending on weather and resultant surface conditions) larger-scale commercial shipment vehicles also are able to utilize various highway and offroad routes to reach these sites, both for fuel, equipment, and supply deliveries. Thus, compared to the South Pole Station and other more remote experimental cosmology and astronomy facilities worldwide, many of which rely on military-grade aircraft for personnel and equipment deliveries and access, experimental cosmology in and around the Chajnantor Plateau is advantaged in that the field can effectively interface with and leverage commercial and civic resources to ensure much of the supply chain and personnel movement to sites in the region.

Additionally, compared with satellite based platforms, ground-based experimental cosmology platforms in the Atacama Desert region have the distinct advantage of enabling a longer-term operational paradigm of incremental technology development and experimental platform upgrades, on sub-decade timescales, compared to the multi-decade technology development paths associated with seminal satellite platform experiments. Moreover, routine accessibility of ground-based experimental cosmology platforms is also advantageous given that technical issues can be readily accessed, diagnosed, and resolved, whereas satellite plat-
forms operate on an inaccessible and more static operational nature - if a satellite-based platform experiences technical issues, these challenges are often difficult or impossible to remedy remotely, and can lead to operational degradation and system failure over time.

2.3.1.1 Optimal CMB Observing Frequency Windows from Cerro Toco

Of course, for astrophysical and cosmological observation, satellite platforms have a central distinct advantage in comparison to ground based experiments - their space-bourne observational perch need not consider significant challenges that ground-based astronomy and cosmology platforms have making observations through Earth’s atmosphere. Fortunately, CMB observational requirements do not fully preclude ground-based observation, provided that optimal geographic and atmospheric conditions, such as those characteristic in and around the Chajnantor Plateau and Cerro Toco, are met. Colloquially, the optimal conditions for probing the CMB from ground-based platforms are generally described simply as sites that are “high and dry.” In principal, a site need only be “dry” for successful CMB observations, but as levels of water vapor in the atmospheric column through which the CMB is observed decrease at higher altitudes, placement of observational platforms at higher altitudes is correspondingly advantageous.

As we discussed in the previous Chapter, observationally the CMB is optimally measured at millimeter wavelengths. Given the low water vapor content and airmass stability characteristic to the region, the ambient atmosphere of the Earth above the Chajnantor Plateau and Cerro Toco is well transparent to millimeter wavelength observations required for ACT+MBAC and ACT+ACTPol CMB measurements. This is due to the fact that the CMB has a thermal blackbody spectrum that peaks in the millimeter and is roughly flat between a few tens to a few hundreds of GHz in frequency. Additionally, considering all-sky survey results from the WMAP and Planck satellites, the observation of CMB anisotropies at high-resolution is further bracketed by contamination by synchrotron emission from the galaxy at lower frequencies, while dust emission begins to dominate at higher frequencies.
Thus, these characteristics set the theoretical useful window for CMB observations, though these are furthermore limited for ground-based CMB observational platforms by atmospheric characteristics. In particular, various atmospheric absorption lines are prevalent across this observational window, thus driving experimental design of CMB receiver optics and detector arrays to create an observational bandpass between these features to avoid confusion of CMB signal results. Without effective optimization of bandpass definition, the more prominent 1/f contribution from observation of these features in the atmosphere can limit large-scale CMB power spectrum measurements. Additionally, these features, each with a higher brightness temperature than at adjacent frequencies (where CMB observations are targeted) can increase photon noise, and hence thermal loading, which in turn limits the ultimate CMB sensitivity of the given experiment.

2.3.1.2 Brightness Temperature and Precipitable Water Vapor

During regional site selection and atmospheric characterization campaigns for the ALMA experiment in the early 2000s, 220 and 225 GHz tipping radiometers were used to verify the atmospheric transparency above the Chajnantor Plateau, as reported in (Radford 2001). These radiometers were used to measure the atmospheric brightness temperature viewed at various zenith angles (e.g. through a variety of airmasses) as the radiometer is tipped from zenith to horizon. With this resultant data, atmospheric transparency could be calculated using the formula for atmospheric temperature brightness as a model, given here as $T_B(z)$, defined in Equation 2.1

$$T_B(z) = [T_{atm}](1 - e^{-\tau A})$$ (2.1)

where $T_{atm}$ is defined as the effective atmospheric radiation temperature, $A$ is the airmass at a given zenith angle $z$ in which the atmosphere is simplified to be considered isothermal with plane-parallel geometry such that $A = sec(z)$, and finally, $\tau$ is the calculated atmospheric optical depth at zenith. These results have a direct physical implication
of the operational design and ultimate operational sensitivity of a given experimental cosmology system, in which (Radford 2001) describes the integration time needed to reach a given operational sensitivity going as the square of the receiver system noise, which itself is dependent on optical depth $\tau$ and receiver temperature $T_{rec}$, given in Equation 2.2 as

$$t \propto T_{sys}^2 = e^{2\tau A}[T_{rec} + T_{atm}(1 - e^{-\tau A})]^2$$

Additionally, the brightness temperature measured at any given time is also dependent on the instantaneous value of what is referred to as precipitable water vapor (PWV), in which periods of higher PWV correspond to higher observed atmospheric brightness temperature (and thus increased observational integration times necessary to reach a given sensitivity during CMB observations). As defined by the American Meteorological Society (AMS), PWV is the “total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels, commonly expressed in terms of the height to which that water substance [vapor] would stand if completely condensed and collected in a vessel of the same unit cross section” (Society 2015). Throughout this manuscript, PWV is measured in mm. Given that experimental cosmology systems observe radiation originating entirely outside of Earth’s atmosphere, PWV can be considered as the entire atmospheric column between the point of observation throughout the entirety of the atmospheric height. AMS thus defines PWV for the entire column of observation, represented in Equation 2.3 as

$$PWV = \int_{p_1}^{p_2} x dp$$

where $p_1$ and $p_2$ are the atmospheric pressures bounding the defined column, $x(p)$ the mixing ratio at a pressure $p$, $\rho$ is the water density, and $g$ is the acceleration due to gravity. Described in detail during our discussion of ACTPol observation operations later in this manuscript, operation of ACT+MBAC and ACT+ACTPol relied on radiometer results provided by the Atacama Pathfinder EXperiment (APEX) weather monitor platform, acquired
at APEX’s nearby site on the Chajnantor Plateau. In particular, real-time APEX PWV monitoring led to decisions to observe (e.g. for significantly high PWV levels over a given observing period, observations may be suspended), and the APEX PWV data was fed into the ACTPol housekeeping data stream to aid in decision making for ACTPol science data cuts. Figure 2.17 illustrates the real-time data stream of APEX radiometer PWV data accessible from the APEX online weather monitor platform (acquired for the 24-hour period ending Saturday, 19 August 2017, 23:00:00 UTC 2017) (Collaboration 2017a). Additionally, Figure 2.18 provides APEX historic radiometer data results for PWV levels recorded between 2007 and 2015, roughly encapsulating the near-entirety of ACT+MBAC and ACT+ACTPol observing operations, as well as historic data indicating the fraction of days between 2006 and 2015 below a given PWV level (Collaboration 2017b). Generally, a PWV level of less than 1.5 is considered acceptable for ACTPol observing operations, while PWV less than 1.0 is considered optimal. APEX, like ACT, seeks to target an operational season in times of historically lower PWV - thus on an annual basis ACT+MBAC and ACT+ACTPol targeted a period of non-observation during the so-called 'Bolivian Winter' between late-December and early-March each year when PWV levels are historically highest during the year (in which prevailing winds force humid continental-tropical airmasses from South America’s Amazon Basin into the Atacama), further non-observation site upgrades and receiver installation are generally completed between March and May as PWV levels decline, before principal observing operations take place between June and December, when PWV levels roughly reach their annual nadir. As APEX is just over 7 kilometers removed from the ACT site, and also roughly 100 meters lower in elevation on the Chajnantor Plateau, while it is reasonable to expect that PWV levels at the ACT site would differ slightly than the APEX site, and that APEX atmospheric transparency results slightly underestimated in comparison to the ACT site given its lower elevation, APEX atmospheric monitoring results are assumed to be reasonably representative of real-time conditions at the ACT site.

Ultimately, both generations of ACT receivers operating on Cerro Toco utilized the
**Figure 2.17**: Example real-time data stream of APEX radiometer PWV data accessible from the APEX online weather monitor platform (acquired for the 24-hour period ending Saturday, 19 August 2017, 23:00:00 UTC 2017) (Collaboration 2017a)

![Real-time Data Stream](image)

**Current Data**

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</tr>
</tbody>
</table>

**Figure 2.18**: Selected APEX historic radiometer Precipitable Water Vapor Data. *(Left)* APEX historic radiometer data results for PWV levels recorded between 2007 and 2015, roughly encapsulating the near-entirety of ACT+MBAC and ACT+ACTPol observing operations. *(Right)* APEX radiometer historic data indicating the fraction of days between 2006 and 2015 below a given PWV level. (Collaboration 2017b)

![Histogram of PWV Levels](image)
![Fraction of Days Below PWV Levels](image)
the characterization of localized atmospheric conditions and related modeling to determine CMB channel band center. MBAC operated TES bolometer arrays with frequency centers at roughly 145, 220, and 280 GHz, while ACTPol operated TES polarimeter arrays with frequency centers at roughly 90 and 150 GHz. With these centers, both generations of receivers could make observations of CMB signal at these frequencies, while avoiding overlap with, and resultant loading from (to the greatest extent possible) atmospheric oxygen emission line features centered at roughly 60 GHz and 117 GHz, as well as the 183 GHz and 325 GHz water emission line features. Figure 2.19 shows the median atmospheric brightness temperature spectrum at various times throughout the year, split by morning and night, corresponding to PWV values, as shown in (Marriage 2006), with MBAC observing bands centered at 147.2 GHz, 215 GHz, and 278.7 GHz indicated. In this case, winter is defined from June to November and Summer from December to May, while morning is defined as 0500-1700 UTC, and evening 1700-0500 UTC. In terms of PWV, Summer Evening corresponds to PWV = 2.15 mm, Summer Morning to PWV = 1.55 mm, Winter Evening to PWV = 0.94 mm, and Winter Morning to 0.69 mm. Figure 2.20 shows the median atmospheric brightness temperature spectrum for PWVs on the range of 0.0-2.0 mm, shown in PWV = 0.25 mm increments, with ACTPol bandpass results overlayed (discussion on the measurement and impact of these bandpass results will be given later in this manuscript) (Thornton et al. 2016). The MBAC-era brightness temperature spectra extrapolations were generated with the use of the atmospheric transmission modeling package Atmospheric Transmission at Microwaves (ATM), described in (Pardo 2001), while the ACTPol-era brightness temperature spectra extrapolations were generated with a repackaged ATM code, the ALMA Atmospheric Transmission Modeling package (Marriage 2006; Pardo 2001) From these figures, the strong dependence between brightness temperature loading contributions from water at increasing PWV levels is clear, while brightness temperature loading contributions from oxygen are fairly consistent with changing PWV level. With these logistical and atmospheric characterization site selection criterion taken into account, the development of
site logistical and scientific observational systems for the Atacama Cosmology Telescope on the southwestern face of Cerro Toco, adjacent to the Chajnantor Plateau, could thus commence, ushering in a permanent presence for ACT operating with three generations of receiver for the observation of CMB temperature, and then temperature and polarization anisotropy characteristics following site groundbreaking in 2007.

2.4 ACT Collaboration Overview

Following centuries of astronomical observation inherent to the ethnographic record of the Northern Atacama Desert region, over a century of internationally-supported temporary observatory platforms inhabiting the same region, and over a decade of pathfinder experiments and temporary site deployments to region on and immediately adjacent to Cerro Toco and the Chajnantor Plateau region, the development of the first permanent experimental cosmology facility based on Cerro Toco began in earnest. In this period, pathfinder experimental results, site selection criterion, and other observational science and operational logistical considerations were taken into account to begin feasibility study phases for the Atacama Cosmology Telescope, culminating with a principal funding proposal to the National Science Foundation early in the decade. Finally, with confirmed U.S. National Science Foundation support and funding initiated on 01 January 2004, the Atacama Cosmology Telescope collaboration was officially formed.

2.4.1 MBAC Era

The U.S. National Science Foundation would provide the principal funding mechanism to allow for the development of the Atacama Cosmology Telescope site, telescope superstructure, operations and logistics, and ACT’s first generation receiver, MBAC. This initial award was entitled, “Collaborative Research with the Atacama Cosmology Telescope...
Figure 2.19: Median Chajnantor-region atmospheric brightness temperature spectrum at various times throughout the year, split by morning and night, corresponding to PWV values, as shown in (Marriage 2006), with MBAC observing bands centered at 147.2 GHz, 215 GHz, and 278.7 GHz indicated. In this case, winter is defined from June to November and Summer from December to May, while morning is defined as 0500-1700 UTC, and evening 1700-0500 UTC. In terms of PWV, Summer Evening corresponds to PWV = 2.15 mm, Summer Morning to PWV = 1.55 mm, Winter Evening to PWV = 0.94 mm, and Winter Morning to 0.69 mm. An atmospheric oxygen emission line appears at 117 GHz, while an atmospheric water emission line appears at 183 GHz.(Marriage 2006; Pardo 2001)
Figure 2.20: Median atmospheric brightness temperature spectrum for PWVs on the range of 0.0-2.0 mm, shown in PWV = 0.25 mm increments, with ACTPol bandpass results overlayed (discussion on the measurement and impact of these bandpass results will be given later in this manuscript). Atmospheric oxygen emission lines appear at 60 GHz and 117 GHz, while an atmospheric water emission line appears at 183 GHz. (Collaboration 2017b)
(ACT): Probing Fundamental Physics Through Observations of Cosmic Structure,” corresponding to NSF Grant Number AST-0408698, with a total award amount of $12,981,621.00. The ACT+MBAC generation of the ACT collaboration allowed for primary experimental site and instrumentation development to be led from a partnership between the University of Pennsylvania, Princeton University, NASA’s Goddard Space Flight Center (Greenbelt, Maryland), the University of British Columbia, and the National Institute of Standards and Technology - NIST (Boulder, Colorado), and others, while theoretical and analysis work for the collaboration was led by the aforementioned institutions, as well as Oxford University, the University of KwaZulu-Natal, the University of Pittsburgh, Rutgers University, and the Pontificia Universidad Católica de Chile. These institutions, as well as a myriad of others, would constitute the principal collaboration structure during the ACT+MBAC era, ultimately joining together universities and federally funded research and development centers (FFRDCs) across five continents (North America, South America, Europe, Africa, and Asia), enabling the sum total of ACT+MBAC technology development and cosmology results over the entirety of the NSF grant period, which terminated on 31 December 2010. A second, separate NSF grant further assisted the strength of ACT’s multinational collaborative partnerships, travel, and exchange between institutions based in the Northern Hemisphere, with those in South Africa, Chile, and Europe. This NSF grant was entitled, “Partnership for International Research and Education (PIRE): Southern Optical Astronomical Survey,” with NSF Grant Number 0530095, and a total award amount of $2,350,000.00.

2.4.2 ACTPol and Advanced ACTPol Eras

The operational lifetime of the Atacama Cosmology Telescope, which closed its third and final season of observing operations with the MBAC receiver in late-2010, was then extended with the approval of the second NSF grant in support of ACT operations. This
grant, entitled “ACTPol: The Atacama Cosmology Telescope with Polarization,” corresponding to NSF Grant Number AST-0965625, and a total award amount of $9,400,000.00 enabled the design, development, on-site deployment, and science operations of ACTPol. This grant was thus initiated on 15 September 2010, and estimated to close on 31 August 2016. The ACT receiver upgrade, ACTPol, would enable ACT for the first time to probe the CMB at millimeter-wavelengths in both temperature and polarization, hence significantly extending the scope of rich early-universe cosmology that could be explored with the Cerro Toco based facility. The grant would also include funding for capitol upgrades to ACT site logistics and operations systems, described later in this chapter, that would both change the operational paradigm for ACT operations to favor an increasingly Atacama-centric approach. Given that ACTPol would also be used as a pathfinder for a number of space technologies that could be integral to the development of future NASA-based CMB and related cosmology missions, including a possible future-generation Inflationary Probe mission, the project was also supported by a set of NASA technology development grants. These included, NASA Grant Number NNX13AE56G, “Development of Feedhorn-Coupled Multichroic Polarimeters for the Inflationary Probe Mission,” and NASA Grant Number NNX14AB58G, “Broad Bandwidth Metamaterial Anti-reflective Coatings for Measurement of the Cosmic Microwave Background,” which aided in the development of the technology central to the third of ACTPol’s three principal polarimeter array packages, namely its focal planes hosting multichroic polarimeter technology, as well as the development of novel metamaterial anti-reflective coated lenses fabricated of high-purity silicon, operating at cryogenic temperatures within the ACTPol receiver.

With ACTPol observing operations fully underway and approach full ACTPol deployment in early 2015, the ACTPol grant was then extended once more by the NSF to enable the development of a receiver upgrade for ACTPol, called Advanced ACTPol. This grant was thus initiated on 15 September 2014, and is estimated to close on 31 August 2019. This grant, simply entitled “Advanced ACTPol” corresponding to NSF Grant Number AST-
1440226 with a total award amount of $7,269,979.00, would allow for both the development of next-generation fully-multichroic polarimeter focal planes and corresponding optics for the ACTPol receiver, which would now allow for operations at a wider frequency range than ACTPol. Whereas ACTPol enabled direct probing of the CMB at primary CMB signal channels of 90 GHz and 150 GHz, Advanced ACTPol would allow for low-frequency channels (for enhanced ability to constrain synchrotron radiation in ACTPol fields) and higher-frequency channels (for enhanced ability to constrain radiation associated with dust emission in ACTPol fields), in addition to central band multichroic polarimeters operating in the same frequency range as ACTPol. ACTPol technology development, integration, instrument characterization, and early science results are central to the following chapters of this dissertation manuscript, followed by a discussion of early technology development and scientific outlook for Advanced ACTPol operations (and beyond) at the close of this manuscript. During the ACTPol and Advanced ACTPol eras, the ACT collaboration would grow to incorporate more than two dozen academic institutions and FFRDCs with a continued international scope from the ACT+MBAC era. In terms of instrument development, design, integration, and validation of the ACTPol receiver and its constituent technologies would still include the University of Pennsylvania, Princeton University, NIST-Boulder, and NASA-Goddard, with detector development (in this case for the ACTPol polarimeter arrays) centered at NIST-Boulder rather than NASA-Goddard, who produced the MBAC arrays. Additionally, over the course of ACTPol development, the University of Michigan would enter early to lead the development of the aforementioned metamaterial anti-reflective coated high-purity silicon lenses, and Cornell University entering later in the ACTPol era, with a focus on detector development and validation. During ACTPol development, Princeton University remained the collaboration lead on the integration and testing of the ACTPol polarimeter array packages, while the University of Pennsylvania led the development of the ACTPol receiver, and its constituent optomechanical subassemblies, system cryogenics, and related interface electronics designs. ACTPol polarimeter array package design
was led in a joint effort between NIST, Princeton, and Penn. Advanced ACTPol development would continue with a similar institutional work breakdown structure, though it should be pointed out that given the interinstitutional, multinational nature of the collaboration, development of receiver technologies for both the ACTPol and Advanced ACTPol eras were virtually coordinated through a robust set of weekly experimental development telecons, related instrument development wikis, and regular in-person inter-institutional research trips and collaboration meetings. As of the writing of this manuscript, the full list of ACT collaborating institutions goes (in alphabetical order) as: Cardiff University, Carnegie Mellon University, CITA/Toronto, Columbia University, Cornell University, Dunlap Institute/Toronto, Florida State, Haverford College, Johns Hopkins University, KwaZulu-Natal, NASA-Goddard, NIST-Boulder, Oxford University, Pontificia Universidad Católica de Chile, Princeton University, Rutgers University, Stanford University, Stony Brook University, University of California at Berkeley, University of British Columbia, Universidad de Chile, University of Illinois at Urbana-Champaign, University of Michigan, University of Pennsylvania, University of Pittsburgh, and West Chester University.

It should also be indicated that throughout the entirety of the MBAC, ACTPol, and Advanced ACTPol eras, cosmology science data analysis and mapping computations were performed on the GPC supercomputer at the SciNet HPC Consortium. SciNet is funded by the Canada Foundation for Innovation (CFI) under the auspices of Compute Canada, the Government of Ontario, the Ontario Research Fund: Research Excellence, and the University of Toronto. Later in the ACTPol era, a second computing cluster, the aptly-named “Hippo” would join SciNet as a second supercomputing resource, based at the University of KwaZulu-Natal. As indicated later in this chapter, the Atacama Cosmology Telescope operates in the Parque Astronómico de Atacama in northern Chile under the auspices of the Comisión Nacional de Investigación Científica y Tecnológica (CONICYT). Throughout the ACTPol era, the ACT Collaboration continued its close partnership with CONICYT, including regular hosting of CONICYT officials at the ACT site on Cerro Toco,
and working with CONICYT and other Chilean federal officials to increase bilateral scientific ties between CONICYT, Chilean institutions, and the constituent entities within the ACT Collaboration. Additionally, work was completed during ACTPol field operations to work directly with officials from CONICYT and those dispatched by the Chilean federal government to further develop the entire Chajnantor-Toco region into an area even more attractive to multinational astronomy collaboration research, including aiding these officials in studies for the feasibility and operational development path for increased Chilean federal infrastructure investment, ranging from improved access roads, telecommunication infrastructure, and diversified energy resources in support of research facilities across this region of the Atacama.

For completeness, the dissertation research represented in this manuscript was individually supported in three phases over the aforementioned 15 August 2009 through 31 August 2015 period, initially through a mix of NSF-ACT and University of Pennsylvania support, and later through a National Science Foundation Graduate Research Fellowship Award and a NASA Space Technology Research Fellowship Award:

i. (15 August 2009 - 31 March 2011) - Mix of support from principal NSF-ACT grants, referenced above, and University of Pennsylvania funding.

ii. (01 April 2011 - 31 May 2011) National Science Foundation Graduate Research Fellowship Award (NSF-GRFP). NSF Grant No. 0822219.

iii. (01 June 2011 - 31 August 2015) National Aeronautics and Space Administration Space Technology Research Fellowship Award (NASA-NSTRF). NASA Grant No. NNX11AN19H.
2.5 Construction of ACT

Throughout Section 2.2, a myriad of predecessor experiments were discussed, which were deployed, characterized, and operated on and around the altiplanic Chajnantor Plateau region of the northern Atacama. In particular, the temporary deployment and operation of both the TOCO and MINT experimental cosmology platforms near the aforementioned abandoned mining facility clearing on the southwestern ascent to the summit of Cerro Toco allowed for direct pathfinder operations leading to the ultimate development and construction of the Atacama Cosmology Telescope. (Fowler et al. 2005; Miller et al. 2002) The commencement of the January 2004 primary ACT National Science Foundation grant of $12,981,621.00 (mentioned in 2.4) enabled the primary commencement of design, development, and North American construction of ACT’s largest-scale principal optomechanical components. Specifically, between the beginning of the NSF grant period, and ultimate 2007 deployment to Chile, ACT superstructural elements, including the ACT telescope pedestal and the ACT warm optomechanical superstructure (housing primary, secondary, and receiver cabin elements) were designed and constructed by the ACT collaboration in close coordination with Canadian large-scale precision dynamical structure engineering firm, Dynamic Structures. In addition to ACT, Dynamic Structures has also played an instrumental role in the design, fabrication, and integration of structural elements of other large-scale moveable astronomy platforms, including the Gemini Telescopes, the W.M. Keck Observatory, and the Subaru Telescope (Structues 2017).

During 2006, members of the ACT collaboration worked with personnel from Dynamic Structures to complete the first full test assembly of the ACT telescope pedestal and warm optomechanical superstructure, which took place in Port Coquitlam (near Vancouver), British Columbia, Canada. Following this test assembly, ACT superstructural elements were disassembled and shipped to Northern Chile, arriving to enable principal ACT site construction operations, which commenced in early 2007 (Swetz 2009). Following site terrain clearing and concrete base preparatory operations, mid-2007 witnessed the deployment
Figure 2.21: Timelapse illustration of the attachment and ultimate operational deployment of the Atacama Cosmology Telescope warm optomechanical superstructure with the ACT Pedestal Base assembly in mid-2007. Images courtesy M. Limon
Figure 2.22: Timelapse illustration of the construction and operational deployment of the Atacama Cosmology Telescope outer ground screen framing and reflective paneling. The ACT outer ground screen is roughly 13 meters in height, and consists of an inverted frustrum-shaped, dodecagonal geometric construction. Images courtesy M. Kaul.
of the ACT telescope pedestal and optomechanical superstructure, followed by the construction of the ACT outer ground screen support and screen panel infrastructure (the presence of a smaller-scale, ‘inner’ ground screen between the ACT primary and secondary mirror panel assemblies is indicated later in this chapter). Taken together, the ACT pedestal and optomechanical superstructure are roughly 12 meters in height (including both the ACT 6 meter primary mirror assembly, and 2 meter secondary mirror assembly, as well as receiver cabin), while the ACT principal outer ground screen assembly is roughly 13 meters in height. Figure 2.21 illustrates timelapse imagery taken during the construction and mounting of the ACT warm optomechanical superstructure assembly to the ACT base pedestal in 2007, followed by Figure 2.22, which includes a timelapse of the construction of the 13 meter high outer ground screen following early motion testing of the ACT optomechanical superstructure and pedestal systems. The ACT outer ground screen, as illustrated, consists of an inverted frustrum-shaped, dodecagonal geometric construction. Due to these large-scale dimensions, as well as the telescope superstructural mass - 40 metric ton warm optomechanical superstructure and 12 metric ton pedestal base - first-generation ACT deployment relied on logistical elements and site access routes to ensure the safe delivery of both principal ACT telescope components and large-scale construction equipment. These ACT first-generation logistical considerations will be described in the section, which follows.

2.6 MBAC-Era Site Infrastructure and Logistics

Given that significant logistical upgrades would ultimately be required to accommodate the deployment of the ACTPol receiver to the ACT telescope warm optical superstructure for ultimate observing operations, it is critical that we first consider the status of site and logistical infrastructure development that took place to enable first generation ACT - MBAC-era - site operations. As Section 2.8 provides details of the full-set of logistical upgrades which were required to enable the deployment of the ACTPol receiver and ACT+ACTPol observing operations, we will only consider critical aspects of the initial MBAC-era site
infrastructure deployment briefly throughout this section, allowing basis of comparison to better understand the significant site upgrades which were required for ACTPol deployment and operations.

2.6.1 Site Access

As discussed in 2.2, we considered that the several generations of post-1990 experimental cosmology sites situated on or adjacent to Cerro Toco, fully exploited the existing infrastructure developed for the mining industry in the Chajnantor region decades earlier to enable rapid site development. The development of a permanent site on Cerro Toco for the Atacama Cosmology Telescope would also mirror this approach - leveraging existing natural geomorphology and developed infrastructure elements inherent to the region in lieu of novel development whenever possible. The ACT+MBAC era site would in particular rely on the dirt road paths (the so-called ‘front roads’) worn from the mining era to reach the site via the aforementioned Paso de Jama highway from San Pedro de Atacama. Figure A.3, which we have previous considered, illustrates the scale of site access via this Paso de Jama and ‘front road’ route. From the ACT+MBAC-era project base camp at Casa Don Esteban in San Pedro de Atacama, site access during this era was generally attained taking a route along the Paso de Jama for roughly 40 kilometers, before exiting the paved highway and accessing the site on one of several unpaved mining-era paths including elevation gain and switchbacking for roughly 10 kilometers. Depending on route conditions, a single direction of travel for ACT+MBAC-era site access was between 45 and 90 minutes in duration. Figure 2.23 illustrates typical ACT+MBAC-era site access route conditions between the paved Paso de Jama and ACT site. While path grading and snow removal equipment were often deployed to these routes to ensure site access when required, the ACTPol-era and establishment of the CONICYT Parque Astronómico de Atacama would lead to the upgrade of these routes for more reliable site access, though road conditions, especially during periods
of snow, were a site logistics challenge during the MBAC-era and remain prevalent during the ACTPol-era in spite of improvement.

2.6.2 Layout of ACT+MBAC Site and Critical Logistics Infrastructure

In addition to the deployment of the Atacama Cosmology Telescope warm optical superstructure and its associated principal ground screens structure, a number of critical logistical infrastructure deployments would be required to enable the operations of ACT+MBAC during this first phase of the project. Although ACT+MBAC was not the only existing experimental cosmology or astrophysics facility in the Chajnantor Plateau region during this phase of the ACT project, while other sites in the region in the era were situated across the Plateau surrounding nearby Cerro Chajnantor (most notably the APEX, NANTEN, ASTE, CBI, and early ALMA high-sites), ACT+MBAC was the only site to utilize the small plateau some 100 meters higher in elevation than these sites, on the southwestern face of Cerro Toco. Even with the previous use of this immediate vicinity for temporary experiments like TOCO, which we discussed earlier, the development of ACT+MBAC as a
permanent site in this location required the removal of existing boulders and surface grading
of a mid-scale site, to allow for not only the installation of the ACT telescope and ground
screen, but also requisite infrastructure to enable this permanent site, including communica-
tions, power generation, receiver integration, control system, and storage structures.

Figure 2.24 provides an overview of these principal site infrastructure elements. In ad-
dition to the ACT telescope warm optical superstructure and ground screen, which will
be discussed in further detail in the section, which follows, all MBAC-era logistical sys-
tems are highlighted. While all of these structures were fundamental to ACT+MBAC
operations, perhaps most notable among these are the site power generation and communi-
cations/control systems. During the MBAC-era all electrical systems on the site, including
the ACT telescope, receiver cryogenics, and all systems necessary for receiver integration,
operation, and data acquisition/communications were supplied with electricity generated
by one of two diesel generators. The need for redundancy in electricity generation for the
ACT site is driven especially by the low pressure and temperature characteristics of the
ACT site on Cerro Toco, which drive a limited duty cycle for each of the generators - while
one generator is used to supply power to the ACT site, the other can be serviced for its next
shift of operation. Typically, the ACT+MBAC site generators operated with a duty cycle
duration of roughly 14 days, and component (e.g. filters, etc.) servicing and replacement
for each generator would take place during one of these off cycles, typically on a monthly
basis. During the MBAC-era, dual XJ150 John Deere (Triton Power Generation) were
deployed, each typically supplying 25-30 kW to the site during full observing operations,
which is substantially lower than the maximum 150 kW sea-level-elevation-operations rat-
ing of these systems, again highlighting the technical limitations of operating the ACT site
at 5190 meters in elevation. At full MBAC observing operations on-site, each generator
typically consume roughly 240 liters of diesel fuel each day, and are fed by an automatic
refueling system, attached to a principal diesel fuel supply tank with a roughly 15,000 liter
maximum capacity. Although the nominal operations duty cycle for each generator required
operations team intervention, in principal this fuel system would allow for about 60 days of fully autonomous site operations, assuming fault-free operations for full-efficiency of all site operations systems, without refueling. Given site access challenges however, especially during precipitation events throughout Austral winter months, common ACT operations practice dictates filling the principal diesel fuel supply tank to at or near its maximum capacity when it reaches at or slightly below 50 percent of its capacity. Thus, roughly every 30 days a diesel refilling truck reaches the site for refilling operations, either via the ALMA or Paso de Jama and Pampa la Bola routes, generally given limitations of vehicles of the scale of diesel tanker trucks transiting the Cerro Toco ‘front road’ (Swetz et al. 2011a).

ACT site communications are achieved via a direct line-of-site microwave data uplink/downlink system, which involved the deployment of a principal site communications antenna tower. As shown in Figure 2.24, the location of this tower is roughly 50 meters removed from the main ACT site, to ensure that the parabolic antenna mounted to the tower could have a direct line of site with the parabolic antenna tower deployed at the ACT base camp in San Pedro de Atacama. During the ACT+MBAC era, this microwave communications system included a 60 centimeter diameter parabolic antenna mounted at the ACT base camp in San Pedro de Atacama, and a 1.2 meter diameter parabolic antenna mounted at the ACT telescope site. The operational frequency of the dual Orthogon PTP600 transreceiver system used to establish the data link is 5.8 GHz and initial alignment was achieved in part using an intense laser source to aid in optimal optical orientation of the antenna pair across a roughly 40 kilometer distance. The MBAC-era data communications rate was roughly 4 MB/s between the site and San Pedro de Atacama, where internet access is established, though given that the San Pedro de Atacama internet connection was roughly 1 MB/s, this provided the maximum site-to-North America communications data limit. Overall the microwave uplink/downlink is used for both site communications and also to transfer daily telescope operations data to San Pedro de Atacama, where it is stored on physical hard drives for transport for processing elsewhere in the ACT collaboration.
The remaining MBAC-era site deployment structures included dual shipping containers for logistical system, supplies, and hardware storage, as well as a control and equipment room container, and the ACT site receiver integration container. The control container is partitioned into two halves, where one side of the container is used for computer data acquisition and control system software operations, with the other half of the container housing, among other systems, the main ACT site electrical bus, the ACT Kuka robotics control system (controlling all ACT telescope warm optical superstructure pointing and slewing operations), as well as cryogenic support equipment, most notably pulse tube compressor systems and cooling equipment. During the MBAC-era, receiver integration was principally completed in North America, with only limited receiver integration (e.g. mostly detector array package deployment) occurring on site. While this allowed the final ACT+MBAC era structure, namely the receiver integration, machine shop, and storage canopy container to be limited in size, it also meant that the MBAC receiver would be required to return to North America between seasons for the deployment of its three bolometer arrays and associated optomechanical subassemblies. Following any diagnostic or laboratory testing required during MBAC operations within the ACT receiver integration and machine shop container, the receiver would then be lifted via come-alongs into the bed of a site operations truck, driven across the site within the ground screen, and then hoisted into the ACT telescope receiver cabin via come-alongs attached to an external I-beam and then rolled into place using a low-riding transfer cart system within the cabin before final positioning and mounting within the receiver cabin. While relatively straightforward, this procedure was found to be time-intensive, and would not be possible given the scale of the ACTPol receiver, calling for perhaps the largest logistical deployment systems upgrade effort for the next-generation of the ACT project, which will be discussed in further detail in Section 2.8 (Swetz et al. 2011a).
Figure 2.24: Atacama Cosmology Telescope: MBAC-era Site Infrastructure Overview. (Center, and Clockwise from Top-left) (a) ACT Telescope Warm Optical Superstructure and Ground Screen. (b) Dual logistical supply and technical hardware storage containers. (c) Principal site diesel fuel storage tank (approx. 15,000 liters maximum capacity). (d) Parabolic antenna tower Providing Line-of-Sight Microwave Uplink/Downlink between ACT site on Cerro Toco and ACT base camp in San Pedro de Atacama. (e) Dual Diesel Generator Shed. (f) ACT site operations control room and cryogenic/robotics-system equipment room container. (g) ACT site receiver integration container, machine shop, and receiver cryostat shell integration/storage canopy.
2.7 ACT Warm Optics

With both the construction and logistical development of both the ACT site and optomechanical superstructure well-described, we now turn our attention to the technology development criterion that led to the design of ACT Warm Optical system. The terms ‘optomechanical superstructure’ and ‘warm optics’ are generally used interchangeably here to describe principal ACT telescope hardware systems that allow for incident CMB radiation to be conveyed from an observable patch of sky to the ACT receiver 300K optical input (vacuum) window for each receiver optomechanical subassembly and corresponding polarimeter array package. Thus, the term ‘warm’ indicates that these systems, including the telescope ground-screens, pedestal and drive motors, primary and secondary mirrors and their mounting infrastructure, and ACT receiver cabin, are operating at ambient, non-cryogenic operating temperatures, though in practice, from a human viewpoint, given the site location and ambient temperature and wind conditions at 5190 meters in elevation, the environment in which they operate is generally anything but ‘warm.’ In this section, we will briefly consider the warm optical design requirements that led to the Atacama Cosmology Telescope configuration that is currently deployed, in particular drawing on development discussions highlighted in (Fowler et al. 2007), and presenting operational results from MBAC and ACTPol era operations and system testing.

2.7.1 Telescope Superstructural Constraints

The development of the ACT telescope optomechanical superstructure resulted from a number of critical motivating factors. These considerations range from optical physics requirements that would enable the ACT telescope and its various receiver systems to meet or exceed primary ACT cosmology goals, to optical and mechanical engineering requirements that ensure the long-term operational efficiency and integrity of the overall system, to practical drivers based on site development, scale, and terrain. Of course, in principle, the
parameter space that could be optimized in the development of a large-scale experimental cosmology system like ACT is rather large, but considering technology development and science operations drivers, this parameter space is rapidly reduced.

At its most basic level, mechanical engineering and experimental development considerations require that the ACT telescope be able to effectively operate in the sometimes harsh wind and weather conditions that Cerro Toco encounters. The ACT telescope also needed to ensure that its design allowed for efficient slewing operations of its large-scale moveable upper superstructure, with the ability to slew and scan at a variety of elevations and azimuths. Thus a mechanically robust pedestal, anchored into the concrete base constructed during initial ACT site development would be key, in addition to a compact, yet reasonably-rigid upper section, housing the primary and secondary mirrors, in addition to a receiver cabin able to effectively house the ACT receiver and its support systems (note that the ACT receiver cabin was of course designed to house MBAC and its support systems and interface electronics - the larger envelope of ACTPol and the introduction of adjacent systems for the operation of its dilution refrigeration cryogenics would require later logistical considerations, discussed in the next section). From a more practical consideration, just as the optomechanical design decisions inside both MBAC and ACTPol often acted to limit the overall mass of the system (for thermal performance and practical engineering purposes), so too would the ACT telescope require both a robust design with mass limitations where possible in its constituent systems, thus reducing both engineering and material costs, and limit, to the extent possible, site energy resources associated with driving the telescope motion operation. As discussed earlier, the ACT telescope pedestal and optomechanical superstructure were designed and fabricated in collaboration with Dynamic Structure (Structures 2017), while the development of telescope motion systems were provided by German factory automation and industrial robotics firm, KUKA AG (AG 2017).

In addition to telescope mechanical engineering concerns related to development cost and site operations, design and implementation of an optimally compact optical design
also has the benefit of reducing the overall torsional forces and mechanical strain on the primary and secondary mirrors and their mechanical support structures by reducing the overall angular momentum on the extrema of the mechanical system. An optical design that would enable the receiver cabin to be placed as near as possible to the telescope rotational origin would also aid in the reduction of vibroacoustical inputs to the receiver, aiding in more stable cryogenic performance, among other factors. Furthermore, optical loading considerations would need to minimize the potential for optical beam spillover and optical interference by higher temperature thermal sources in the ambient environment. An off-axis, clear aperture design would aid in this objective as well as to minimize the potential for scattering, with a selected geometry designed to avoid beam clipping or other optical interference. Additionally, to achieve small angular scale probes of cosmology at high $\ell$ and to ensure the ability to measure Sunyaev-Zel’dovich (SZ) galaxy clusters in unbiased ACT surveys across all redshifts, a telescope design with arcminute angular resolution would be needed.

### 2.7.2 Gregorian Optical Design Goals and Constraints

With some of the design requirements of the ACT warm optical superstructure now defined, we can first consider what primary diameter would be required to ensure the requisite arcminute angular resolution needed to achieve ACT primary science goals. A back-of-the-envelope calculation of angular resolution can then be considered to determine the range of possible primary diameters, where angular resolution, $R$, in radians, is given in Equation 2.4 as:

$$ R = \frac{\lambda}{D} \quad (2.4) $$

where $\lambda$ is the wavelength of radiation to which the receiver is sensitive, and $D$ is the diameter of the telescope primary mirror. If we consider a projected central operational frequency of the 150 GHz channel for both MBAC and ACTPol, then using the formula
\[ c = (\nu)(\lambda) \] for speed of light \( c \) and frequency \( \nu \), this corresponds to a central operational wavelength of 1.99 mm. Thus to achieve angular resolution for the telescope system in the arcminute range, a primary mirror in the several meter scale is required. Ultimately, a primary mirror of 6 meters in diameter was selected for operation on ACT, taking into account scientific drivers, along with cost and overall system impact, giving an achievable angular resolution at 150 GHz operation of roughly 1.14 arcminutes, while at 90 GHz this corresponds to an angular resolution of roughly 1.89 arcminutes. In the final ACT warm optics configuration, the secondary was selected to be 2 meters in diameter. Additionally, as described in (Fowler et al. 2007) the ACT optical design criterion also aimed to maintain its compact design by incorporating a fast primary focus (f-number \( \leq 1 \)) and a fast (f-number \( \sim 2.5 \), to limit receiver window diameter within a compact telescope configuration), diffraction limited focal plane and a 1.0 square degree field of view. When we refer to ‘f-number’ speed, faster optics have a lower f-number, where f-number is defined as f-number = \( f/(D) \), where \( f \) is the focal length, and \( D \) is the effective (illuminated) diameter of the primary.

With these optical design constraints taken into account for the ACT telescope warm optics, an off-axis, aplanatic, Gregorian configuration was selected as the baseline design configuration since it allowed for many of the aforementioned design criterion to be satisfied in terms of its basic geometry. An alternative Cassegrain design was also investigated, though the off-axis Gregorian was ultimately selected for a base optical model given that it enabled greater vertical clearance between light moving between the primary and secondary, and the secondary focus, which enabled greater mechanical clearance for the position of the receiver and support structures forming the receiver cabin (Fowler et al. 2007). With this base model selected, numerical modeling was then performed to optimize image quality over the aforementioned 1.0 square degree field of view, using the Code V optical design software platform (Synopsys 2017). Ultimately, the numerical modeling process yielded a warm optical design approximating an ideal aplanatic Gregorian configuration with no leading-order spherical aberrations or coma in the focal plane (Swetz et al. 2011a), in which
primary and secondary mirrors are coaxial, each are off-axis segments of ellipsoids. (Fowler et al. 2007) further defines the final mirror geometry according to Equation 2.5,

$$z(x, y) = z_{\text{vert}} + (((x^2 + y^2)/R)/(1 + \sqrt{1 - ((1 + K)(x^2 + y^2)/R)}))$$    \hspace{1cm} (2.5)$$

where for \( z \) along the shared optical axis of symmetry, \( z_{\text{vert}} \) is the position of the vertex in which the primary vertex is set as \( z = 0 \), \( K \) is the defined as the conic constant where for ellipsoid eccentricity \( e \), \( K = -e^2 \), \( R \) is the radius of curvature at the vertex, and \( x \) and \( y \) represent positions in the telescope \( xy \)-plane, for an \( x \) direction parallel to the telescope elevation axis and \( y \) orthogonal to \( x \) and \( z \). The resulting mirror parameters describing the ACT warm optics are given in 2.1, where \( a \) and \( b \) correspond to the semi-major and semi-minor axes in the \( x \) and \( y \) directions, respectively (Fowler et al. 2007).

<table>
<thead>
<tr>
<th>Mirror</th>
<th>( z_{\text{vert}}(m) )</th>
<th>( R(m) )</th>
<th>( K )</th>
<th>( y_0(m) )</th>
<th>( a(m) )</th>
<th>( b(m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>0.0000</td>
<td>-10.0000</td>
<td>-0.940935</td>
<td>5.000</td>
<td>3.000</td>
<td>3.000</td>
</tr>
<tr>
<td>Secondary</td>
<td>-6.6625</td>
<td>2.4938</td>
<td>-0.322366</td>
<td>-1.488</td>
<td>1.020</td>
<td>0.905</td>
</tr>
<tr>
<td>Gregorian Focus</td>
<td>-1.6758</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: ACT Warm Optical Parameters (corresponding to 2.5). Here, \( z_{\text{vert}} \) is the position of the vertex in which the primary vertex is set as \( z = 0 \), \( K \) is the defined as the conic constant where for ellipsoid eccentricity \( e \), \( K = -e^2 \), \( R \) is the radius of curvature at the vertex, and \( x \) and \( y \) represent positions in the telescope \( xy \)-plane, for an \( x \) direction parallel to the telescope elevation axis and \( y \) orthogonal to \( x \) and \( z \), and where \( a \) and \( b \) correspond to the semi-major and semi-minor axes in the \( x \) and \( y \) directions, respectively. (Fowler et al. 2007)

Furthermore, in characterizing achievable image quality, according to (Swetz et al. 2011a) the final warm optical design of the telescope allowed ACT to reach a Strehl ratio of greater than 0.9 across the 1.0 square degree field of view at the Gregorian focus of the optical system, calculated for the MBAC operational frequency channel of 280 GHz. By definition, the Strehl ratio refers to the ratio between the maximum intensity of the point spread function and the maximum theoretically-achievable intensity of a system of the same
2.7.3 Telescope Superstructural Design

The mechanical design of the ACT warm optomechanical superstructure is given in Figure 2.25. (Swetz 2009) This overview indicates the final implemented mechanical design for the ACT primary and secondary mirrors, optomechanical backing structure, receiver cabin, and elevation axis. Additionally, the dual ACT ground screen designs are indicated, with the overall ACT telescope reaching \( \sim 12 \) meters in height, and its primary, fixed outer ground screen reaching \( \sim 13 \) meters in height. A secondary, inner ground screen is located on both sides of the telescope between the primary and secondary mirrors, and is co-moving with the warm optomechanical superstructure during operations. In addition to ambient weather protection of the telescope superstructure to wear associated with wind and weather events, the primary objective of this dual ground screen approach is to reduce receiver thermal loading associated with optical pickup of radiation sources in the ambient environment (e.g. ground, structures, etc.) that are at \( \sim 270 \) K, by ensuring that these ground screen surfaces are coated with reflective paint and geometrically designed such that, to the greatest extent possible, they are reflective of colder radiation from the sky at \( \sim 20 \) K. Furthermore, given the potential for optical spillover from the ACTPol cryogenic Lyot stop (detailed in the next Chapter), reflective baffling has been introduced to reduce loading from the observation of structures near the primary and secondary mirrors. While improvements were made during the MBAC-era to reduce the primary mirror spillover from 2% to \( \leq 2 \% \) (Swetz et al. 2011a), a variety of baffling arrangements during observations were
introduced during both MBAC and ACTPol observing eras to ensure maximal reflection of spillover to the cold sky, rather than ambient temperature structures in the vicinity of ACT. Figure 2.26 provides imagery of the final ACT primary and secondary mirror assemblies, with an iteration of secondary baffling shown from during the 2015 ACTPol observing season. Figure 2.27 illustrates the ACT telescope superstructure overlayed with the raytrace of the ACT warm optical design, with receiver cabin wall cutaway to indicate the relative position of the ACTPol receiver, and inner, co-moving ground screen removed for greater raytrace visibility. This figure illustrates the configuration of ACT when at an observing angle of 60 degrees, corresponding to a level receiver cabin floor as is experienced during on-site receiver cabin servicing operations (Thornton et al. 2016). Finally, Table 2.2 provides a summary of the relevant ACT telescope site, superstructure, optical design, and telescope motion characteristics described throughout this section (Swetz et al. 2011a).

2.7.4 Overview of ACT Primary, Secondary, and Receiver Critical Alignment

With the principal warm optical design properties of the ACT telescope now characterized, mirror dynamics and system alignment are now critical to consider. First, it should be noted that rather than casting a monolithic primary and secondary out of aluminum, at 6 meter and 2 meter diameter, respectively, the ACT warm optics are segmented. The ACT primary consists of 71 rectangular aluminum panels, and the ACT secondary consists of 11 aluminum panels. This segmented approach was necessary given the alternative cost and engineering considerations associated with what would have been a very large scale monolithic optic for both the primary and the secondary mirrors. Additionally, given the potential for thermal deformation (associated with diurnal and seasonal temperature fluctuations of the ambient environment over long-term operations) of the large primary diameter and optomechanical backing structure, referred to as the ACT BUS (back-up structure), a segmented approach with modular and position-adjustable constituent mirrors was likewise
Figure 2.25: ACT Warm Optics: Optomechanical Superstructure, Optics, and Dual Ground Screens. This overview indicates the final implemented mechanical design for the ACT primary and secondary mirrors, optomechanical backing structure, receiver cabin, and elevation axis. Additionally, the dual ACT ground screen designs are indicated, with the overall ACT telescope reaching ~12 meters in height, and its primary, fixed outer ground screen reaching ~13 meters in height. A secondary, inner ground screen is located on both sides of the telescope between the primary and secondary mirrors, and is co-moving with the warm optomechanical superstructure during operations. (Swetz 2009)
Figure 2.26: ACT Warm Optics: Primary and Secondary Mirror Imagery. (left) Image of ACT primary taken during 2013 ACTPol observing season. (right) Image of ACT secondary taken during 2015 ACTPol observing season with extended baffling configuration installed.
Figure 2.27: ACT Warm Optics: Optomechanical Superstructure and Optical Design Raytrace. ACT telescope superstructure overlayed with raytrace of the ACT warm optical design, with receiver cabin wall cutaway to indicate the relative position of the ACTPol receiver, and inner, co-moving ground screen removed for greater raytrace visibility. This figure illustrates the configuration of ACT when at an observing angle of 60 degrees, corresponding to a level receiver cabin floor as is experienced during on-site receiver cabin servicing operations. (Thornton et al. 2016)
advantageous. The geometry of each primary and secondary panel were achieved through custom surface machining in order to ensure that the integrated ACT primary and secondary mirror overall assemblies met the geometric specifications given in earlier in this section. The general geometric configuration for the primary and secondary mirrors can be seen in 2.26, in which ACT primary mirrors are nearly rectangular with edge lengths roughly 0.65 m x 0.85 m, while the ACT secondary has a central decagonal mirror of 0.50 m x 0.80 m in rough extent, surrounded by ten trapezoidal mirrors of 0.35 m x 0.80 m rough extent. These constituent mirror segments of the ACT primary and secondary warm optics were fabricated by Forcier Machine Design, with metrology performed to characterize the resultant surface characteristics of each panel using a coordinate-measuring machine, or CMM, and shown to be approximately 3 μm (Design 2017; Swetz et al. 2011a).

With individual primary and secondary mirror elements fabricated and characterized, these mirror segments were then integrated with the ACT telescope optomechanical superstructure, with each element attached in four locations near their geometric vertices using threaded manual mechanical actuators, allowing for course and fine adjustment of each mirror. With all mirrors installed to the ACT telescope optomechanical superstructure, and the ACTPol receiver roughly installed within the ACT receiver cabin using the ACT-Pol Critical Alignment Mount described in Section 2.8, consideration must now be taken toward ensuring that all optical and receiver elements are aligned closely with the ideal ACT optical design constraints. The procedure for ACT+ACTPol alignment has many central similarities with the alignment of the ACT+MBAC system, though the continuous operational paradigm of the ACTPol observing strategy, described in Section 2.9, required several key process- and metrologically-oriented improvements to be made.

Generally, the ACT warm optical system is brought into critical alignment to enable the commencement of observing operations at optimal performance through a three-phase approach: primary and secondary mirror surface alignment, receiver critical alignment, and final secondary positioning. Realization of the first two alignment conditions (for mirrors
and receiver) are completed through the introduction and operation of external industrial metrology systems (without receiver operation), while the final positioning of the ACT secondary utilizes the receiver in an operational state, bringing the entire telescope optical system into final focus through the observation of a bright point source, generally a planet. Thus, to ensure that best focus and image quality of the receiver-telescope system is achieved in the final stage of alignment, it is critical that the warm optics and receiver are already in their near optimal position within the ideal Gregorian optical design described earlier in this section.

Alignment of the primary and secondary mirrors are completed in order to minimize deviation from the ideal surface prescription of the optical design. The metric by which the tolerance of ACT primary and secondary mirror alignment is defined is given by the Ruze formula. As described in (Ruze 1966), RMS errors from an ideal optical surface for a given optical collecting surface for a mirror-coupled antenna system must be minimized in order to limit loss in the forward gain of the antenna to the greatest extent practically possible. According to the Ruze equation, this relationship between antenna forward gain and RMS alignment error in the radiation-collecting optical surface is given in Equation 2.7.4 as:

\[
G(\epsilon) = G_0 e^{-((4\pi \epsilon)/\lambda)^2} \tag{2.6}
\]

where \(G(\epsilon)\) is the operational forward gain of the antenna coupled to a mirror surface of a given RMS deviation from ideal, \(G_0\) is the theoretically achievable forward gain of the antenna at zero RMS surface deviation of its coupled mirror surface, \(\lambda\) is the operational wavelength of the system, and \(\epsilon\) is the RMS deviation of the mirror surface from ideal. Thus, for \(\lambda = (c)/\nu\) for speed of light \(c\) and operational frequency \(\nu\), and defining the ratio of achievable forward gain to the theoretical forward gain limit for an ideal optical surface as \(R_{gain} = (G(\epsilon))/G_0\), we then have:
\[-\ln(R_{\text{gain}}) = -\left(\frac{4\pi \epsilon}{\lambda}\right)^2\]  

(2.7)

finally giving the RMS deviation of the mirror surface from ideal as:

\[\epsilon = \left(\frac{\epsilon}{4\pi \nu}\right) \sqrt{-\ln(R_{\text{gain}})}\]  

(2.8)

With this relation now in hand, we can consider that during the initial development of the ACT telescope for MBAC operations, an operational target of 90\% of the ideal theoretically achievable forward gain for the system was designated for the 277 GHz MBAC frequency channel (given that lower frequency channels would have more relaxed tolerances). Thus, to achieve this threshold at 277 GHz, ACT warm optical mirror alignment needed to realize a lower surface RMS than \(\epsilon \approx 27 \mu m\). ACTPol, which operates at 150 GHz and 90 GHz would thus need only reach a more relaxed tolerance under the Ruze formula to achieve the 90\% gain target: to reach the target at 150 GHz would require a surface RMS lower than \(\epsilon \approx 51 \mu m\) and 90 GHz operations would require a surface RMS lower than \(\epsilon \approx 86 \mu m\).

For the alignment of the ACT primary and secondary mirrors, as well as the critical alignment of the receiver in the ACT receiver cabin, the ACT+MBAC era saw the use of a commercially-sourced FARO laser tracker system, designed for large-scale industrial surface metrology (FARO 2017). The ACT+ACTPol era also used the FARO laser tracking system, though this was ultimately replaced with the use of a dedicated precision V-STARS photogrammetry system from Geodetic Systems, Inc (Inc. 2017). For primary and secondary mirror alignment, the FARO system was used for surface RMS characterization primarily during nighttime alignment campaigns, since given both thermal-mechanical properties of the ACT optomechanical superstructure, as well as practical operational considerations. Given that MBAC operated with cryogenics offering a roughly 300 mK bath temperature to its detectors that needed to be recycled on a maximum of 12 hour intervals, MBAC observing operations nominally took place during the night given both atmospheric conditions (lower PWV levels, etc.) and better optical performance of the telescope structure itself. Due to
diurnal heating of the entire upper moveable structure of the ACT telescope, associated mechanical deformation of the ACT telescope superstructure takes place, especially degrading both the relative positions of primary, secondary, and receiver, as well as mirror alignment quality during the daytime. Fortunately, lower ambient nighttime operational temperatures allow for thermal contraction of ACT superstructure mechanical elements, bringing both relative positions and mirror alignment back to nominal characteristics, with peak optical performance of the system. For this reason, it was most important that MBAC-era mirror alignment characterization took place at night, since these results would correspond to the optical geometry inherent to observing operations. Additionally, operation of the FARO laser tracker is more straightforward at night, when its laser can be more easily observed.

The FARO laser tracker method of ACT mirror and receiver alignment can be described as time-intensive and iterative, using the method described in (A. D. Hincks and Zhao 2008). Using the FARO system, a single set of measurements for all constituent mirrors of both primary and secondary can take over four hours, and require multiple iterations that generally need to take place over multiple nights (during which observing can not proceed). Generally, the FARO laser tracker operates by emitting a laser pulse which is reflected off of a spherically-mounted retroreflector (SMR) to measure the pulse time of flight, and thereby determines the distance to the SMR. To characterize the ACT mirrors, the FARO system is physically mounted to a fixed surface above the receiver cabin, between the primary and secondary mirrors. For primary mirror measurements, a ladder is installed to allow all mirrors to be reached during the survey by a cosmologist holding a long rod with an SMR attached to its end. A set of 10 fiducial SMRs is then installed to a selection of locations across both the primary and secondary, and at nearby fixed locations on the telescope structure itself. Calibration of the FARO with these fiducials allow for the FARO to be defined within the reference frame of the telescope, and thus make accurate measurements relative to its defined location and other fixed fiducial points around the telescope optomechanical superstructure. The survey is then completed by the cosmologist on the ladder intercepting
the laser pulse from the FARO laser tracker, and moving the SMR-rod assembly such that the SMR contacts each of the mirror vertices, as close to the manual mechanical actuator locations as possible. A measurement is then recorded upon contact with a given vertex surface, which is completed four times for each location, with mirrors measured in groups of roughly six to minimize movement of the ladder during a given survey, and fiducials measured between panel group measurements to quantify effects of thermomechanical drift of the system during the period of the measurement. This procedure is continued until the entire primary and secondary are surveyed twice. With this data set now in hand, measurements were fit in relation to the fiducial measurements while also accounting for translation, rotation, and scaling. This overall fit was then likewise fit to the ideal optical geometry of the telescope warms optical system described earlier, surface RMS for each given measurement point (orthogonal to the mirror surface) determined, and then an extrapolation computed to determine the RMS deviation from ideal at each of the mechanical actuator positions, thus giving the distance necessary to move each actuator to best approach the ideal theoretical optical geometry. Following this prescription, actuator adjustments were then made, when necessary, to the mirror vertices, and the entire survey process repeated, generally yielding an acceptable alignment result after a few iterations. An overall measurement error for the primary and secondary went as ~ 15µm and ~ 10µm for these surveys, respectively. The ACT receiver is likewise iteratively moved into an acceptable critical alignment during this FARO survey process (both MBAC and ACTPol had three fixed fiducial mounting locations machined into their respective 300K window flanges), with the entire optical reference frame established. Figure 2.28 shows a view of a FARO laser tracker-enabled survey of the ACT primary in progress, with FARO laser tracker mounting position, fiducial mounting region, and cosmologist with SMR/mirror characterization arm assembly indicated (A. D. Hincks and Zhao 2008; Dunner 2015).

Ultimately, the FARO laser tracker surface characterization method was able to offer consistent nighttime alignment results across the MBAC and (early) ACTPol operational
ACT Warm Optics Alignment:
FARO Laser Tracker Contact Surface Metrology Method

Figure 2.28: FARO Laser Tracker Contact Surface Metrology Characterization Method. View from ACT secondary mirror position of FARO laser tracker-enabled survey of the ACT primary in progress, with FARO laser tracker mounting position, fiducial mounting region, and cosmologist with SMR/mirror characterization arm assembly indicated.
Figure 2.29: Selected FARO-characterized Mirror Alignment Results (Night). FARO-characterized mirror alignment results taken at night on 09 January 2011, following the conclusion of MBAC operations, in which primary mirror survey results are shown with an RMS of 24.12\textmu m.

As described in (Swetz et al. 2011a), six surveys of the ACT primary and secondary (generally performed at the beginning and end of each operational season) showed a primary RMS in the range \(25 - 30\mu m\), and secondary RMS in the range \(10 - 12\mu m\) for nighttime measurements, or in other words, generally near or within the acceptable RMS alignment range to achieve a target of 90% forward gain for MBAC 277 GHz (and lower) frequency operations. Figure 2.29 provides a selected FARO-characterized mirror alignment results taken at night on 09 January 2011, following the conclusion of MBAC operations, in which primary mirror survey results are shown with an RMS of 24.12\textmu m.
The introduction of the ACTPol receiver to the ACT warm optics system placed a number of new requirements and operational realities that led to the development of a new procedure and system for next-generation mirror and receiver alignment metrology platform. Unlike with the daily cryogenic cycling required during MBAC operations, ACTPol would operate with a pulse-tube-backed dilution refrigeration system allowing for sub-100 mK bath temperatures without the need for regular cycling. Thus, ACTPol operations would open the ability of the ACT experiment to perform observing operations during both the night and day. This change in operational paradigm would thus result in the need for a reliable mirror alignment diagnostic that could accurately characterize the ACT mirror and receiver optical system in both daytime and nighttime ambient environments with highly repeatable results. For this purpose a dedicated photogrammetry system and characterization method was developed with Geodetic Systems, Inc. (GSI) using GSIs V-STARS photogrammetry software platform. Photogrammetry is a remote-sensing method for dimensionally characterizing a given physical environment or system by analysis of precision photographic results of a given system. Photogrammetry has a host of diverse industrial applications ranging from static dimensional analysis of both small- and industrial-scale systems, to dynamic analysis of industrial system motion. Generally, the commercial photogrammetry system developed for use on ACT by GSI functioned by placement of adhesive retroreflective targets across the ACT warm optical and ACTPol 300 K receiver window plate surfaces, with three-dimensional projection of the entire system produced by software triangulation of target positions photographed in high-resolution from a variety of positions. A full discussion of the operational principal and operation of the GSI V-STARS photogrammetry system can be found at (Inc. 2017). Figure 2.30 illustrates the survey setup for a typical ACTPol-era optical system alignment photogrammetry run. For system characterization, retroreflective targets are placed on the vertices of each mirror (above mechanical actuator positions) and at the three fiducial points on the 300 K front window plate of the ACTPol receiver, while coded retroreflective targets are placed around
the entire optical system, both on moveable mirror and receiver locations, as well as on fixed structures around the warm optical system analogous to fiducial mounting positions for FARO measurements. The coded retroreflectors are necessary for the GSI V-STARS software to automatically decode and form a reference frame for the optical system. With retroreflectors in place, a high-resolution photogrammetry camera with suitable depth of focus is then used to image the entire optical system and receiver from a variety of angles to ensure maximum coverage of all targets within a set of images. The resultant image set is then read in by the V-STARS photogrammetry software platform, which provides the resulting analytical model of the positions of the entire optical system, which is then compared to the theoretical optical design ideal to determine system alignment RMS and provide a prescription of adjustments that may need to be made to mirror and receiver positions. This procedure is then continued iteratively until a suitable alignment is achieved. The V-STARS software typically reports measurement error as low as 10μm following characterization analysis (Dunner 2015).

The speed by which the entire photogrammetry process is completed provides a strategic advantage for ACTPol operations. Unlike the hours-long, multi-day process for each survey iteration under the FARO laser tracker characterization method, nighttime photogrammetry measurements (once entire system is targetized) only take around 15 minutes. Daytime measurements take slightly longer, on the order of one-hour, given that the camera flash used needs to be of higher intensity than at night to properly image the retroreflector targets, thus requiring a longer flash recycle time. Analysis completed using the commercial GSI V-STARS software of the resultant photographic measurements generally take less than one hour to complete, meaning that alignment iterations can generally take place in direct succession, rather than waiting for analysis to be completed the next day as in the FARO case.

Selected results from ACTPol photogrammetry measurement operations are shown in Figures 2.31, 2.32, and 2.33. Figure 2.31 provides nighttime photogrammetry character-
Figure 2.30: ACT Photogrammetry Non-Contact Surface Metrology Method. Shown here is the survey setup for a typical ACTPol-era optical system alignment photogrammetry run. For system characterization, retroreflective targets are placed on the vertices of each mirror (above mechanical actuator positions) and at the three fiducial points on the 300 K front window plate of the ACTPol receiver, while coded retroreflective targets are placed around the entire optical system, both on moveable mirror and receiver locations, as well as on fixed structures around the warm optical system, allowing for the system photogrammetry characterization method described in the text.
ization results from the first ACTPol photogrammetry survey prior to ACTPol Season 1 observing operations. This survey corresponded to a primary mirror RMS of 32.95μm and secondary mirror RMS of 13.14μm. Figure 2.32 provides daytime photogrammetry characterization results from the first ACTPol photogrammetry survey prior to ACTPol Season 1 observing operations, as well as daytime results taken prior to ACTPol Season 3 operations, for comparison. These surveys corresponded to a primary mirror RMS of 77.41μm for the 2013 daytime measurement example and primary mirror RMS of 73.80μm for the 2015 daytime measurement example. Figure 2.33 illustrates the capability of the GSI V-STARS photogrammetry software to rapidly produce a fully-rendered 3D projection of positions of the entire ACT optical system, including receiver, for target and coded-target positions. This 3D projection can be imported into mechanical engineering CAD software, such as Solidworks, for manipulation and comparison with ACT 3D mechanical models.

Following the results shown for the initial ACTPol Season 1 photogrammetry survey, mirror alignment and receiver position adjustments were made to enable final ACTPol Season 1 nighttime primary mirror alignment RMS to reach 28μm, and secondary mirror alignment RMS to reach 13μm. A characterization of half of the ACT primary mirror using the previous FARO laser tracker method was also completed, and yielded comparable results to the photogrammetry system, with a primary mirror RMS measured to be 30μm. It should be noted, that nighttime inter-seasonal alignment did not vary significantly from the final alignment position of the ACT primary shown in Figure 2.29 following the end of MBAC operations in 2011, and that when ACTPol operations commenced in 2013, indicating positive mechanical alignment consistency for nighttime operations in the long term. Recalling from our earlier discussion of the Ruze condition, since reach the target of 90% forward gain at 150 GHz would require a surface RMS lower than $\epsilon \approx 51\mu m$ and 90 GHz operations would require a surface RMS lower than $\epsilon \approx 86\mu m$, for nighttime operations, both photogrammetry and FARO results indicated that ACTPol observing operations would satisfy these requirements for both ACTPol operational frequencies. Considering daytime
Figure 2.31: ACT Selected Photogrammetry-characterized Mirror Alignment Results (Night). Nighttime photogrammetry characterization results from the first ACTPol photogrammetry survey prior to ACTPol Season 1 observing operations. This survey corresponded to a primary mirror RMS of 32.95µm and secondary mirror RMS of 13.14µm.
Figure 2.32: ACT Selected Photogrammetry-characterized Mirror Alignment Results (Day). Daytime photogrammetry characterization results from the first ACTPol photogrammetry survey prior to ACTPol Season 1 observing operations, as well as daytime results taken prior to ACTPol Season 3 operations, for comparison. These surveys corresponded to a primary mirror RMS of 77.41μm for the 2013 daytime measurement example and primary mirror RMS of 73.80μm for the 2015 daytime measurement example.
Figure 2.33: 3D Photogrammetry Projection of Entire ACT Warm Optical System. Illustration of the capability of the GSI V-STARS photogrammetry software to rapidly produce a fully-rendered 3D projection of positions of the entire ACT optical system, including receiver, for target and coded-target positions. This 3D projection can be imported into mechanical engineering CAD software, such as Solidworks, for manipulation and comparison with ACT 3D mechanical models.
operation, photogrammetry results indeed indicated thermomechanical deformation of the optomechanical superstructure, thus degrading primary alignment during the day, though results were fairly consistent across seasons as shown in Figure 2.32. Nonetheless, for 90 GHz operations the 90% forward gain target would still be met with these results, for example the daytime primary RMS of 77.41µm from Season 1. Furthermore, for daytime operations at 150 GHz, this alignment would still correspond to a forward gain of ~ 79%. We will see in later chapters, that although this thermomechanical deformation during daytime operations did have an impact on beam quality during the day, the ACT optomechanical superstructure was still able to make scientifically impactful CMB maps during daytime observations.

Additionally, with photogrammetry shown to be a reliable system for ACT optical metrology, it is possible to conceive of future-generation telescope upgrades that would allow for fully-automated ACT optical initial alignment or the potential for adaptive optical elements. Given that a single photogrammetry camera must be physically moved around the telescope structure to yield sufficient overlapping images for the V-STARS software to analyze the retroreflective targets from various angles, operations would need to cease while the camera is moved to acquire these images. With multiple photogrammetry cameras mounted around the entire warm optical system, the need for human intervention to move and acquire images from a variety of angles would be mitigated. Therefore, if ACT observations are not shown to be significantly degraded by excess loading by the presence of permanent small-scale photogrammetry targets covering a small percentage of the reflective surfaces (thus far observations have not been shown to be significantly degraded with targets deployed, though they are generally removed for seasonal science operations), the entire system could acquire real-time photogrammetry data on a continuous basis. Were this then developed in tandem with remotely controlled motorized actuators (replacing existing mirror vertex manual actuators), one could imaging the ability to dynamically alter mirror positions to overcome some of the deformation associated with thermomechanical changes.
to the telescope structure, maintaining more consistent mirror alignment throughout a given
24-hour cycle.

For the 2013 ACTPol Season 1 photogrammetry survey, the initial placement of the
ACTPol receiver within the ACTPol Critical Alignment Mount (CAM), which will be de-
scribed further in Section 2.8, attempted to meet alignment conditions in which the ACTPol
boresight would be aligned \(\sim 33\) mm below the physical center of the receiver cabin window,
with 300 K cryostat front flange surface placed within the optical system \(\sim 30\) mm closer to
the ACT secondary mirror in the z-axis than the corresponding MBAC 300 K front flange
placement. Following rough installation, the initial ACTPol receiver position fixed to the
ACTPol CAM was found to be within one centimeter of the focus position. In able to allow
for redundancy in the measurements, both FARO and photogrammetry results were used
for this initial ACTPol receiver alignment, ultimately showing that the receiver was aligned
within 1.5 mm of ideal in the x, y, and z axes using the FARO laser tracker (surveyed over
half of the primary), and using photogrammetry, the alignment was shown to \(< 5\) mm from
the ideal position in all three axes, with a tip/tilt of 1 mm over 30 cm. It was also observed
that the physical locking of ACTPol receiver mounting hardware down to the ACTPol CAM
for final receiver mounting did have an effect to introduce slight changes in receiver align-
ment at the sub-mm level between the initial ‘unlocked hardware’ mounting position, and
the final ‘locked hardware’ mounting position - given the large-scale hardware necessary
to mount a massive receiver like ACTPol it would be difficult to exceed this performance.
Subsequent ACTPol observing seasons were able to achieve receiver alignment within 1 mm
of the ideal position.

Finally, with the ACT primary and secondary mirrors aligned to an acceptable RMS
deviation from ideal, and the ACTPol receiver in an acceptably position relative to the ideal
optical design prescription, the final focusing of the ACT telescope is able to take place. To
achieve final focus, the ACTPol receiver must be brought into observing operations, and
then a bright point source, in this case planets, are observed while the secondary position is
remotely adjusted to achieve maximum detector response and image quality. As described in (Swetz et al. 2011a), motorized linear actuators coupled to the secondary allow for its positioning ± 10 mm in the x and y axes, as well as rotations of ±1° in azimuth and elevation. Following this procedure, which can be remotely controlled through from the ACT control container, the ACT+ACTPol system is fully aligned to allow for the commencement of observing operations!

2.8 ACTPol-Era Site Infrastructure and Logistics

As indicated earlier in this chapter, the development of a second-generation receiver upgrade in ACTPol, and thus, extended operations of the Atacama Cosmology Telescope offered an opportunity for an extension and improvement of both ACTPol receiver deployment protocols, and support infrastructure. In the following sections, principal site access and development upgrades, as well as receiver deployment, critical mobility and mounting systems all were developed and implemented for ACTPol operations. Resulting from each of these upgrades, the ACT+ACTPol era would result in drastically-altered paradigms for the deployment, operations, and in-situ upgrades now achievable with these systems.

2.8.1 CONICYT Parque Astronómico de Atacama and Site Access

The beginning of ACTPol Season 1 deployment and commencement of observing operations after first light in mid-2013 corresponded to two other milestones in terms of the development of improved logistics for observatory operations in the region of the Chajnantor and the surrounding region. First, in March 2013, the Atacama Large Millimeter Array, or ALMA, began full operations, with an inaugural ceremony taking place at the ALMA high-altitude Chajnantor site shortly after the arrival of the first ACTPol deployment shipment, including the arrival of the ACTPol receiver to the ACT site on Cerro Toco. Second, building on earlier small-scale land concessions granted to CONICYT from the Chilean Federal
Government for the development of telescope facilities in the greater Chajnantor region, including the ACT site itself, in 2013 the Chilean government increased the scope of these initial concessions, forming the Parque Astronómico de Atacama. The Parque Astronómico de Atacama, administered by CONICYT solidified as a protected area the longstanding history of astronomy in the greater Chajnantor region, while looking to the future to extend the contemporary Chilean role as a global center for modern research in astronomy and cosmology. Figure 2.34 illustrates this 50 year land concession, which encompasses all of the existing telescope facilities in the Cerro Toco, Cerro Chajnantor, Chajnantor Plateau, and Pampa la Bola region in an area covering 363.81 km². The Parque, with ALMA land concession shown at center, has begun identifying suitable sites for next-generation telescope facilities, indicated in colored circles on the map.

The establishment of the large-scale, long-term concession for the Parque Astronómico de Atacama also provided a vehicle for CONICYT and other Chilean federal agencies to protect the uniquely optimal observing conditions inherent to the region through the passage of legislative and regulatory measures that formalize and extend light pollution restrictions that already exist across the northern Atacama. Additionally, CONICYT, working in conjunction with the Chilean Ministry of Telecommunications, formally established a fully radio quiet region within a 30 km radius of the Parque, with an additional 120 km radius defined, within which any radio licensing would need to be coordinated with the Ministry for technical approval. Specifically, the radio quiet area limits broadcast frequencies, which must be less than 31.3 GHz within the 30 km radius. Beyond regulatory definitions, the Parque also formally enabled CONICYT to continue and expand its earlier-generation work to enhance security and preserve natural resources in the region, ensuring that any resource exploitation or management in the region would not impede scientific operations, while also working in support of educational and development programs to underscore the importance of and expand work with indigenous communities, further highlighting the rich cultural
heritage of the northern Atacama region, and further integrating Chile’s historical roots with its burgeoning future as a leader of multinational science and technology development.

The ACTPol collaboration, through its on-site deployment and CMB science observing operations, ably demonstrated positive cooperation with CONICYT activities associated with the development of the Parque Astronómico de Atacama. As mentioned earlier, work was completed during ACTPol field operations to work directly with officials from CONICYT and those dispatched by the Chilean federal government to further develop the entire Chajnantor-Toco region into an area even more attractive to multinational astronomy collaboration research, including aiding these officials in studies for the feasibility and operational development path for increased Chilean federal infrastructure investment, ranging from improved access roads, telecommunication infrastructure, and diversified energy resources in support of research facilities across this region of the Atacama. A key early improvement under the auspices of the Parque Astronómico de Atacama was site access improvements, including gated access to the Parque grounds and increased road grading and clearing operations and coordination (in comparison to the MBAC era), offering improved operational efficiency and resumption of nominal site operations following occasional weather events, including snowfall the impeded the commencement of ACTPol first light in 2013, and requiring several days of snowshoeing to the site to maintain operations, as shown in Figure 2.35. During ACTPol operations, continued coordination and planning with CONICYT has allowed for the possibility of further improved site access through road maintenance, energy access, and telecommunications, some of which will be briefly mentioned under the planning for future-generation cosmology facilities, including Advanced ACTPol and the Simons Observatory, in later chapters.
Figure 2.34: Physical Extent and Layout of Parque Astrónomico de Atacama. Shown is the 50 year land concession, which encompasses all of the existing telescope facilities in the Cerro Toco, Cerro Chajnantor, Chajnantor Plateau, and Pampa la Bola region in an area covering 363.81 km$^2$. The Parque, with ALMA land concession shown at center, has begun identifying suitable sites for next-generation telescope facilities, indicated in colored circles on the map. (Bustos 2014)
Figure 2.35: Illustration of Occasional Snowfall Events Impeding ACTPol Site Operation. Shown in the images above is the impact of a May 2013 snowstorm on Cerro Toco and the Chajnantor Plateau that required several days of high-altitude snowshoeing to reach the ACT site to maintain operations. Further logistical improvements and road-clearing coordination under the development of the Parque Astronómico de Atacama have helped to improve site access resiliency to weather events in comparison to the MBAC era, though further coordination and planning will yield further increases in operational efficiency.
2.8.2 Receiver Integration: Site High Bay and ALMA Operations Support Facility (ALMA-OSF)

When fully integrated, the ACTPol receiver cryostat has a cylindrical extent with dimensions of 1.5 m in length and 1.1 m in diameter, with full dimensional envelope slightly larger than this, given extensions from the cylindrical baseline including the ACTPol dilution refrigeration system and pulse tube assemblies, as well as base mounting hardware and readout conduit for Multi-Channel Electronics crates, all of which are described in the next Chapter. Ultimately, the ACTPol receiver is roughly 10% longer and 20% wider than MBAC, and more massive, with a fully-integrated mass of roughly 820 kg. This increase in instrument dimensional envelope and mass led to the requirement for logistical upgrades to the site both for receiver integration and deployment operations. Additionally, a shift in operational paradigm was made in the transition from MBAC to ACTPol operations: namely, the ACTPol receiver would not be shipped to North America for integration of each set of polarimeter array package and associated optomechanical subassemblies between each observing season in order to increase operational efficiency and maximize observing time when possible. This contrasts from the operational concept used in the MBAC era, in which the MBAC receiver was returned to North America for detector and optics integration between each season, until all three sets of detectors and optics were completed with receiver fully-integrated in MBAC’s third observing season.

Described in more detail in later chapters, generally the ACTPol receiver was designed for modular deployment of its three polarimeter array packages and associated anti-reflective coated, metamaterial, high-purity silicon optics. The first season of ACTPol operations would observe with a single 150 GHz polarimeter array (PA1) deployed, season two with dual 150 GHz polarimeter arrays deployed (PA1 and PA2), and third season with a multichroic polarimeter array deployed, with simultaneous 150 GHz and 90 GHz sensitivity (PA1, PA2, and PA3), with this stage representing the instrument operating at full deployment. Given the larger envelope of the ACTPol receiver, inter-seasonal receiver upgrade
deployments could not be achieved in the aforementioned ACT ‘white container,’ which had been used as a dual-use machine shop and array integration facility in the MBAC era. To accommodate ACTPol receiver integration operations on-site, a new high-bay facility was developed and constructed on the ACT site, directly adjacent and with internal access to the the machine shop ‘white container.’ This structure would provide both much needed laboratory, storage, and work space for receiver integration operations, as well as provide dual axis crane space, to lift and manipulate the various large-cylindrical cryostat shields comprising the ACTPol receiver. Figure 2.36 illustrates high-resolution Solidworks design renderings of critical operational upgrade facilities and systems, including the ACT site high-bay receiver integration facility, as well as upgraded receiver installation systems for safely moving and installing the fully-integrated ACTPol receiver into its final critical alignment position within the ACT warm optical design in the receiver cabin of the ACT telescope superstructure. Pre-designed human solid model renderings are included to indicate scale, with personnel, receiver, and installation systems dynamically examined under three-dimensional motion study within the Solidworks environment to better identify and mitigate any potential operational limitations with the ACTPol-era site upgrades. Figure 2.37 illustrates images of the ACTPol receiver undergoing first season integration and deployment operations in early 2013. A large-scale rolling entry door allows for the receiver installation systems to be interfaced directly between high bay and telescope superstructure, and provides clearance for heavy equipment to enter the high bay workspace to deliver and move heavy equipment, including the ACTPol receiver. During the development of ACTPol, collaboration with both CONICYT and personnel from the nearby ALMA experiment on the Chajnantor Plateau also afforded ACTPol to have a more suitable facility for precise work on the re-integration and functional characterization (i.e. continuity checking) of the ACTPol polarimeter array packages. Figure 2.38 illustrates the ACTPol polarimeter arrays under inspection and re-integration following shipment to Chile within the ALMA medium-altitude Operational Support Facility, or OSF, which allowed clean-room laboratory space
for the ACTPol polarimeter arrays to be interfaced with in an operational environment more suitable for work sensitive detector systems than the ACTPol field site could afford at high-altitude. Transport of the polarimeter arrays between the ACT site and the ALMA OSF was completed through a careful, low-velocity drive on the ALMA and Chajnantor Plateau roads to ensure array damage was mitigated during transport.

2.8.3 Receiver Installation Systems

When fully integrated, with all pre-installation cryogenic and optical performance characterization performed inside and at the entrance of the ACT site high bay, the ACTPol receiver would then undergo final installation and systems deployment to the receiver cabin within the ACT telescope superstructure. Given the large dimensional envelope and mass than MBAC, ensuring the safe and accurate integration of ACTPol with the ACT telescope superstructure required the development of upgraded receiver deployment and alignment mounting systems. These systems, which were all designed to work in direct consort with one another, included the ACTPol Receiver Alignment Mechanism (RAM), RAM Access Mobility Platform (RAMP), and Critical Alignment Mount (CAM). These three systems would allow the receiver to be conveyed from the high bay to installation in the receiver cabin, with the RAM tasked with moving the receiver to the outer ground screen entrance near the telescope pedestal, the RAMP enabling the RAM to move between the ground and receiver cabin, and the CAM allowing the ACTPol receiver to be brought (iteratively) into final alignment position. The design and installation procedure described for these systems, as follows, is illustrated in Figure 2.39, which provides (reading from top left, to bottom right) images of the entire receiver deployment procedure, from transfer to telescope base using the RAM system, transfer to receiver cabin using the RAMP system, and final mounting and critical alignment with the CAM system.
Figure 2.36: ACTPol Pre-Deployment Site Layout and Receiver Installation Design Renderings. Illustrated are high-resolution Solidworks design renderings of critical operational upgrade facilities and systems, including the ACT site high-bay receiver integration facility, as well as upgraded receiver installation systems for safely moving and installing the fully-integrated ACT-Pol receiver into its final critical alignment position within the ACT warm optical design in the receiver cabin of the ACT telescope superstructure. Pre-designed human solid model renderings are included to indicate scale, with personnel, receiver, and installation systems dynamically examined under three-dimensional motion study within the Solidworks environment to better identify and mitigate any potential operational limitations with the ACTPol-era site upgrades.
**Figure 2.37:** ACTPol Receiver Integration and Deployment Operations in ACT Site High Bay Facility Upgrade. The images shown are of the ACTPol receiver undergoing first season integration and deployment operations in early 2013. A large-scale rolling entry door allows for the receiver installation systems to be interfaced directly between high bay and telescope superstructure, and provides clearance for heavy equipment to enter the high bay workspace to deliver and move heavy equipment, including the ACTPol receiver.
Figure 2.38: ACTPol Polarimeter Array Re-Integration and Functional Characterization at the ALMA Operational Support Facility (OSF). The images illustrate the ACTPol polarimeter arrays under inspection and re-integration following shipment to Chile within the ALMA medium-altitude Operational Support Facility, or OSF, which allowed clean-room laboratory space for the ACTPol polarimeter arrays to be interfaced with in an operational environment more suitable for work sensitive detector systems than the ACTPol field site could afford at high-altitude. Transport of the polarimeter arrays between the ACT site and the ALMA OSF was completed through a careful, low-velocity drive on the ALMA and Chajnantor Plateau roads to ensure array damage was mitigated during transport.
Figure 2.39: ACTPol Full Receiver Cabin Installation and Critical Alignment Procedure Imagery. (Reading from top left, to bottom right) Images of the entire receiver deployment procedure, from transfer to telescope base using the RAM system, transfer to receiver cabin using the RAMP system, and final mounting and critical alignment with the CAM system, taken during ACTPol Season 1 deployment operations in 2013.
2.8.3.1 Receiver Alignment Mechanism (ACTPol RAM)

The ACTPol Receiver Alignment Mechanism (RAM) is illustrated in Figure 2.40. All
designed elements of the RAM assembly were fabricated from 1018 alloy steel to ensure
for mechanical robustness of the system under the receiver load when encountering forces
associated with its motion across the site, with principal frame members constructed from
3-inch square steel channel profile beams. In order to convey the ACTPol receiver to the
ACT telescope for receiver cabin installation, several design variants were developed, with
a merger of two design concepts, one using desert-capable, all-terrain tires for motion across
the site terrain, and the other using dual rail systems to move ACTPol between the high
bay and telescope superstructure. Ultimately, both design variants were integrated into the
final RAM design, giving the RAM both tire and rail motion capabilities, given concerns
with changing, uneven terrain across the site creating a potential impediment to smooth rail
motion over the entire site travel extent. The low-profile characteristics of the RAM design,
with rail wheel axes set below the RAM body elements, were driven by the tight vertical
clearance between the receiver cabin floor and ceiling below the receiver cabin window.
Additionally, the design needed to provide the capability for the receiver to rotate along the
optical axis such that receiver dimensional extensions, namely the dilution refrigerator and
pulse tube assemblies, could clear this ceiling location before the receiver was moved to the
rear of the receiver cabin for mounting. To enable this, two semicircular steel flanges were
fabricated and attached to the front and rear flanges of the ACTPol 300K cryostat (with
stops at each end), so that these flanges would fit within dual roller channels at the ends
of the RAM assembly. With these semicircular flange-roller channel assemblies integrated,
the ACTPol cryostat could be easily rotated by hand. The ultimate horizontal extent of
the RAM assembly was set by the spacing of the rail assemblies, which were fabricated to
match the gauge (33 inch gauge) of the receiver cabin rail spacing already existing in the
MBAC era. These rail wheels were selected to have a 90-degree-channel profile to match
the 90-degree rail profile. To ensure that the receiver would not rotate or decouple from
the RAM assembly, flanges were included in the design on all sides of the RAM to allow for mounting strap interfacing. Finally, mechanical roller jacks were installed with actuator reach greater than tire assembly height, allowing the entire assembly to be lifted in place to transfer to and from tire/rail wheel operation.

2.8.3.2 RAM Access Mobility Platform (ACTPol RAMP)

With the ACTPol cryostat fully integrated with the RAM assembly, the receiver would then be slowly pushed (in all-terrain tire mode) from inside the high bay to the point in which the ACTPol RAMP would begin. The ACTPol RAMP system is illustrated in Figure 2.41. The RAMP assembly has three subassemblies: two 90-degree channel profile interlocking
ground rail assemblies (fabricated from 1018 alloy steel channel and plate), and an interface ramp to move the RAM-mounted ACTPol from the ground rails to the receiver cabin, the base ramp of which was a commercially-sourced ramp assembly for truck loading, rated for masses greater than the mass of the ACTPol-RAM assembly). Each of the dual ground rail assemblies are 3 meters in length, with male and female sheet metal features with locking pin flanges, allowing the two sections to remain secured to each other when the ACTPol+RAM assembly rolls between them. The rail assemblies also have handles so that the rail can be moved to continue the conveyance of the ACTPol+RAM assembly: once ACTPol+RAM is moved forward off of one rail, that rail is then picked up and moved to interlock in front of the second rail assembly, and so on. In the multiple deployments of the ACTPol receiver, the flexible design of the RAM and RAMP systems allowed for multiple motion configurations. In one iteration, the ACTPol+RAM assembly was pushed on tires to the RAMP rails and transferred onto the rails using the vertical actuator jacks before moving along the track. In another iteration, the tires were again used, but a chain fall mounting point on the ACT ground screen was used to lift the receiver for tire to rail wheel motion. Finally, the ground rails were also used to convey the assembly from the high bay to the ramp-rail interface assembly, again using the chain fall, for repositioning of the rail angle to ensure smooth rail-to-ramp transfer. When the ACTPol-RAM assembly reaches the interior of the ACT ground screen area, the telescope is moved to -30° elevation, and the ramp-rail subassembly is then attached to the receiver cabin using mounting hooks and a receiver cabin interface flange, with subassembly further secured with mounting straps. The ACTPol-RAM assembly is then attached to a motorized winch system (attached by a steel subassembly to the rear receiver cabin wall, between the two rear vertical members of the ACTPol CAM assembly), and with safety straps deployed, moved up the ramp-rail subassembly until it is entirely inside the ACT receiver cabin. The ramp-rail subassembly is then removed, receiver cabin doors closed, ACTPol Anti-Roll-Out-Door-Device (ARODD) steel bar installed across the receiver cabin door frame, and then the entire telescope is moved into horizontal servicing.
position. The ACTPol receiver is then allowed to rotate to allow for dilution refrigerator and pulse tube rotation and moved on the receiver cabin rails to the rear of the receiver cabin. The receiver is then attached to three mechanical chain falls, and lifted to allow for RAM decoupling. The RAM is finally moved to the front of the receiver cabin, where it is subsequently removed via the ramp-rail assembly following installation of the CAM, when ACTPol again is mechanically fixed in place, allowing for telescope motion again. This entire motion process from high-bay to receiver cabin has been completed in less than an hour if all support elements are pre-staged, and motion from ground to receiver cabin once at the end of the ramp-rail subassembly takes less than five minutes, indicating operational improvements in receiver installation time in comparison to the MBAC-era.

2.8.3.3 Critical Alignment Mount (ACTPol CAM)

With the ACTPol receiver mounted in space within the ACT receiver cabin, it is finally fixed in place using the ACTPol Critical Alignment Mount, or CAM. The ACTPol CAM design concept is illustrated in Figure 2.42. The ACTPol CAM assembly nominally-uses aluminum 6061 alloy 6-inch-u-profile channel for the principal structural members of the assembly, which were deemed sufficiently robust for ACTPol operational mounting using Solidworks simulation software packages to perform finite element analyses. Given the horizontal width of the ACTPol cryostat, the ACTPol CAM must be assembled in place, since the ACTPol+RAM assembly would not have horizontal clearance to move beyond the front vertical members of the CAM during installation, and additionally, this larger size required a relatively lower nominal mounting position of the cryostat compared to MBAC. The larger size of the ACTPol receiver did not allow for usage of elements of the MBAC receiver cabin mounting structure, though its four vertical u-channel aluminum beams were recycled in the redesign and fabrication process given that they have receiver cabin receiver mount interface flange locations set in their design. With the ACTPol receiver suspended on by its three chain fall locations, l-profile receiver interface flanges are installed (using
Figure 2.41: ACTPol RAM Access Mobility Platform (RAMP) Design and Assembly. (Annotated)
3/4-inch steel hardware with locking screws) directly to a set of bulkheads on each side of the ACTPol receiver. The remaining receiver cabin interface vertical and cross-bracing members are then installed, followed by diagonal member that is set to bring ACTPol into near its nominal mounting position under critical alignment within the optical design of the telescope warm optics. On these diagonal members, supporting both sides of the receiver, are mounted planar phosphor-bronze bearings to enable improved motion during ACTPol receiver alignment. With all of these principal CAM members now in place, receiver alignment can occur (using either the FARO laser tracking method, or the photogrammetry methods described earlier in this chapter). The CAM allows for motion in five axes: the x, y, and z, axes of the ACT warm optics design, and also allows for limited ‘front-back’ (yz-plane) rotation, and ‘side-to-side’ (xz-rotation). Motion in these axes on the CAM are enabled by the three chain falls, as well as by two pneumatic linear actuator jacks for linear motion in the z-axis (line of sight), and x-axis by dual ACME wide-thread-gauge and flange subassemblies attached to the two front vertical CAM receiver cabin interface members. Loose mechanical tolerances for all CAM assembly components allow for the system to reach a sufficiently-wide dimensional parameter space (e.g. the receiver interface brackets have 4-inch long, 1-inch wide channeled interfaces for receiver positioning in a variety of locations) to reach critical alignment and also overcome overconstraint in the mechanical design. In practice, the ACTPol CAM has performed remarkably well during installation, often reaching sub-centimeter deviations from the ideal x, y, z position of the receiver in the telescope optical design, and only requiring a few hours of iteration to reach sub-millimeter alignment deviation from ideal.

2.9 Overarching Strategy for ACT Observations

With all ACT+ACTPol warm optical critical alignment complete, and logistical considerations taken into account for the commencement of ACTPol observing operations, we can now frame some of the central characteristics of ACTPol observations, described in later
Figure 2.42: ACTPol Critical Alignment Mount (CAM) Design and Assembly. (Annotated)
chapters. First, whereas the total ACT telescope superstructure mass is 52 t, the upper moveable structure, housing the ACT warm optics, optomechanical superstructure, inner ground screen, and receiver cabin has a mass of 40 t. From Table 2.2, this massive moveable ACT+ACTPol telescope superstructure has an azimuth range of ±220°, maximum azimuth velocity of 2°/second, and maximum azimuth acceleration of 19°/second². Furthermore, the operational reachable elevation range is 30.5° – 60°, and with maximum elevation velocity going as 0.2°/second. Throughout the observation of ACTPol calibration targets and CMB fields, both design and observational strategy is selected to ensure that systematic and atmospheric effects do not contribute to the pickup of signals with scan synchronicity. In particular, the ACT+ACTPol warm optics, optomechanical superstructure, and receiver are fixed relative to one another and moved as a single optical system to ensure that signals are not introduced to the detectors associated with a dynamic optical environment. Likewise, this entire warm optics and receiver chain are used to observe ACTPol CMB fields by moving the telescope moveable structure to a given elevation and scanning back and forth in azimuth with elevation held fixed, at a rate of 1.5°/second, with 0.4 second turnarounds, where each scan ranges from 10-20 seconds in total duration. As given in (Swetz et al. 2011a), this rate is selected such that the ACT beam is moved on timescales faster than the 1/f knee of the low frequency noise and slower than the detector time constants, allowing observed CMB signal to be distinguished from signal contributed from detector and atmospheric drifts. Given fluctuations in the airmass through which ACTPol observes, observing in azimuth at a constant elevation is effective at reducing the impacts of these fluctuations by performing observations within each scan looking at as constant an airmass as possible, thus stabilizing the amount of loading from atmospheric radiation. In practice, to take into account impacts from changing loading conditions when observing through airmasses at various elevations, ACTPol detector biases are modulated and time constants checked to determine the effect of loading during observations at a given elevation. Additionally, as illustrated in 2.43, ACTPol observations are performed as described at constant elevations
to achieve cross-linking at multiple parallactic angles by observing fields as they rise and set in their rotation around the South Celestial Pole, on the east and west side of the South Celestial Pole, respectively. Using this approach instrumental and celestial polarization are separated, and, as described in (Tegmark 1997) is necessary to remove $1/f$ striping in resultant CMB maps. Ultimately, ACTPol CMB fields map out an annular region on the sky relative to the South Celestial Pole, as illustrated (Swetz et al. 2011a; Tegmark 1997; Thornton et al. 2016).

As described in Section 2.2, the location of the Atacama Cosmology Telescope site has a number of distinct advantages for observing and achievable science. As a mid-latitude ($\sim 23^\circ$ South) site, the location and achievable sky coverage of ACT allows for observing overlap with a myriad of multi-wavelength observatories for follow-up observations, which allows for increased data richness and expands the range of achievable science goals. Figure 2.44 illustrates the maximum observable range of sky reachable under ACTPol observing operations. This range, illustrated as the light section of the all-sky map shown covers $\sim 25,000 \text{ deg}^2$, allowing significant sky overlap with many leading astrophysical and cosmological observing facilities, including all contemporary observatories operating on and around the Chajnantor Plateau (e.g. ALMA, APEX, ABS, PolarBear, CLASS, NANTEN, ASTE), as well as Gemini (Chile), SDSS-BOSS, VLT, and others. Planned ACTPol Deep Field target regions are indicated by red circles. Prior to the commencement of ACTPol operations, which ultimately achieved three observing seasons in 2013, 2014, and 2015, three distinct observing regimes were considered: (i) ACTPol Deep, which would cover $\sim 600 \text{ deg}^2$, (ii) ACTPol Wide, which would cover $\sim 3500 \text{ deg}^2$, and (iii) ACTPol Ultra-Wide, which would potentially cover $\sim 60\%$ of the entire sky. These three regimes would be fundamentally enabled by the introduction of both day and night operations accessible to ACTPol, which would operate with a sensitivity projected to be nearly four-times that of MBAC provided by a three-times colder bath temperature, two-times the number of detectors operating at 150 GHz, and improved optical throughput, among other factors, which will be described
Figure 2.43: Illustration of ACTPol CMB Field Observing Strategy. ACTPol observations are performed as described at constant elevations to achieve cross-linking at multiple parallactic angles by observing fields as they rise and set in their rotation around the South Celestial Pole, on the east and west side of the South Celestial Pole, respectively. Using this approach instrumental and celestial polarization are separated, and, as described in (Tegmark 1997) is necessary to remove $1/f$ striping in resultant CMB maps. Ultimately, ACTPol CMB fields map out an annular region on the sky relative to the South Celestial Pole, as illustrated. (Swetz et al. 2011a; Tegmark 1997; Thornton et al. 2016). Illustration courtesy of M. Niemack (Niemack 2008)
in the next two chapters. Ultimately, we will present in later chapters the description of the final ACTPol observing fields performed, in which an early emphasis was placed on deep field observing strategies, followed by the introduction of wide field observing strategies.

2.10 Summary

Throughout this Chapter, we have been able to view the geographic, scientific, and logistical factors that led the Atacama Desert region of northern Chile to become a preeminent location to host modern, large-scale experimental platforms dedicated to the study of astrophysical and cosmological phenomenon. A particular attention was placed on the proper historiographic contextualization of these modern facilities - most notably the principal driver for this dissertation manuscript, the Atacama Cosmology Telescope and its second-generation receiver ACTPol - within the broadest view of the regions ethnographic record. Such an approach is fitting, given that the primary scientific driver of the Atacama Cosmology Telescope and its three generations of constituent receivers is to enable the international scientific community to effectively probe the nature of our cosmic origins within the Universe - a lofty objective that would be as well recognized by the first skyward-gazing human beings to reach this barren region of South America as it is by contemporary populations around the globe. In the three Chapters, which follow, our focus will shift to the design, operation, and performance characteristics of the integrated assembly of critical space technologies, which enabled the ACTPol receiver to extend our understanding of the early Universe in this same spirit, in this case through the mapping of the temperature and polarization anisotropies of the Cosmic Microwave Background at small angular scales.
Figure 2.44: Maximum Observable Range on Sky of ACTPol Observations. Here, the maximum observable range of sky reachable under ACTPol observing operations is shown. This range, illustrated as the light section of the all-sky map shown covers \( > 25,000 \text{ deg}^2 \), allowing significant sky overlap with many leading astrophysical and cosmological observing facilities, including all contemporary observatories operating on and around the Chajnantor Plateau (e.g. ALMA, APEX, ABS, PolarBear, CLASS, NANTEN, ASTE), as well as Gemini (Chile), SDSS-BOSS, VLT, and others. Planned ACTPol Deep Field target regions are indicated by red circles.
### ACT Location

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### ACT Telescope Characteristics

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### ACT Optical Design Characteristics

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### Table 2.2: ACT Warm Optomechanical Superstructure Characteristics (Swetz et al. 2011a)
Chapter 3

ACTPol: A Millimeter-Wavelength, Polarization-Sensitive Receiver for the Atacama Cosmology Telescope

The ship went on with solemn face;
to meet the darkness on the deep,
the solemn ship went onward.
I bowed down weary in the place;
for parting tears and present sleep,
had weighed mine eyelids downward.

The new sight, the new wondrous sight!
the waters around me, turbulent,
the skies, impassive o’er me,
calm in a moonless, sunless light,
as glorified by even the intent
Over the course of Chapters 1 and 2, we have examined several overarching thematic elements. Throughout Chapter 1, we considered the manner by which theoretical predictions and data gathered via subsequent discovery and empirical characterization of the Cosmic Microwave Background (CMB) during the twentieth century became key drivers of technologies comprising twenty-first century experimental cosmology platforms, including those able to measure and constrain the temperature anisotropies of the CMB at small-angular scales, including the Millimeter Bolometer Array Camera, or MBAC. During Chapter 2, we examined the broad geopolitical, historiographic, and technical drivers that led to the ultimate development of the Atacama Cosmology Telescope site near the summit of Cerro Toco in the Atacama Desert of Northern Chile, as well as the pragmatic design considerations that led to the evolution of the ACT telescope optical superstructure and site support infrastructure to accommodate the transition to a second-generation ACT receiver.

Certainly, it would be an over-simplification to claim that the technology developed to realize this resultant second-generation ACT receiver would merely reflect a system designed within a parameter space yielded though the consideration of characteristics ranging from advanced areas of theoretical cosmology or rudimentary logistical concerns. Of course, these considerations do represent the primary factors leading to the development of next-generation experimental cosmology technologies, but to move fundamental understanding within the field forward through empirical observations of meaningful impact, the core approach of (in this case) space technology development must be one of bidirectional optimization. In this manner, bidirectional optimization of space technology development within experimental cosmology is achieved by allowing theoretical predictions and prag-
matic realities define a broad framework under which a baseline technology is defined, and by incorporating strategic risk within the development process, which allow novel systems to be developed through the consideration of subsystem technologies perhaps not immediately associated with observations connected to the core theoretical discipline, which thus lead to transformational observational results that inform the next-generation of theoretical standards. Such a paradigm is not unique to the discipline of experimental cosmology, though the field of instrumentation development for cosmological observation readily exemplifies this fundamental dynamic.

It is within such a lens of optimization that we consider the development of ACTPol: A Polarization-Sensitive, Millimeter-Wavelength Receiver Upgrade for the Atacama Cosmology Telescope. Given the scale and complexity of the fully-integrated receiver system, we will consider the development of all constituent instrumentation comprising ACTPol, partitioned across two chapters. Broadly, Chapter 3 will focus on the design and integration of the ACTPol cryostat, optomechanical subassemblies, interface electronics, and receiver cryogenics subsystems, while Chapter 4 will provide a detailed characterization of the three polarimeter array package subassemblies, which, taken together, comprise the ACTPol focal plane in its entirety.

For the moment, we will constrain our focus on Chapter 3, which is organized across two thematic areas, which aim to define the overarching critical design flow characteristics for ACTPol space technology development at large, and also provide an overview of all ACTPol subsystem instrumentation comprising the fully-integrated ACTPol cryostat, apart from the polarimeter array packages comprising the ACTPol focal plane. Section 3.4 includes via presentation of design-flow figures and descriptions the definitions, *inter alia*, of the nominal design-flow dynamics and best practices utilized for the development of ACTPol technologies, relevance of ACTPol advanced space technology development within the context of National Aeronautics and Space Administration (NASA) Grand Challenges, Mission Directorate objectives, technical readiness levels (TRLs), and technology area breakdown
structures (TABS), National Academy of Sciences (NAS) decadal survey goals, in addition to the core design management dynamics. Section 3.4 also highlights via critical design imagery the ACT site- and telescope-superstructural design and logistical characteristics that impacted corresponding development constraints of the fully-integrated ACTPol receiver, the macro-level technology overview of which is provided in earlier in the Chapter.

The remaining Sections that comprise Chapter 3 focus on four distinct systems-level design areas contributing to the overarching ACTPol receiver design. In particular, the ACTPol cryostat superstructural elements and bandpass-defining optical filters and infrared-radiation blocking filters are described. Additionally, the operational principals and technical description of field-deployed ACTPol cryogenic technologies, including a pulse-tube cryocooler, and a novel $^3$He-$^4$He Dilution Refrigerator (DR) are described in Section 3.1, as well as providing an overview of the ACTPol thermomechanical hardware elements that allow for the operationalization and interface of the cryogenics systems with the primary optomechanical and polarimeter array elements of the receiver. Chapter 3 also highlights the design considerations resulting in the realization of the ACTPol 4K and 1K optomechanical subassemblies associated with the three ACTPol polarimeter array packages that are described in the next Chapter, as well as the design and fabrication of high-purity silicon reimaging optics with metamaterial anti-reflective coatings in 3.2, before concluding with an overview of the ACTPol beams and polarization angles.

Ultimately, taken together with the following Chapter, throughout this instrumentation characterization, we will recognize that the fully-integrated ACTPol receiver not only represents a fully-operationalized experimental cosmology platform for the mapping of small-angular-scale CMB intensity and polarization properties, but also represents a field-deployed pathfinder experiment, with direct impact on informing critical technology development considerations for both next-generation ground- and balloon-borne CMB polarization experiments, but also future-generation, seminal orbital CMB mapping platforms, including a future-generation NASA-led Inflationary Probe mission, referred to also interchangeably

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within this dissertation manuscript as CMBPol. Note that this Chapter includes selected work presented in (Thornton et al. 2016), the seminal work describing the ACTPol instrument, to which I was a principal coauthor.

3.1 Cryomechanical Design

The cryostat is a custom aluminum (primarily alloy 6061) structure fabricated by Precision Cryogenics.\textsuperscript{3} Shown in Figure 3.1, it is a cylinder 1.5 m in length and 1.1 m in diameter. The size was limited by what could fit inside the existing telescope receiver cabin. The design was motivated, in part, by the success of the MBAC cryostat (Swetz 2009; Swetz et al. 2011b). The front plate of the shell serves as the optical bench to which all of the cold optics and radiation shields are sequentially mounted. The 40 K optics plate, which supports a filter stack (Figure 3.7), is attached to the cryostat front plate via a G10 fiberglass cylinder. The 4 K optics plate is in turn attached to the 40 K optics plate via a second G10 fiberglass cylinder. The 4 K optics plate is made out of alloy 1100 aluminum for increased thermal conductivity and acts as the primary support for all of the optics tubes. Nested 40 K and 4 K aluminum radiation shields surround the optics and cryogenics at those temperatures. Welded to the 40 K radiation shield are high-purity aluminum strips for improved heat removal from the 40 K filters.

3.1.1 Principal Cryogenics Systems

The remote site location makes the use of non-recycled liquid cryogens both difficult and expensive. Thus, every effort was made to include closed-cycle cooling systems wherever possible. A single Cryomech\textsuperscript{4} PT410 pulse tube refrigerator is responsible for cooling the optics and cryostat structures attached to the 40 K and 4 K stages (Figure 3.6). These include the 40 K and 4 K cold plates, radiation shields, 40 K filters, and the 4 K components.

\textsuperscript{3}7804 Rockville Rd, Indianapolis, IN 46214
\textsuperscript{4}http://www.cryomech.com.
Figure 3.1: Model of the as-built cryostat. For scale, the length of the cryostat is 1.5 m. The PA3 optics tube and most of the radiation shields have been removed for clarity. A combination of flexible copper sheets and copper braid are used to reduce vibrational coupling between the pulse tubes and internal cryostat components.

(first lens, baffles, filters) contained within the upper halves of all three optics tubes (Section 3.1.2). To minimize vibrations from the pulse tubes and scan turnarounds, acoustically deadened copper braid and flexible copper sheets are used to attach the PT410 cold stages to the rest of the internal cryostat structures (Figure 3.1). The receiver is located near the telescope azimuthal axis, which also reduces scan-induced vibrations.

All remaining components are cooled below 4 K using a pulse tube (Cryomech PT407)
backed custom $^3$He–$^4$He dilution refrigerator (DR; Shvarts et al. 2014) manufactured by Janis Research Corporation. The 1 K stage or “still” of the DR is responsible for cooling the back end of the optics tubes: the Lyot stop, the second and third lenses, and filters. The 100 mK stage or “mixing chamber” of the DR sets the bath temperature for all three detector arrays and can continuously supply over 100 $\mu$W of cooling power at 100 mK, making the DR an excellent choice when compared to more conventional 100 mK adiabatic demagnetization refrigerators due to the latter’s limited cooling power. The DR’s lower base temperature (thereby improved detector sensitivity) and continuous run-time also out-perform the $^3$He adsorption fridges used in the MBAC cryostat.

Cooling the cryostat to base temperature typically takes 14 days with all three sets of optics installed. This is due in large part to the considerable thermal mass contained within its optical components, focal-plane arrays, and many low-temperature thermal interfaces. The vast majority of the cool-down (> 13 days) is the time required for all components to reach the base temperature of the pulse tube stages. During this process, the 1 K and 100 mK components are connected to the 4 K stage of the DR pulse tube via a mechanical heat switch. Once the pulse tube base temperatures are reached, the heat switch is disengaged and the $^3$He–$^4$He mixture is allowed to condense while being circulated within the DR insert to complete the cool-down. An additional 4–5 hours are needed for the DR mixing chamber to drop below 100 mK once this final step has been initiated. Throughout the cool-down, as well as during normal operations, the DR is monitored via an ethernet link connected to its gas-handling system computer inside the receiver cabin of the telescope.

The lowest temperature reached by each cryogenic stage depends on a number of operational and environmental factors, including exterior temperature, telescope elevation, scanning motion, and the detector read-out electronics. Table 3.1 lists the measured base temperatures and estimated thermal loading for each cryogenic stage during optimal cooling conditions – note that the temperature of the coldest stage (the DR mixing chamber)
The ACTPol Dilution Refrigeration system allows for liquid-cryogen free cooling of all receiver 1K and 0.1K components and subsystems, with pre-cooling of 40K and 4K components and subsystems relegated to a receiver-integrated pulse tube cryogenic cooling system (PT410 module).

**Figure 3.2**: ACTPol Receiver-deployed Dilution Refrigeration System: Design and System. The ACTPol Dilution Refrigeration system allows for liquid-cryogen free cooling of all receiver 1K and 0.1K components and subsystems, with pre-cooling of 40K and 4K components and subsystems relegated to a receiver-integrated pulse tube cryogenic cooling system (PT410 module).
Figure 3.3: ACTPol central thermal bus tower design evolution overview. Given the evolving thermomechanical and vibroacoustic performance and requirements of the central thermal distribution bus tower, multiple designs and ultimate field-deployed iterations of this design were necessary for baseline, and improved thermal performance of optical and polarimeter components. Note that even with v5 existing as the initial field-deployed version of the central thermal bus tower, additional modifications to improve thermal path throughput and mechanical installation operations continued to be integrated through final-season ACTPol deployment.
Figure 3.4: ACTPol receiver thermomechanical conduit design evolution overview. (Top, Left/Right) ACTPol initial cryogenic testing included thermomechanical conduit fabricated from custom formed, gold-plated, and heat-annealed OFHC-purity copper of 0.25 inch diameter cylindrical profile; ACTPol deployment testing upgraded this conduit design to include 0.375 inch diameter cylindrical-profile, gold-plated, heat-annealed 5N purity copper for improved thermal performance of 1K and 0.1K stages. (Bottom, Left/Right) Design evolution from 0.375 inch square profile 1K and 0.1K gold-plated thermal distribution conduit from central bus tower to respective stages, to a final-deployment 0.375 inch diameter welded braid/square profile gold-plated hybrid design.
Figure 3.5: ACTPol receiver 1K stage passive gas-gap heat switch design concept. A Simon Chase passive gas-gap heat switch was installed between 4K PT410 cooled copper tower, and central thermal bus tower 1K stage to aid in 1K hardware cooling speed and performance. Ultimately, this system was removed following ACTPol initial deployment operations following uncertain impact on performance and potential thermomechanical shorting between 1K and 3K stages, potentially due to failure of internal heat switch inter-stage thermal isolation when deployed in a cantilevered design variant.
may be up to 13 mK warmer during typical observing operations (telescope in motion and detector read-out powered on). Since a lower bath temperature results in higher detector saturation powers (and thus a larger dynamic range over atmospheric loading conditions (see Section 4.2), gold-plated high-purity (99.999%) annealed copper links were used to make thermal connections between the DR and the focal-plane arrays to minimize temperature gradients. During observations, the typical array temperature with all three sets of optics installed ranged from 100 to 115 mK.

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<td>DR Mixing Chamber</td>
<td>82.4 ± 0.5 mK</td>
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</tr>
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**Table 3.1:** Measured base temperatures and thermal loads of the receiver cryogenic stages with three sets of optics during optimal cooling conditions (detector electronics powered down and telescope at rest).

### 3.1.2 Optomechanical Support Structures

Each of the three sets of optics is contained in a cylindrical optics tube. To minimize weight, aluminum was generally used to mount optical elements between 300 K and 1K. For 100 mK assemblies, where conductivity is critical and where aluminum is superconducting (resulting in reduced thermal conductivity), oxygen-free high-conductivity copper (OFHC) was generally used. Another reason for using mostly copper below ≈ 1 K is potential problems with magnetic flux expelled by superconducting aluminum alloys, which is problematic for the SQUIDs (Section 3.1.3).

The three optics tube assemblies are of similar design, yet self-contained to allow each one to be deployed individually. A cross-section of the PA3 optics tube is shown in Figure 3.6.
Figure 3.6: Cutaway view of the PA3 optics tube showing the internal optics, mechanical structures, magnetic shielding, and cold straps.

All lenses and LPE filters are clamped with a spiral beryllium copper spring around the perimeter of one side of each element to accommodate differential thermal contraction and to provide a uniform clamping force against the brittle silicon. The spring is a commercial product designed primarily for shielding from electromagnetic interference. Most of the cylindrical structures comprising each optics tube are mounted perpendicular to the cold plates. Individual lens and array tilts were achieved through custom angled mounts that hold each component at the proper angle with respect to each optics tube.

The first lens, nominally at 4K, is supported from the 4K cold plate via an aluminum...
tube, inside of which are machined steps that precisely locate baffles. The baffles are blackened with a mixture of 2850 FT Stycast, loaded with 5 - 7% carbon lampblack by weight, so that the minimum thickness exceeds 1 mm and is textured. The Lyot stop, second and third lenses, and surrounding low-pass filters are all maintained near 1 K. To reduce the load on the DR, these structures are supported from the 4 K cold plate using a custom-made carbon fiber tube. Attached to this 1 K framework is a second, re-entrant carbon fiber suspension that is 0.6 mm thick for thermally isolating the 100 mK array package from the 1 K components.

3.1.3 Magnetic Shielding Considerations

The SQUID multiplexers and amplifiers, as well as the TESes themselves, are sensitive to changing magnetic fields and therefore require magnetic shielding from both Earth’s field and AC fields associated with the telescope motion. To complement shielding around the SA modules and at the PCBs, additional magnetic shielding was provided for the collection of SQUIDS for each array by enclosing the lower half of each optics tube (Figure 3.6) with Amumetal 4 K₇ (A4K). This is a proprietary material with a high nickel concentration and prepared with a heat treatment process to give it a high magnetic permeability at cryogenic temperatures. To achieve the maximum attenuation, the thickest available A4K (1.5 mm) was used. Each optics tube has two layers of shielding separated by approximately 6 mm since, given sufficient spacing, using additional layers approaches the limit of multiplicative increases in the field attenuation.

⁷A trademark of Vacuumschmelze GmbH in Hanau, Germany. Local Distributor: Amuneal Manufacturing Corporation, 4737 Darrah St., Philadelphia, PA 19124, USA, info@amuneal.com, (800)-755-9843.
3.2 High-Purity Silicon Cryogenic Optics

3.2.1 Optical Design Overview

Three independent cryogenic optics tubes are used to reimage the Gregorian focus of the telescope onto the detector arrays. These refractive optics are designed to maximize the optical throughput and instrument sensitivity. Each optics tube uses three anti-reflection (AR) coated silicon lenses to reimage a $\sim 1^\circ$ diameter portion of the Gregorian focus. The primary elements of each set of camera optics are a cryostat window and IR blocking filters (Tucker and Ade 2006) at ambient temperature; followed by a combination of blocking filters and low pass edge (LPE) filters (Ade et al. 2006) at 40 K; the first lens and accompanying filters at 4 K; the Lyot stop, two more lenses, and additional low pass filters all at 1 K; and the final LPE filter and array package at 100 mK. A ray trace of the cold optics is shown in Figure 3.7.

The size of each optics tube is limited by both the size of the cryostat (which had to fit in the existing receiver cabin) as well as the maximum diameter of the low-pass edge filters (Section 3.2.3). To minimize the size of the entrance optics, the receiver is positioned such that the Gregorian focus is located between the receiver window and first lens. The Gregorian focus is not telecentric, which is a requirement for a large, flat feedhorn-coupled detector array (see Hanany et al. 2013). To achieve a telecentric design, small offsets and tilts were incorporated into the three lenses. The final design is diffraction-limited across each focal plane.

3.2.2 Lens Characterization

Silicon was chosen for the lens material due to its high thermal conductivity, high index of refraction ($n = 3.4$), and low loss at our wavelengths. The high index of refraction necessitates the use of AR coatings. ACT previously used Cirlex coatings (Lau et al. 2006), but
they incurred an estimated 15% net efficiency reduction (Swetz et al. 2011b). For ACT-Pol, we created “meta material” AR coatings produced by removing some of the silicon to controlled depths from the surfaces of each lens at sub-wavelength scales using a custom three-axis silicon dicing saw, creating layers of square pillars. The resulting coating has a coefficient of thermal expansion matching that of the rest of the lens. Lenses based on a two-layer design (Figure 3.8a) are used in both the PA1 and PA2 optics. Simulations showed that the resulting coating has low-reflection (<1%) for angles of incidence up to 30° with low cross-polarization (Datta et al. 2013). Figure 3.8b shows reflectance measurements verifying the simulated performance. Transmission measurements were not performed on the deployed lenses due to the difficulty of dealing with curved surfaces as well as the measured loss tangent (\( \tan \delta < 7 \times 10^{-5} \)) of silicon at cryogenic temperatures (Datta et al. 2013). The meta material method was extended to a three-layer pillar design for the wider bandwidth

Figure 3.7: Ray trace of the cold optics. The upper trace shows the PA3 (multichroic) optical path and the lower trace shows the PA1 path. The PA2 optical path is a mirror image to that of PA1 and has been removed for clarity. The constituent elements are described in the text.
of PA3. The measured performance agrees with predictions, and both PA1/2 and PA3 are consistent with sub-percent level reflections (Datta et al. 2016).

Figure 3.8: (Left) Isometric view of a two-layer antireflection coating showing how the material removal process creates “pillars” on the lens surface. For scale, the pillar pitch is 450 µm. (Right) Comparison between simulated and measured reflectance of a two-layer coating on one side of a flat silicon sample.

3.2.3 Filters and Optical Bandpasses

Each optics tube has its own circular, 6.4 mm-thick window made of ultra-high molecular weight polyethylene with an expanded Teflon AR coating. The PA1 and PA2 windows are 32 cm in diameter and the PA3 window is 34 cm in diameter. Although thinner windows would have reduced in-band loading, the increased deformation would have interfered with the blocking filters immediately behind them (Figure 3.7). There are IR blocking filters (Tucker and Ade 2006) at 300 K, 40 K, and 4 K that reflect high-frequency out-of-band radiation to reduce the optical load, in particular, on the poorly thermally conducting LPE filters. These LPE capacitive mesh filters (Ade et al. 2006) are used at 40 K, 4 K, 1 K, and 100 mK to limit loading on successive stages. Filter sets with a range of cutoff frequencies allow suppression of out-of-band leaks from individual filters. For PA1/2, these LPE filters
are also used to define the upper edge of the band. The lower edge of the PA1/2 band is set by a waveguide cutoff at the end of each feedhorn (Section 4.2.1). The PA3 bands are set by on-chip filters (Section 4.2.2).

![Figure 3.9: Plot of the ACTPol bandpasses for all three arrays (shown with arbitrary scaling) superimposed on the atmospheric brightness displayed for a range of PWVs. The predominant atmospheric features are the 60 GHz and 117 GHz oxygen lines and the 183 GHz water line. The loading due to water increases with the atmospheric water vapor content while the oxygen emission remains relatively constant. Because of its proximity to the 183 GHz line, the 148 GHz band is significantly more sensitive to weather variation than the 97 GHz band. The atmospheric transmission was generated with the ALMA Atmospheric Transmission Modeling (AATM) code, which is a repackaging of the ATM code described in Pardo et al. (2001).](image)

Each filter’s frequency response at room temperature was measured with a Fourier transform spectrometer (FTS). After the filters were installed in the receiver, additional FTS measurements were made on the fully cooled system before shipping to the site, as were
tests with thick-grill filters (e.g., Timusk and Richards 1981) to check for high frequency leaks. A final set of FTS measurements was performed after the receiver was installed on the telescope so that bandpasses could be taken in the same configuration as science data acquisition. These on-site measurements were made using a Martin-Puplett type interferometer operating in a step-and-integrate mode. The bandpasses, which were corrected for the transmission of the FTS coupling optics and a source blackbody spectrum, are shown in Figure 3.9. These spectra represent an average of 21 detectors for PA1, 84 detectors for PA2, 18 detectors for PA3 97 GHz, and 28 detectors for PA3 148 GHz.

Using each array’s measured bandpass, we follow the method of Page et al. (2003) for calculating the effective central frequency for broadband sources, as well as the CMB and SZ effect. The effect of the varying source spectra on the band center is to shift it slightly. The results are given in Table 3.2.

3.3 Characterization of On-Sky Beams and Polarization

3.3.1 Beams

The telescope beams are characterized with observations of planets. Saturn is used to align and focus the secondary reflector at the start of each season, but observations of Uranus are ultimately used for beam characterization because its brightness is low enough to not saturate the detectors.

A single planet observation is achieved by scanning the telescope back and forth in azimuth, at fixed elevation, while the planet rises or sets through an array’s field of view. The resulting time-ordered data are reduced to a single map of the celestial sky, centered on the planet, for each detector array and frequency band. This mapping process relies on knowing the relative pointings of the detectors on the sky, and on an accurate calibration of each detector’s response to the source.
Figure 3.10: ACTPol receiver cryogenic data acquisition system (DAQ) and thermometry interface electronics integrated concept. All DAQ from the three ACTPol polarimeter array packages, via their associated series array interface electronics were realized via 100-pin constantan TekData cables routed from receiver-external multi-channel electronics (MCE) crates. Receiver thermometry and housekeeping also pictured, interfacing with ACTPol cryogenic break-out-box (CBOB), also utilizing constantan TekData “spider” cables.
Figure 3.11: Overview of ACTPol PA1 4K Optomechanical Subassembly. Integrated and subsystem-level views indicated.

Figure 3.12: Overview of ACTPol PA1 1K Optomechanical Subassembly. Integrated and subsystem-level views indicated.
Figure 3.13: ACTPol Receiver Vacuum Window, Infrared-blocking and band-pass-defining filter, and 40K canopy thermal region integration overview.
Figure 3.14: ACTPol Band-Pass-Edge-Defining and Infrared-Radiation-Blocking Filter Stack Design Overview. (Left) ACTPol PA1 Optomechanical Subassembly vacuum window, infrared-blocking filter, and band-pass-edge defining filter stack design concept, deployed at 300K, 40K, and 4K stages. Vacuum channel conduit included between consecutive IR-blocking filters to ensure the minimization of vacuum pressure differentials within filter stack that could lead to degraded optical performance or filter mechanical failure. (Right, Above) Cardiff University fabricated low-pass-edge defining filter. (Right, Below) Cardiff University fabricated infrared blocking filter.
Figure 3.15: Overview of ACTPol cryostat vacuum shell and radiation shielding fabrication at Precision Cryogenic Systems, Inc. (Indianapolis, Indiana, USA). ACTPol 300K radiation shield/vacuum shell and 3K radiation shield shown fabricated from aluminium alloy 6061, whereas for increased thermal cooling performance, 40K radiation shield fabricated from aluminum alloy 1100, with high-purity 4N aluminum alloy strips welded to principal shell and canopy cylinders for enhanced component-level thermal conductivity performance.
Figure 3.16: Beam maps for the ACTPol arrays, showing the response to a point source in a coordinate system such that North is in the direction of increasing altitude and West is in the direction of increasing azimuth. Both axes have units of arcminutes. These maps include the data from all responsive detectors, averaged over 81, 86, 39, and 37 observations for the PA1, PA2, PA3/148, and PA3/97 arrays, respectively. The white contour lines denote where the response falls to half of its peak value.

The detector positions are determined from Saturn and Uranus observations by fitting a model for the source to the time-stream data directly. A single average pointing template is computed for each season and array, and used for all subsequent planet mapping. The relative positions of the detectors are constrained at roughly the arcsecond level, and thus
the pointing template uncertainty contributes negligibly to beam degradation.

The detector calibrations are determined independently for each mapped observation by comparing the amplitude of each detector’s response to the common mode from atmospheric emission.

Each planet map provides a measure of the telescope’s “instantaneous” beam, averaged over all responsive detectors in each array and band. The average instantaneous beams are shown in Figure 3.16. Beam properties, which are derived using an elliptical cone model, are provided in the subsequent Table. The primary cause of the ellipticity in PA3 is field distortion, as the optics tubes span a larger FOV than that for which the telescope was originally designed. The effective point spread function of the telescope in the CMB survey maps differs from the instantaneous beam primarily due to the impact of pointing variance\(^\text{12}\), which acts as a low-pass spatial filter, and due to the way in which sky rotation symmetrizes the beam by stacking up observations at a variety of parallactic angles. For the interpretation of CMB survey maps, the beam’s harmonic transform and its covariance are determined following the procedure described in Hasselfield et al. (2013b).

### 3.3.2 Polarization Angles

The ability to separate polarized intensity into E and B components depends upon how accurately detector polarization angles are known. For each hex and semi-hex wafer, a feed horn couples to an OMT pair having one of two possible orientations, which is set by lithography during fabrication. When this is combined with both the orientation of the semi-hex and hex wafers within an individual array as well as the orientation of each array as a whole into the cryostat, a roughly equal distribution of detector angles, covering every 15 degrees, is produced. Figure 3.17 shows these resulting detector polarization angles as seen on the sky.

\(^\text{12}\)The estimated pointing variance was less than 60 arcsec\(^2\) for PA1 and PA2 during Seasons 1 and 2. Analysis of Season 3 data is ongoing.
Figure 3.17: Plot of relative detector positions and polarization angles as seen on the sky. PA1 is in the lower right, PA2 the lower left, and PA3 on top. Each hex/semihex wafer has OMT pairs in two different orientations, which results in six different detector polarization angles in each array. There is a slightly higher number of physical detectors than there are available readout lines for, resulting in the region of seemingly “missing” detectors in each array.
Apart from the physical OMT orientations, however, there is also a polarization rotation introduced by the ACTPol optical chain as seen on the sky. The optics-induced rotations, as well as the detailed mapping from the focal plane position to projected angle on the sky, are determined using a polarization-sensitive ray trace through a model of the telescope in the optical design software CODE V.\textsuperscript{13} Given a point on the sky, the software calculates the polarization state across the entrance pupil diameter. This polarization state, averaged across the pupil and propagated to the focal plane, produces the polarization output for a single point on the focal plane. Given a perfectly polarized input state of known angle, the difference between the output polarization state and the input state results in the polarization rotation. The resulting polarization rotation output is produced at twenty five points on the focal plane for each of the three ACTPol arrays. This rotation on the focal plane is then fit to a simple 2D quadratic model, which is in turn used to produce the polarization angle rotation at the location of each feed horn in all three arrays. The optics-induced rotations have a range of approximately $3^\circ$. While this is too small to be seen in Figure 3.17, it is too large to be ignored in the analysis.

Thus far the measured polarization angles from the Crab Nebula (see, for example, Farese et al. 2004) and minimizing the EB spectrum (Keating et al. 2013; Naess et al. 2014b) are consistent with the calculated polarization angles based on the optics design and detector layout. Further analyses will be presented in future papers, e.g. Koopman et al. (2016).

\subsection*{3.4 Additional Receiver Project Development Charts and Receiver Design Imagery}

\footnote{\url{http://www.synopsys.com}}
Figure 3.18: Overview of ACTPol Systems-level Technology Development Flow, including all key design, integration, deployment, and operations milestones to enable the realization of the full-suite of space technology subsystems comprising the ACTPol receiver, laboratory and in-field qualification and optimization, as well as science and performance analysis contributing to proposal-level technology assessment for next-generation experimental cosmology systems.
Figure 3.19: NASA Technical Readiness Level (TRL) Chart. TRL definitions characterize the assessed stage of technical development for system-, subsystem-, and component-level space technologies. NASA currently defines space technology TRL in nine steps, ranging from the initial concept phase of TRL 1 (“Basic principals observed and reported”) to fully-realized, space-demonstrated technologies TRL 9 (“Actual system 'flight proven' through successful mission operations”). Typically, ACTPol receiver and on-site optical superstructure and logistical support technologies are defined within the an Intermediate Technology Development regime, generally between TRL 3-5.
Figure 3.20: Master ACTPol Polarimeter Array Package (PA1) Mechanical Component Fabrication Supply Chain Chart.

Figure 3.21: Sample ACTPol Design Development Gantt Chart for PA1 Optomechanical Subassembly Preliminary Design Review (PDR).
Figure 3.22: Design illustration of optomechanical development constraints for the definition of the ACTPol receiver envelope within the ACT telescope warm optical superstructure including ray trace of incident CMB radiation. ACTPol receiver front plane definition and alignment to the optical boresight is defined by ACT off-axis Gregorian optical configuration, further constraining the effective ACTPol receiver envelope.
Figure 3.23: Scaled structural overview of ACTPol millimeter-wavelength imaging technology development. Clockwise from top left: ACT site with Ground Screen, ACT Telescope Superstructure, ACTPol Receiver in ACT Receiver Cabin, Cross-Section of ACTPol Cryostat Design with Dual 150 GHz Arrays and High-Purity, Normal-Incidence Silicon Optics, ACTPol 150 GHz Polarimeter Array Package Design (Principal components indicated)
Figure 3.24: Schematic overview of ACTPol cryostat design. Shown is a cross-sectional view cut across ACTPols dual 150 GHz polarimeter arrays and coupled optical assemblies, with all principal detector, cryogenic, and optical elements indicated.
Figure 3.25: ACTPol PA1 (150 GHz monochromatic sensitivity) Optomechanical Subassembly Structural Design Overview. At full deployment, ACTPol has successfully fielded three unique optics tubes based on structurally-similar designs to this first-deployed subsystem. Ultimately, deployed optomechanical subassemblies went as: Initial Deployment (2013) - Single 150 GHz module; Full Deployment (2014-2015): Dual (similar) 150 GHz modules, single multichroic module with simultaneous 90 GHz and 150 GHz sensitivity. (Principal components indicated)
Table 3.2: Effective central frequencies for broadband compact and diffuse sources. The values are obtained by averaging over individual detectors and based on the measured response of the receiver on the telescope. The uncertainties are equal to the standard deviation of the measured detectors. The measurement resolution of the FTS was \( \sim 0.8 \) GHz and has not been deconvolved. Assumed spectral indices: synchrotron emission \( (\alpha = -0.7) \), free-free emission \( (\alpha = -0.1) \), Rayleigh Jeans emission \( (\alpha = 2.0) \), dusty source emission \( (\alpha = 3.7) \). The bandwidth uncertainty for PA1 and PA3 \( (90) \) is higher than the central frequency uncertainty because a couple of detectors in each of these arrays were measured to have significantly different bandwidths (wider in the case of PA1 and narrower in the case of PA3 \( 90 \)) than the mean.
### Table 3.3: Beam parameters, as derived from the maps in Figure 3.16. The “elliptical FWHM model parameters” are obtained by fitting an elliptical cone to only the points of the map which show a response within 10% of the half-maximum level, and are intended to give an idea of beam size and ellipticity. FWHM major angle is measured from the North, increasing towards the East. Formal errors on FWHM parameters are insignificant, but the ACTPol beams differ significantly from a gaussian shape and thus any analysis of the ACTPol maps must incorporate the measured ACTPol beam function.

<table>
<thead>
<tr>
<th>Array – Band</th>
<th>Solid Angle (arcmin$^2$)</th>
<th>Elliptical FWHM model Major axis (arcmin)</th>
<th>Minor axis (arcmin)</th>
<th>Major angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA1 – 148 GHz</td>
<td>2.27 ± 0.05</td>
<td>1.37</td>
<td>1.32</td>
<td>-49</td>
</tr>
<tr>
<td>PA2 – 148 GHz</td>
<td>2.12 ± 0.03</td>
<td>1.33</td>
<td>1.31</td>
<td>56</td>
</tr>
<tr>
<td>PA3 – 148 GHz</td>
<td>3.12 ± 0.13</td>
<td>1.58</td>
<td>1.33</td>
<td>-3</td>
</tr>
<tr>
<td>PA3 – 97 GHz</td>
<td>6.62 ± 0.22</td>
<td>2.13</td>
<td>2.00</td>
<td>-2</td>
</tr>
</tbody>
</table>
Chapter 4

ACTPol Polarimeter Array
Package Development

Love me, sweet friends, this Sabbath day.
The sea sings round me while ye roll
afar the hymn, unaltered,
and kneel, where once I knelt to pray,
and bless me deeper in your soul
because your voice has faltered.

And though this Sabbath comes to me
without the stolèd minister,
and chanting congregation,
God’s spirit shall give comfort.
He who brooded soft on waters drear,
creator on creation.

He shall assist me to look higher,
He shall assist me to look higher,
where keep the saints, with harp and song,
   an endless, endless Sabbath morning,
   an endless Sabbath morning,
and, on that sea, commixed with fire,
on that sea, commixed with fire,
oft drop their eyelids raised too long
to the full Godhead’s burning,
the full Godhead’s burning.

from Edward Elgar’s “Sea Pictures: Sabbath Morning at Sea”

Across this dissertation manuscript, thus far, we have provided an overview of several of the large-scale integrated space technologies required to enable the successful science operation of ACTPol coupled to the ACT telescope optomechanical superstructure, as both a standalone experimental cosmology facility dedicated to polarization-sensitive characterization of the Cosmic Microwave Background at millimeter wavelengths. Additionally, we have provided an overview of the manner by which the technology development inherent to the ACT+ACTPol system enables the operation of ACTPol to also be a pathfinder experiment for future-generation ground, balloon, and satellite-based facilities dedicated to the mapping of the CMB in polarization and temperature, and, ultimately, to probe a possible inflationary epoch of the primordial Universe, as was discussed in the first Chapter. While we have heretofore described the macro-level logistical and observing technology systems, ranging from site selection, to optomechanical superstructure (ACT telescope), and ACTPol receiver (optomechanical subsystems, high-purity silicon reimaging optics with novel metamaterial anti-reflective coating geometries, and a fully-integrated, field-deployable dilution refrigeration system), we have yet to characterize perhaps the most vital subsystem required for the mapping of incident CMB radiation in both temperature and polarization.
We therefore provide this brief Chapter dedicated exclusively to the discussion of the principal components of the ACTPol focal plane, which consists of three separate polarimeter array package assemblies. The first two polarimeter arrays, generally referred to as PA1 and PA2, are twin systems - both are designed to map the CMB in both temperature and polarization with 150 GHz sensitivity, while the third polarimeter array, PA3, allows for multichroic operation, with simultaneous-sensitivity performance at both 90 and 150 GHz - frequencies we have already defined as essential to probing the anisotropies in both temperature and polarization of the CMB blackbody power spectrum. The Chapter, which follows, will briefly characterize prototyping work that was performed to pilot some of the critical subsystems comprising the ultimately field-deployed polarimeter array packages of ACTPol, followed by an overview of the subsystem components and their resultant qualification testing, readout, and early performance characterization. Note that this Chapter includes selected work presented in (Thornton et al. 2016), the seminal work describing the ACTPol instrument, to which I was a principal coauthor. Additionally, while a fully-exhaustive characterization of the ACTPol receiver would duplicate the characterization of each of the three polarimeter array package subassemblies, for brevity, this Chapter will discuss the general properties consistent across all three polarimeter array package subassemblies, pointing out significant design splits between the assemblies only when necessary to describe the evolution of the critical space technologies relevant to the successful operation of the ACTPol instrument.
4.1 ACTPol Focal Plane Design Flow, Prototyping, and Development Management Dynamics

4.1.1 From MBAC Bolometers to ACTPol Polarimeters: The NIST CMB6 Prototype Polarimeter Array

The development of the ACTPol polarimeter array packages were primarily developed following extensive prototyping work performed by groups from Penn and Princeton working in tandem with researchers at NIST-Boulder. In particular, concurrent to the close of ACT+MBAC operations, researchers at NIST were active in developing several single-pixel transition-edge sensor polarimeter pixels wafer stacks, which would be coupled, for initial qualification testing, to single gold-plated corrugated silicon feedhorn pixels, with all silicon components fabricated using fully-integrated production processes developed at NIST and featuring deep reactive ion etching (DRIE) techniques. While five such single-pixel prototype systems, referred to as CMB1, CMB2, CMB3, CMB4, and CMB5 were developed to serve as the basis for both ACTPol and potentially other contemporary CMB polarization imagers utilizing TES-based polarimeter technologies, the development of CMB6, which was central to the earliest work conducted under the auspices of this dissertation period, was specifically aimed at the development of array-scale component technologies that would ultimately be scaled to form the basis of the ACTPol polarimeter array package designs. In particular, the development of CMB6 can be described as an early attempt at work toward integration of efforts between rival groups within the experimental cosmology communities, since its development was performed under the auspices of the so-called TRUCE collaboration, in which resources and resultant technology development was performed and shared between both the Atacama Cosmology Telescope and South Pole Telescope collaborations via joint work at NIST. The resulting prototype polarimeter array assembly is illustrated in Figure 4.1, which provides imagery of the completed CMB6 prototype polarimeter array assembly, consisting of 84-pixels operating at 150 GHz sensitivity, featuring a hexago-
nal, gold-plated, corrugated silicon feedhorn array, a polarimeter array stack consisting of four principal components (e.g. waveguide interface plate, detector wafer, backshort cavity plate, and backshort cap), high-trace-density flexible readout circuitry, and gold-plated OFHC interface hardware. Figure 4.2 illustrates additional prototype testing of subsystem components of the CMB6 prototype assembly. In this case, a test feedhorn array stack consisting of 32 wafers of 500 micron thickness with rectangular dimension of 1 cm by 2 cm was assembled to cryogenically test mechanical features that would ultimately be utilized on both CMB6 prototype and ACTPol polarimeter array package subassemblies. Ultimately, both CMB6 and related test subassemblies were able to demonstrate that under multiple cryogenic cycling at 4K, that all OFHC-Si mechanical interface designs would be sufficiently robust to scale up to full polarimeter array package design components, which will be further described in the next sections. Additionally, initial sensitivity, readout, and beam testing for the CMB6 prototype array package were assessed to be within the operational ranges ultimately required for the successful science grade operations of each final polarimeter array package to be deployed on the ACTPol receiver.

4.2 Overview of Principal Components and Assembly Dynamics of ACTPol Polarimeter Array Packages

The section, which follows, describes the core characteristics of the principal components of each of the three ACTPol polarimeter array packages, along with an overview of the array integration procedure and relevant mechanical design splits that allowed for the ultimate smooth integration of all three ACTPol polarimeter arrays. ACTPol has three superconducting focal plane arrays, each consisting of silicon micro-machined feedhorns that direct light to matched, photon-limited bolometric detector arrays (Yoon et al. 2009). The feedhorns, detectors, and SQUID multiplexing components are fabricated at NIST. PA1 and PA2 each has 512 feeds, which couple to 1024 bolometers (one per linear polarization) and
Figure 4.1: Imagery of the completed CMB6 prototype polarimeter array assembly, consisting of 84-pixels operating at 150 GHz sensitivity, featuring a hexagonal, gold-plated, corrugated silicon feedhorn array, a polarimeter array stack consisting of four principal components (e.g. waveguide interface plate, detector wafer, backshort cavity plate, and backshort cap), high-trace-density flexible readout circuitry, and gold-plated OFHC interface hardware.
Figure 4.2: Additional prototype testing of subsystem components of the CMB6 prototype assembly. In this case, a test feedhorn array stack consisting of 32 wafers of 500 micron thickness with rectangular dimension of 1 cm by 2 cm was assembled to cryogenically test mechanical features that would ultimately be utilized on both CMB6 prototype and ACTPol polarimeter array package subassemblies. Ultimately, both CMB6 and related test subassemblies were able to demonstrate that under multiple cryogenic cycling at 4K, that all OFHC-Si mechanical interface designs would be sufficiently robust to scale up to full polarimeter array package design components.
operate at 148 GHz; PA3 has 255 feeds that couple to 1020 bolometers (one per linear polarization per frequency) and operate simultaneously at 97 and 148 GHz. Each array is approximately 15 cm in diameter and is located behind a 100 mK LPE filter (Figure 3.7). Figure 4.3 is provided at the outset of this section to illustrate the principal component-level technologies that were developed for the final integration and operation of the ACTPol polarimeter array package, where in this case the principal components of the assembled first ACTPol polarimeter array package, namely ACTPol PA1, which operates with 150 GHz sensitivity is shown. This includes a gold plated monolithic corrugated silicon feedhorn array, six detector wafer stacks (three each of hexagonal and semihexagonal variants) each consisting of four principal components - a waveguide interface plate, a polarimeter wafer, a backshort cavity plate, and a backshort cap wafer - gold-plated OFHC mounting and clamping components for interface to the feedhorn and detector array components, flexible readout circuitry consisting of high-trace density (100 micron center-to-center pitch), detector stack interface printed circuit boards (PCBs), TekData cables used to interface these PCBs to corresponding series array circuit boards, as well as an integrated low pass edge filter cell, all of which operate at the 0.1K cryogenic stage of the ACTPol receiver. The following subsections will describe in greater detail the utility and characteristics of each of the principal polarimeter array package components, presented in order of their assembly into the a fully-integrated array package. Broadly, this order of assembly begins with the preparation of the feedhorn array coupled to the gold-plated OFHC interface hardware, followed by the simultaneous modular deployment of each of the six pairs of polarimeter array stacks coupled (via wire-bonded flexible readout circuitry) to their corresponding interface readout PCBs, and integration of final detector-feedhorn coupling hardware subassemblies prior to integration of the completed polarimeter array package to the 0.1K stage of each corresponding optomechanical subassembly within the ACTPol receiver.
Figure 4.3: Illustration of the principal component-level technologies that were developed for the final integration and operation of the ACTPol polarimeter array package, where in this case the principal components of the assembled first ACTPol polarimeter array package, namely ACTPol PA1, which operates with 150 GHz sensitivity is shown. This includes a gold plated monolithic corrugated silicon feedhorn array, six detector wafer stacks (three each of hexagonal and semihexagonal variants) each consisting of four principal components - a waveguide interface plate, a polarimeter wafer, a backshort cavity plate, and a backshort cap wafer - gold-plated OFHC mounting and clamping components for interface to the feedhorn and detector array components, flexible readout circuitry consisting of high-trace density (100 micron center-to-center pitch), detector stack interface printed circuit boards (PCBs), TekData cables used to interface these PCBs to corresponding series array circuit boards, as well as an integrated low pass edge filter cell, all of which operate at the 0.1K cryogenic stage of the ACTPol receiver.
4.2.1 Au-Plated Monolithic Corrugated Silicon Feedhorn Arrays

Assembly of each of the ACTPol polarimeter array packages begin with the assembly of each of the ACTPol gold-plated, monolithic corrugated silicon feedhorn arrays. ACTPol features large-scale, 137 mm diameter, monolithic corrugated feedhorn arrays consisting of 33 gold-plated silicon wafers forming a corrugation profile. Use of gold-plated silicon wafers allows for improved thermal expansion coupling to the gold-plated silicon semihexagonal and hexagonal polarimeter stacks, and the introduction of corrugation geometry allows for broad bandwidth (> 25 percent), and suppression of cross-polarization and side lobes to <-30dB. The overall geometry of each of the feedhorn arrays is that of an equilateral nonagon with truncated vertices forming an irregular octakaidecagon geometry. All wafers in each feedhorn stack are 500 microns thick, with principal corrugation feature thickness 250 microns (for layers containing corrugations). In all the 33 wafers in the stack comprise a 1.65cm total stack thickness, in which five feedhorn geometry partitions comprise the ACTPol 150 GHz feedhorn array, such that from detector to sky-facing side we have: 1 wafer with circular waveguide geometry for coupling to the polarimeters, 5 wafers with square waveguide geometry defining the lower band edge, 4 wafers with circular waveguide geometry forming a conical flare (non-corrugated), 7 corrugated wafers with circular waveguide geometry allowing for the TE to HE transition, and finally 16 corrugated wafers with circular waveguide geometry forming the linear plus sin² taper region. At each truncated vertex on the perimeter of the feedhorn array, rectangular registration features are present, initially intended for mechanical coupling but ultimately used as stycast trenches for additional mechanical coupling, as well as silver epoxy trenches for improved thermal coupling to the gold-plated OFHC array mechanical infrastructure. Polarimeter stack alignment pin holes are also included in the first seven layers of the feedhorn stack for alignment of the detector wafer stacks to the feedhorn apertures. Figure 4.5 provides an overview of the custom mechanical coupling hardware, including gold-plated OFHC l-bracket and custom beam avoidance nuts, that provide the mechanical interface to which the gold-plated OFHC
principal array mounting assembly can couple to the silicon feedhorn and detector elements of the polarimeter array package.

Figure 4.4 provides an overview of some of the principal design concept and geometric cross-section of the ACTPol 150 GHz feedhorn array assembly. The feedhorns impedance-match radiation from free space to the detector wafers and their dimensions are optimized for a suitable bandwidth (Britton et al. 2010; Nibarger et al. 2012). The feedhorn arrays are assembled from stacks of silicon wafers with micro-machined circular apertures that correspond to individual corrugations (Figure 4.6). The individual silicon wafer platelets are etched, RF sputter coated with a Ti/Cu layer on both sides, stacked, aligned, and finally copper and gold electroplated to form a close-packed feedhorn array. This approach preserves the advantages of corrugated feedhorns such as low sidelobes, low cross-polarization, and wide-band performance while reducing the difficulty of building such a large array using traditional techniques like direct machining or electroforming individual metal feeds. While similar arrays can be made from metal platelets, difficulties associated with weight, thermal mass, and differential thermal contraction are avoided with the silicon platelet array concept. Furthermore, tolerances achievable with optical lithography and silicon micro-machining make for extremely good array uniformity. The feedhorn profiles for all three arrays contain sections to define the low-frequency cutoffs of the detector bandpasses. The wider band of PA3 motivated a section of ring-loaded platelets (Takeichi et al. 1971) for that array (see Figure 4.6 and McMahon et al. 2012).

4.2.2 ACTPol Hexagonal and Semihexagonal Transition Edge Sensor Polarimeter Array Stacks

Behind the feedhorns, radiation is coupled onto the polarimeters via planar orthomode transducers (OMT). The detectors are fabricated on monolithic three-inch silicon wafers in two different varieties: a hexagonal (“hex”) wafer and a semi-hexagonal (“semihex”) wafer. Each hex wafer has 127 pixels in the 148 GHz design and 61 pixels in the dichroic design,
while the semihexes have 47 and 24 pixels, respectively. Each hex and semihex section is actually composed of four silicon wafers: a top, waveguide interface plate, an OMT and detector wafer, and a two-piece quarter-wave backshort wafer. A full ACTPol array is assembled from three hex wafers and three semihex wafers. An overview of the characteristics of all four polarimeter array stack wafers is given in Figure 4.8. The waveguide interface plate, or WIP, provides the waveguide interface between the exit aperture of the feedhorn array and the detector wafer, while providing co-planar thermal coupling, which is enhanced given that both the feedhorn array and WIP are fabricated from gold-plated silicon for improved thermal characteristic matching. The WIP wafer is 500 microns thick and has an additional 250 micron thick boss feature centered around each pixel. The polarimeter wafer houses both OMT and TES detectors and provides interface to the readout flex via interface bondpads, and is 275 microns thick. Behind the polarimeter wafer is the backshort cavity wafer, which provides a reflective surface between each pixel’s OMT microstrip, while pro-
Figure 4.5: Overview of the custom mechanical coupling hardware, including gold-plated OFHC l-bracket and custom beam avoidance nuts, that provide the mechanical interface to which the gold-plated OFHC principal array mounting assembly can couple to the silicon feedhorn and detector elements of the polarimeter array package.
Figure 4.6: (Left) Design of a single horn-coupled multichroic polarimeter, consisting of a broad-band ring-loaded corrugated feedhorn and a planar detector array. A broad-band Ortho-Mode Transducer (OMT), shown in magenta, separates the incoming radiation according to linear polarization. (Right) Photograph of a cross-section of a PA3 test feedhorn. There are a total of 25 gold-plated silicon wafers, five of which are ring-loaded to form a broad-band impedance matching transition between the corrugated input waveguide and the round output guide.

viding an absorptive surface behind each TES detector via semicircular stycast-filled gulch features. The backshort cavity plate also provides mechanical standoff from the detector wafer traces to avoid shorting the readout traces via a backshort cavity plate corral feature, which has a 25 micron thickness and allows for a limitation of light escaping or reflecting around each pixel across the array. Finally, the backshort cap wafer is the top-wafer mechanical protection for the entire polarimeter wafer stack, and allows the gluch stycast to be contained, with a principal 500 micron wafer thickness. Epoxy holes are provided for assembly and coupling of the backshort cap and backshort cavity plate across the center of each wafer, while perimeter trenches present in the polarimeter wafer, backshort cavity plate, and backshort cap are provided for coupling of all layers to each other mechanically, while perimeter thermal bondpads allow for wirebonding between coupled detector stack wafers, thus enhancing thermal heat sinking between the adjacent detector stack layers.

Changes in radiation power are detected using superconducting TES bolometers (Lee et al. 1996; Irwin and Hilton 2005). When a TES is appropriately voltage biased, negative
electrothermal feedback maintains it at the transition temperature, $T_c$, under a wide range of observing conditions. Its steep resistance-vs-temperature curve transduces temperature fluctuations into current fluctuations, which are read out by the use of superconducting quantum interference device (SQUID) amplifiers using a time-domain multiplexing architecture (Reintsema et al. 2003) and room temperature electronics (Battistelli et al. 2008).

Photographs of a hex wafer, an ACTPol pixel, and a TES bolometer for the 148 GHz band are shown in Figure 4.7. Opposing pairs of OMT antenna probes separate the orthogonal polarization signals. The signals travel through a coplanar waveguide to microstrip transition, which is impedance-matched to reduce loss, to Nb microstrip lines, where they exit. On a PA3 dichroic pixel, diplexers comprised of two separate five pole resonant stub band-pass filters separate the radiation into 75-110 GHz and 125-170 GHz pass-bands. The signals from opposite OMT probes within a single sub-band are then combined, using a hybrid tee to reject high order modes, and the desired signal is routed to a TES island bolometer. Each PA3 pixel has four bolometers for the two linear polarization signals at each frequency. Details about the pixel design can be found in Datta et al. (2014). We define the detector optical efficiency $\eta$ as the ratio of the power detected by the bolometer’s TES to the optical power incident on the OMT. Both signal reflections and signal loss can cause $\eta < 1$. We originally projected $\eta \leq 0.76$ and $\eta \leq 0.66$ for the 97 and 148 GHz bands, respectively (Datta et al. 2014). Table 4.1 shows median measured values for the PA3 wafers, indicating the achieved dielectric loss tangents were slightly better than the conservative projections.

For all three arrays, the Nb microstrip lines terminate at a pair of TES islands, where the power is deposited as heat through lossy gold meanders. Each island is connected to the bulk silicon through four SiN legs of length 61 $\mu$m and widths that range from 14 $\mu$m to 53 $\mu$m, depending on the wafer. These legs carry the TES bias/CMB signal lines onto the island and determine the thermal conductivity $G$ to the thermal bath. The superconducting element of the ACTPol TES design is a MoCu “bilayer” with a $T_c$ tuned to approximately
150 mK through the choice of the molybdenum and copper geometry and thickness. In
the design of the TES, the choice of $T_c$ and $G$ represents a balance between minimizing
the thermal noise and increasing the maximum operational optical loading power, $P_{\text{sat}}$. To increase the stability of the TES through increased heat capacity to slow the detector response, a region of PdAu is coupled to the TES bilayer. A summary of the detector characteristics and parameter measurements is shown in Table 4.1.

The response of the ACTPol detectors to a delta function signal diminishes with time due
to the electro-thermal time constant, $\tau$, of the TES architecture. The median time constants for the three arrays are 1.9 ms, 1.8 ms, and 1.3 ms. With a scan speed of 1.5 deg/s, these values are equivalent to 3 dB points at multipoles $\ell$ between roughly 30,000 and 40,000. The time constants are loading dependent. We find that $f_{3\text{dB}} = 1/2\pi\tau$ typically varies by less than 20 Hz/pW.

Median array sensitivities based on detector noise power spectra are: $\sim 23 \mu K \sqrt{s}$ for PA1, $\sim 13 \mu K \sqrt{s}$ for PA2, $\sim 14 \mu K \sqrt{s}$ for PA3 (97 GHz), and $\sim 20 \mu K \sqrt{s}$ for PA3 (148 GHz). These sensitivity estimates are for PWV/sin(alt)= 1 mm (because the detectors are photon-noise limited, their sensitivities are dependent on the level of optical loading), and represent the array white noise level, evaluated near 20 Hz (which corresponds to angular scales of about 3 arcminutes). The detector noise spectra are typically flat from approximately 100 Hz down to where the atmospheric contamination begins, between 1 and 10 Hz. These noise equivalent temperature measurements are $\sqrt{2}$ higher than preliminary estimates in Ho et al. (2016) and Datta et al. (2016) due to a coding error (which did not affect noise equivalent power estimates). The time streams are calibrated using observations of Uranus and the Uranus brightness temperature model given in Hasselfield et al. (2013b). The error in this calibration is of order 2%.
4.2.3 ACTPol Polarimeter Array Package Readout

The final stage of the ACTPol polarimeter array package integration process includes the lowering onto the assembled OFHC mechanical structure, already-coupled to the monolithic feedhorn array of each polarimeter wafer stack (which can be done in a modular fashion for each of the six subassemblies). Each polarimeter wafer stack is physically connected to the detector interface PCB by flexible circuitry, in which each readout channel is connected between bondpads on the detector wafer and the flexible circuitry, and the flexible circuitry to bondpads on the interface PCB via precision wirebonds. To install the wirebond connections, the detector stack, flex, and interface PCB assembly are installed into an assembly jig in a flat configuration, wirebonds provide the physical connection between the three components, and then the jig is bent (along the flexible circuitry) into a 90 degree orientation, after which the entire PCB, flexible circuitry and detector stack assembly is lowered onto the feedhorn array and gold-plated OFHC mechanical structure, with alignment pins for both the detector stack and interface PCB allowing for proper mechanical alignment before final hardware coupling. Figure 4.10 shows above a Solidworks design created for the interface PCB principal readout chip components - the wiring chip, the MUX chip, and the Shunt/NyQuist chip - along with their interface readout wirebond design concept. Below are images of the BeCu tripod springs which are attached to the so-called ‘snaketongue’ assemblies to provide pressure to planar couple the hexagonal and semihexagonal polarimeter wafer stacks (snaketongue/tripod assembly is shown for a hexagonal wafer coupling subassembly in 4.3. Initial design variants had included the possibility of using groove-captured SPIRA shield (the same RF-shielding/spring components used for the lens cells described in the previous chapter) in a ‘lasso’ assembly variant, but ultimately the snake-tongue/tripod spring assembly was deemed the most appropriate for planar coupling the polarimeter wafer stacks to the feedhorn array wafers. In initial fabrication runs, the BeCu tripod springs were photo-etched as flat components, and then were hand formed into their nominal (pre-thermal contraction) spring position using a custom mandrel. This process
was ultimately not able to allow for 5 mil precision to be regularly held across large numbers of tripod forming runs, which led to poor planar coupling given the presence of tripod spring pads that did not contact, and therefore did not pressure the polarimeter wafer to be coplanar. Ultimately this led to thermal performance inconsistency across the PA1 array in early testing. To overcome the irregularities in coupling force, a second sub-contractor was used for precision forming of the flat tripod springs, with resultant precision less than 5 mil across a run of hundreds of tripod springs. This process allowed for improved results for uniformity in coupling force provided and therefore led to improved $P_{\text{sat}}$ across all arrays for later ACTPol operations.

The time-domain multiplexing (TDM) readout scheme employs three stages of SQUID amplification. The multiplexing of the readout has the advantage of reducing the wiring requirements to limit the thermal load on the cold stage. The current through each TES couples to the input coil of a corresponding SQUID amplifier, called the first-stage SQUID (SQ1). A set of 32 SQ1s are coupled to one second stage SQUID (SQ2) through a summing coil. Each SQ2 and its corresponding SQ1s are housed on a multiplexing chip (“MUX11c”). The multiplexing readout is achieved through rapid sequential biasing of each of these 32 SQUIDs. The final stage of amplification is accomplished by a set of SQUID series arrays (SA). Twisted pair NbTi cables carry the SQ1, SQ2, and detector lines from the five SA boards housed on the 1 K stage to nine other printed circuit boards (PCBs) on the 100 mK stage, which hold the multiplexing and other readout chips. Each detector is voltage biased onto its transition using an $\sim 180 \, \mu \Omega$ shunt resistor housed on the interface chip, which also contains a 600 nH “Nyquist” inductor designed to band limit the response.

The detector bias lines are carried from the readout PCBs onto the detector wafers through flexible circuitry consisting of a Kapton base and superconducting aluminum traces connected on both ends by aluminum wire-bonds. Both PA1 and PA2 as well as the hex wafers in PA3 are assembled with two layers of 200 micron pitch flexible circuitry made by
Tech-Etch. For the PA3 semihexes, single-layer, 100 micron pitch flex fabricated by the ACT collaboration is used (Pappas 2015). The biasing and multiplexing are handled by the Multi-Channel Electronics (MCE) crate (Battistelli et al. 2008; Hasselfield 2013). From the MCE box, a set of five 100-pin cables carry the bias and readout lines for the SQUIDs and detectors to the SA boards.

The total achieved readout yield for each arrays, where the yield is based on detectors with functional IV curves, is 67% for PA1, 77% for PA2, and 83% for PA3. The number of detectors used for CMB analysis is typically somewhat less than this (e.g., about 500 detectors for PA1), depending on observing conditions and the number of detectors that can be successfully biased. The fabrication yield of the detector wafers was high, with many wafers having perfect physical yield of the bolometers. Most detector loss originated from problematic SQUID biasing and readout lines, each of which corresponds to 32 TESes, and individual detector opens and shorts in the flexible circuitry. Through improvements in assembly protocols, higher yield was achieved with each successive array. Figure 4.9 shows part of the readout electronics architecture as well as a fully assembled array package.

### 4.3 ACTPol Polarimeter Array Package Vibroacoustic Testing and Initial Performance Characteristics

As has been discussed earlier in this manuscript, although ACTPol is only intended for ground-based deployment to the ACT telescope, the subsystem-level technologies under development for the project represent pathfinder-level instrumentation for next-generation, orbital-platform missions, such as a future Inflationary Probe mission - a critical priority defined under the NASA Science Mission Directorate Astrophysics Technology Needs Technology Area Breakdown Structure-08 (TABS-08) roadmap defined earlier. In particular, the development of high-pixel-density, millimeter-wavelength-sensitive, compact focal planes, as

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is represented by the ACTPol Polarimeter Array Packages, readily supports the objectives of the TABS-08 Epoch of Inflation Technology Development program, allowing for the potential improvement in focal plane subsystem development to a strong Technical Readiness Level (TRL) 5 qualification (to the level of a fully conceived proposal, though not yet tested in a relevant space-based environment necessary to achieve a true TRL 6 rating), as it will represent a fully-integrated subassembly-level system within an operational pathfinder observatory. In other words, by subjecting critical subsystems of the ACTPol receiver during its development to qualification testing appropriate for both ground-based performance in Chile, but also commensurate with inputs experienced by orbital-platforms, the development of ACTPol can have a direct and positive impact on assessing subsystem designs that could seed the design concepts of a future-generation inflationary probe mission.

Thus, to aid in the development of qualified technologies required for a strong TRL 5 classification for various subsystems of the ACTPol receiver, vibroacoustic characterization was performed to assess the mechanical performance of the ACTPol polarimeter array package design, with both simulations and laboratory testing performed at vibroacoustic levels appropriate for observing operations at a ground-based facility (e.g. ACT), a balloon-based platform, and an orbital platform. To achieve this evaluation of the mechanical robustness, and vibrational characteristics intrinsic to the ACTPol polarimeter array package design, both random vibrational analysis simulations and kinetic vibrational testing of the actual mechanical system were performed, with the latter kinetic testing taking place at the Vibrational Testing Facility (VTF) at NASA’s Goddard Space Flight Center (GSFC). Ultimately, while the ACTPol PA1 polarimeter array package underwent initial receiver integration testing at Penn, its mirror-designed array package, ACTPol PA2, was selected as the subsystem that would be qualified at NASA GSFC. Given that the ACTPol PA2 subassembly was not a prototype assembly, but rather the actual hardware that would ultimately be deployed to the ACTPol receiver for science-grade observing operations beginning in ACTPol Season 2, it was appropriate to classify the GSFC VTF tests under
the framework of a Subsystem Protoflight Test. Defining these tests in such a way was necessary to allow for appropriate precaution to be taken since, unlike a prototype system, which is a dedicated hardware system not intended for flight (or in this case deployment), and can in principal be tested with the intent of finding modes of mechanical failure, the ACTPol PA2 test subsystem was intended for eventual field deployment, and thus was only subjected to tests which mitigate probabilities for mechanical failure, whenever possible, by placing the subsystem under tests within acceptable safety factors. Additionally, testing the ACTPol PA2 subassembly to flight-grade vibrational conditions will serve to inform design and development decisions of future TRL 6 level proposals toward an inflationary probe mission. For a subsystem protoflight test, both general acoustic testing and random vibrational testing can be performed. Ultimately, it was deemed that the ACTPol PA2 Polarimeter Array was not appropriate for acoustic testing as it did not represent a large area-to-weight ratio structure (e.g. MLI blankets, solar panels), and is also therefore not necessarily susceptible to direct acoustic impingement at the subsystem level. With this in mind, however, the ACTPol PA2 Polarimeter array was deemed suitable for low-frequency, random vibration testing as it is a compact subsystem (<1000 lb) and as systemic vibrational responses are driven by mechanically transmitted random vibration from the surrounding vibroacoustic environment. In this case, these mechanically transmitted random vibrations can occur through kinetic impacts or vibrations experienced during laboratory integration, shipment, on-site re-integration, and telescope slewing operations for ground-based operations. For balloon and orbital operations for this subsystem technology, greater magnitude low-frequency inputs can be experienced by the subsystem during launch and suborbital/orbital operations.

Prior to testing within the NASA GSFC VTF, Solidworks software simulations were performed to optimize qualification testing configurations. In particular using the Solidworks 2010 Simulation suite, Linear Dynamic Analysis, Random Vibrational Analysis, and Harmonic Analysis Software Sub-package testing was performed to simulate protoflight-
grade vibroacoustical testing at the NASA GSFC VTF. Initial simulations were performed to treat the PA2 subsystem as a summation of mass-spring-damper simple harmonic oscillator systems, undergoing forced vibration with damping from the test environment. The simulation strategy was selected to closely resemble the hardware configurations and applied forced vibrations that would later take place in the GSFC VTF, with preliminary vibrational test boundaries reflecting the minimum workmanship levels of the subsystem. Moving toward kinetic testing, as the ACTPol PA2 Polarimeter Array weighs less than 110 lb, a minimum workmanship random vibration test was ultimately recommended, where all verification tests needed to envelope the Maximum Expected Flight Levels (MFELs) plus 3 dB. It was ultimately projected that the operational environment of the ACTPol PA2 Polarimeter Array deployed to ACT will be sufficiently modeled by the low-frequency testing associated with verification at the minimum workmanship level, and that any MFEL verification beyond this would be completed subsequently to the ground-based MFEL level, to qualify the subsystem for future balloon and orbital launch environments. For a protoflight test, the NASA VTF standards led to 1 minute testing durations, at MFEL plus 3 dB, with a minimum component vibration workmanship test beginning at 6.8 g, for the ground-based scenario. The frequency inputs for all three scenarios (ground-based, balloon-based, and satellite-based) were ultimately run on a frequency range spanning 20–2000 Hz, with acceleration spectral density (g²/Hz) in <25 Hz frequency bandwidth steps, where the ground-, balloon-, and satellite-based tests corresponded to maximum inputs of 6.8 g, 10 g, and 25 g, respectively.

The NASA GSFC qualification testing run ultimately allowed the entire ACTPol PA1 subsystem to be subjected to random vibrational testing, to determine noise-levels and mechanical resonances of the focal plane and interface electronics assemblies (feedhorn array and partially populated mechanical detector stack proxies, as well as interface PCB assemblies) and determine critical damping solutions. The testing run was performed as is depicted in Figure 4.11, which illustrates the final testing configuration and focal-plane vi-
broacoustic sensor placement during the NASA Goddard Space Flight Center Vibroacoustic Testing Facility qualification testing, performed at maximum input levels run using the facility’s capabilities for sine-sweep, sine burst, random, and sinusoidal vibration testing. The specific inputs and durations are based on subsystem protoflight test standards published by NASA itself, and that the maximum expected flight levels (MFELs) for ground based telescope slewing, balloon-borne launch testing (10g), and satellite rocket launch testing (25g). The ultimate results matched the expected Solidworks simulations, and the test system (attached to the vibroacoustic test platform at GSFC via a custom designed mount, with design depicted in Figure 4.11) survived all inputs through the 25g level (note that after multiple 25g tests, the work-hardening of the hardware itself resulted in the l-brackets ultimately failing mechanically, though the system would never have to undergo multiple 25g inputs in a single mission profile - a future inflationary probe would be unlikely to undergo multiple launches!) The detection of vibrational resonances intrinsic to various components during initial testing runs at the NASA GSFC VTF allowed for design modifications to be made to dampen these resonances, which were mitigated in subsequent testing runs at the GSFC VTF, with these improved components integrated to all three ACTPol polarimeter array packages prior to the commencement of initial site operations. While the GSFC testing results indicated a design sufficiently robust for ground-based operations, with a configuration that could be considered appropriate for scaling to future balloon- and satellite-based platforms, a final check on the ultimate focal plane TES response to significant kinetic inputs to the receiver was performed prior-to and following deployment of the integrated receiver in Chile. Figure 4.12 shows the results of these so-called ‘ping’ tests performed at Penn and on the ACT site prior to ACTPol Season 1 operations. In this, the same vibrational inputs that produced a clear response during Penn testing for a subset of wafers were largely mitigated, so that following on-site deployment the ping-testing did not produce responses that exceed the detector noise levels - the changes in detector response were ultimately found to be the result of inconsistent tripod spring clamping, which
was entirely mitigated following the fabrication decision to subcontract to a precision sheet metal forming firm in Rochester, New York.

### 4.4 ACTPol Polarimeter Array Package Initial Performance Characteristics

Although the on site operational regimes developed for ACTPol science operations, as well as early science performance results will be described in subsequent Chapters for the ACTPol CMB Deep Field, galaxy cluster survey, and galactic field data sets, we provide here selected early ACTPol polarimeter array package performance results, shown in Figure 4.13, Figure 4.14, Figure 4.15, and Figure 4.16. Figure 4.13 shows on the left, the results of the ACTPol Season 1 150 GHz polarimeter array package (PA1) median detector sensitivity following one season of single-array deployment data, which indicated that even for a relatively poor PWV condition season that was experienced during ACTPol Season 1, with limited optimization required, excellent per-detector sensitivity was achieved (median detector sensitivity in noise equivalent temperature went as 340 $\nu K(2)^{1/2}$). On the right, the figure shows the ACTPol PA1 detector optical efficiency, or the power that is detected when a photon is incident on a detector. E.g. for ACTPol PA1 if we observe a 70mK blackbody, we can expect to detect only 60% of the incident power with the hexagonal arrays, and 47% for semihex 1A and 21% for semihex 2A - these efficiencies were ultimately deemed sufficient for ACTPol Season 1 operations and fabrication improvements across later seasons allowed for increased optical efficiencies to be gained across the entire focal plane at full deployment. Figure 4.14 illustrates ACTPol PA1 Season 1 operational results for detector saturation power $P_{sat}$, critical temperature $T_c$, and thermal conductivity $G$, which have target values of 13.5 pW, 150 mK, and 240 pW/K, respectively. In all, the semihexagonal and hexagonal subarray $P_{sat}$ values differed by 15pW and, as expected, performed with greater sensitivity than with MBAC; the semihexagonal and hexagonal subarray $T_c$ values 10mK, but this was
acceptable because the bath temperature provided by the dilution refrigeration system for Season 1 operations was sub-90mK - this would be problematic if bath temperature was much closer to $T_c$, of course; and $G$ values were found to be well within the acceptable target range for the initial deployment season. Figure 4.15 shows ACTPol PA1 Season 1 on-telescope saturation power measurements completed with full Lyot-stop aperature installed, in which it was shown that the introduction of a semicircular baffle structure reduced excess loading on the receiver since resultant detector $P_{sat}$ values increased. Finally, Figure 4.16 shows selected ACTPol Season 1 beam results taken at various ‘daytime’ and ‘nighttime’ UTCs (definitions discussed in greater detail in later Chapters), in which beam profiles are shown to be wider and more variable during the early afternoon, when primary and secondary mirror superstructures heat up and alignment degrades, while beam profiles are more compact, circular, and less variable during the evening, when primary and secondary mirrors cool and regain ‘nominal’ alignment - even though daytime beams were slightly degraded, data from both day and night were excellent, as will be discussed later.

4.5 Summary

Throughout this Chapter, we briefly characterized the principal design and operational performance drivers that yielded the design and ultimately fully-integrated ACTPol focal plane. This focal plane, which has thus far performed with excellent characteristics, has enabled initial operational qualification, and resultant CMB science data, which we will discuss in more detail in the Chapters, which follow. Next, we discuss the development of the operational protocols that were developed to enable the operation of ACTPol coupled to the ACT optomechanical superstructure with increased data coverage and efficiency in comparison to previous-generation ACT+MBAC results, ultimately leading to the initial CMB and galactic plane science data analysis, which is presented later.
Figure 4.7: (Left) An ACTPol 148 GHz hex wafer containing 127 pixels and 254 TESes. Each array consists of three hex wafers and three semihex wafers for a total of 522 pixels. (Middle) A single ACTPol pixel. The incident radiation couples to each detector via the central OMT antenna (the different fin shape than that in Figure 4.6 is a characteristic of the single-band versus multichroic design). Niobium microstrip lines carry the power to one of the two bolometer islands on the edges. (Right) An ACTPol TES bolometer. The power is deposited on the island as heat through the lossy Au meander. The island is thermally isolated from the bath, connected only through four SiN legs which also carry the TES bias and signal lines. The electrical power dissipated in the voltage biased MoCu superconducting “bilayer” monitors the power deposited in the lossy Au meander.
Figure 4.8: An overview of the characteristics of all four polarimeter array stack wafers for an example semihexagonal polarimeter wafer stack. The waveguide interface plate, or WIP, provides the waveguide interface between the exit aperture of the feedhorn array and the detector wafer, while providing co-planar thermal coupling, which is enhanced given that both the feedhorn array and WIP are fabricated from gold-plated silicon for improved thermal characteristic matching. The WIP wafer is 500 microns thick and has an additional 250 micron thick boss feature centered around each pixel. The polarimeter wafer houses both OMT and TES detectors and provides interface to the readout flex via interface bondpads, and is 275 microns thick. Behind the polarimeter wafer is the backshort cavity wafer, which provides a reflective surface between each pixel’s OMT microstrip, while providing an absorptive surface behind each TES detector via semicircular stycast-filled gulch features. The backshort cavity plate also provides mechanical standoff from the detector wafer traces to avoid shorting the readout traces via a backshort cavity plate corral feature, which has a 25 micron thickness and allows for a limitation of light escaping or reflecting around each pixel across the array. Finally, the backshort cap wafer is the top-wafer mechanical protection for the entire polarimeter wafer stack, and allows the gluch stycast to be contained, with a principal 500 micron wafer thickness. Epoxy holes are provided for assembly and coupling of the backshort cap and backshort cavity plate across the center of each wafer, while perimeter trenches present in the polarimeter wafer, backshort cavity plate, and backshort cap are provided for coupling of all layers to each other mechanically, while perimeter bondpads allow for thermal wirebond-coupling between detector stack wafers.
Figure 4.9: (Left) An assembled hex wafer viewed edge-on. A hex is read out using two PCBs, each serving four readout columns. The circuitry of each column includes a mux chip, an interface chip, and a wiring chip. The wiring chip provides superconducting 90° bend routing from the flex wire bonds to the interface chip wire bonds. Connections to the PCB for the SQ1 bias and feedback lines, SQ2 bias and feedback lines, and detector bias lines are made via aluminum wire-bonds. The detector bias lines are carried from the PCB to the wafer via the folded flex which is wire-bonded at either end. (Right) A fully assembled ACTPol array (PA2). The hex and semihex wafers are sitting on the feedhorn array in the center with the readout PCBs arranged vertically around the edge. The feedhorn apertures are pointed down in this photo.
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<td>199 ± 5</td>
<td>16 ± 2</td>
<td>276 ± 48</td>
<td>65 ± 5</td>
</tr>
<tr>
<td></td>
<td>FH6</td>
<td>H</td>
<td>142 ± 7</td>
<td>14 ± 4</td>
<td>469 ± 111</td>
<td>62 ± 2</td>
</tr>
<tr>
<td></td>
<td>SH3B</td>
<td>SH</td>
<td>135 ± 8</td>
<td>9 ± 2</td>
<td>259 ± 55</td>
<td>51 ± 2</td>
</tr>
<tr>
<td></td>
<td>SH4A</td>
<td>SH</td>
<td>150 ± 11</td>
<td>12 ± 3</td>
<td>320 ± 43</td>
<td>51 ± 8</td>
</tr>
<tr>
<td></td>
<td>SH4B</td>
<td>SH</td>
<td>129 ± 8</td>
<td>15 ± 5</td>
<td>436 ± 138</td>
<td>51 ± 2</td>
</tr>
<tr>
<td>12*PA3</td>
<td>2*FH2</td>
<td>HA</td>
<td>162 ± 2</td>
<td>11 ± 1</td>
<td>297 ± 13</td>
<td>83 ± 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HB</td>
<td>161 ± 2</td>
<td>12 ± 1</td>
<td>318 ± 17</td>
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<tr>
<td></td>
<td>2*FH3</td>
<td>HA</td>
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<td>12 ± 1</td>
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<td>HB</td>
<td>157 ± 2</td>
<td>12 ± 1</td>
<td>333 ± 16</td>
<td>75 ± 7</td>
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<tr>
<td></td>
<td>2*FH4</td>
<td>HA</td>
<td>152 ± 2</td>
<td>10 ± 1</td>
<td>293 ± 15</td>
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<td>HB</td>
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<td>10 ± 1</td>
<td>302 ± 15</td>
<td>37 ± 7</td>
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<td>SHA</td>
<td>148 ± 1</td>
<td>8 ± 1</td>
<td>240 ± 10</td>
<td>71 ± 3</td>
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<td></td>
<td></td>
<td>SHB</td>
<td>146 ± 2</td>
<td>8 ± 1</td>
<td>247 ± 13</td>
<td>79 ± 2</td>
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<td></td>
<td>2*SH1B</td>
<td>SHA</td>
<td>152 ± 2</td>
<td>10 ± 1</td>
<td>249 ± 13</td>
<td>70 ± 1</td>
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<tr>
<td></td>
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<td>9 ± 1</td>
<td>257 ± 7</td>
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<td>SHA</td>
<td>170 ± 1</td>
<td>13 ± 1</td>
<td>314 ± 11</td>
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<td></td>
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<td>SHB</td>
<td>169 ± 1</td>
<td>14 ± 2</td>
<td>339 ± 10</td>
<td>71 ± 4</td>
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Table 4.1: The measured average ACTPol detector parameter values by wafer. The “Wafer” column gives unique identifiers related to the fabrication generation. The “Type” column distinguishes hex (H) and semihex (SH) wafers; for PA3, the additional designator A (B) distinguishes the 97 GHz (148 GHz) devices. We tabulate the mean critical temperatures ($T_c$); the mean bias powers to bring the detectors to 90% of their normal resistances when the bath temperature is 80 mK in the absence of significant optical loading ($P_{\text{sat}}$); the mean thermal conductances from the detector islands to the bath ($G$); and the mean detector efficiencies ($\eta_{\text{det}}$).
Figure 4.10: Above: a Solidworks design created for the interface PCB principal readout chip components - the wiring chip, the MUX chip, and the Shunt/NyQuist chip - along with their interface readout wirebond design concept. Below: images of the BeCu tripod springs which are attached to the so-called ‘snaketongue’ assemblies to provide pressure to planar couple the hexagonal and semihexagonal polarimeter wafer stacks (snaketongue/tripod assembly is shown for a hexagonal wafer coupling subassembly in 4.3.)
Figure 4.11: The final testing configuration and focal-plane vibroacoustic sensor placement during the NASA Goddard Space Flight Center Vibroacoustic Testing Facility qualification testing, performed at maximum input levels run using the facility’s capabilities for sine-sweep, sine burst, random, and sinusoidal vibration testing.
Figure 4.12: The results of the so-called ‘ping’ tests performed at Penn and on the ACT site prior to ACTPol Season 1 operations. In this, the same vibrational inputs that produced a clear response during Penn testing for a subset of wafers were largely mitigated, so that following on-site deployment the ping-testing did not produce responses that exceed the detector noise levels - the changes in detector response were ultimately found to be the result of inconsistent tripod spring clamping, which was entirely mitigated following the fabrication decision to subcontract to a precision sheet metal forming firm in Rochester, New York.
Figure 4.13: Left: the results of the ACTPol Season 1 150 GHz polarimeter array package (PA1) median detector sensitivity following one season of single-array deployment data, which indicated that even for a relatively poor PWV condition season that was experienced during ACTPol Season 1, with limited optimization required, excellent per-detector sensitivity was achieved (median detector sensitivity in noise equivalent temperature went as $340 \nu K(2^{1/2})$).

Right: the figure shows the ACTPol PA1 detector optical efficiency, or the power that is detected when a photon is incident on a detector. E.g. for ACTPol PA1 if we observe a 70mK blackbody, we can expect to detect only 60% of the incident power with the hexagonal arrays, and 47% for semihex 1A and 21% for semihex 2A - these efficiencies were ultimately deemed sufficient for ACTPol Season 1 operations and fabrication improvements across later seasons allowed for increased optical efficiencies to be gained across the entire focal plane at full deployment.
Figure 4.14: ACTPol PA1 Season 1 operational results for detector saturation power $P_{sat}$, critical temperature $T_c$, and thermal conductivity $G$, which have target values of 13.5 pW, 150 mK, and 240 pW/K, respectively. In all, the semihexagonal and hexagonal subarray $P_{sat}$ values differed by 15pW and, as expected, performed with greater sensitivity than with MBAC; the semihexagonal and hexagonal subarray $T_c$ values 10mK, but this was acceptable because the bath temperature provided by the dilution refrigeration system for Season 1 operations was sub-90mK - this would be problematic if bath temperature was much closer to $T_c$, of course; and G values were found to be well within the acceptable target range for the initial deployment season.
Figure 4.15: ACTPol PA1 Season 1 on-telescope saturation power measurements completed with full Lyot-stop aperture installed, in which it was shown that the introduction of a semicircular baffle structure reduced excess loading on the receiver since resultant detector $P_{sat}$ values increased.
Figure 4.16: Selected ACTPol Season 1 beam results taken at various ‘daytime’ and ‘night-time’ UTCs (definitions discussed in greater detail in later Chapters), in which beam profiles are shown to be wider and more variable during the early afternoon, when primary and secondary mirror superstructures heat up and alignment degrades, while beam profiles are more compact, circular, and less variable during the evening, when primary and secondary mirrors cool and regain ‘nominal’ alignment - even though daytime beams were slightly degraded, data from both day and night were excellent, as will be discussed later.
Part III

ACTPol Operational Performance and Early Science
Chapter 5

ACTPol Operations and Data Coverage

The deeps have music soft and low,
when winds awake the airy spry,
it lures me, lures me on to go
and see the land where corals lie.
The land, where corals lie.

By mount and mead, by lawn and rill,
when night is deep, and moon is high,
that music seeks and finds me still,
and tells me where the corals lie.
And tells me where the corals lie.

from Edward Elgar’s “Sea Pictures: Where Corals Lie”

Across the first two sections of this dissertation manuscript, background was provided
regarding both the scientific and technology development motivations of an experimental cosmology platform such as ACTPol, a polarization-sensitive, millimeter-wavelength receiver upgrade for the Atacama Cosmology Telescope.

Part I provided the scientific basis that justified the development of the ACTPol receiver, including the direct characterization of the temperature and polarization anisotropies of the Cosmic Microwave Background at small-angular-scales, allowing for probes of cosmological parameter constraints and power spectrum measurements to better assess predictions of $\Lambda$CDM cosmology models of the Universe. The rich scientific portfolio accessed by an experimental cosmology platform like ACTPol would thus allow an extended understanding of our cosmic origins, the growth of large-scale structure in the Universe, probes of galaxy clusters detected via the Sunyaev-Zel'dovich effect, and would provide the technical and scientific basis for future observational probes of the Cosmic Microwave Background to test inflationary models of the primordial Universe.

Part II included a comprehensive overview of the integrated component, subsystem, and systems-level technologies required to acquire data that could enhance our understanding of these core objectives in contemporary experimental cosmology research, especially focused on probes of the Cosmic Microwave Background at small-angular scales. This included the historiographic contextualization of the Atacama Cosmology Telescope under ACTPol-generation receiver operations in the broader continuum of Atacama-based astronomy and cosmology research, as well as the description of the characteristics of the Atacama Cosmology Telescope superstructural warm optical system, and the development of ACTPol-era upgrades to this optomechanical environment and novel logistical deployment system upgrades. The following two chapters included an overview of the assemblage of novel space technologies developed for the critical realization of the ACTPol receiver itself, including the development of essential subsystems, including a field-deployable dilution refrigeration system, high-purity silicon reimaging optical elements, and three transition edge sensor polarimeter array packages, two with 150 GHz sensitivity (PA1 and PA2), and a third mul-
tichroic polarimeter array with simultaneous polarization sensitivity at 90 GHz and 150 GHz (PA3).

Taken together the first two Parts of this dissertation allowed for a parameter space to be defined both for contributions to be made toward the pursuit of grand challenges in cosmology through direct observation of the Cosmic Microwave Background at well-defined energy and sensitivity regimes, as well as the extension of critical space technologies necessary for the continued advancement of millimeter-wavelength imaging technologies for cosmology and allied-field applications. This section, Part III, includes two chapters under which resultant data sets probing areas of this parameter space are explored. The Chapter, which follows, provides a brief overview of the nature of, and challenges encountered during the three-stage deployment and operation of the ACTPol receiver. These three stages include the initial deployment of the ACTPol receiver with PA1 installed (single 150 GHz polarimeter array) in 2013, a second-stage of deployment in 2014 (dual 150 GHz polarimeter arrays), and a final-stage of deployment in 2015 with the compliment of all three polarimeter arrays, including the multichroic 90/150 GHz array package. During each season, operational protocols were developed and enhanced, which are described, along with their quantifiable impact on increasing science observation efficiency during the span of ACTPol receiver operations. Finally, a brief overview of observational data coverage for ACTPol operations are provided, which offers a prelude to an exploration of ACTPol early cosmology and associated science results, in the next Chapter. In all, the deployment, operations, and data acquisition and coverage discussion of this Chapter should inform the reader not only of the manner by which ACTPol was able to operate as an effective experimental cosmology facility throughout its operational lifetime, but also provide scientific and technological (as well as operational) lessons-learned to enhance the potential for success of next-generation observational platforms, whether they be ground, balloon, or satellite-borne, for the precision measurement of the Cosmic Microwave Background toward possible future confirmation of models of inflationary cosmology.
5.1 Overview of ACTPol Deployment Operations

The Section, which follows, provides an overview of the key milestones and challenges that occurred over the deployment and operations timeline of the ACTPol receiver integrated with the ACT telescope superstructure through all three phases of ACT+ACTPol qualification, characterization, and science observations. The following two subsections are based on text provided as internal reporting under the auspices of a NASA Space Technology Research Fellowship grant, and in particular focus on details of Atacama-based on-site deployment and North America-based remote observing operations between 2013 and 2015. Given the experiential and real-time development characteristics described, a first-person perspective has been maintained. Generally, this deployment and operations overview spans the period beginning in mid-January 2013, following the shipment of the ACTPol receiver and supporting logistical systems from the University of Pennsylvania to the ACT site (via the Panama Canal to the Port of Iquique, Chile before ground transport to Cerro Toco), and providing detail through full ACTPol deployment, though with a particular focus on ACT+ACTPol Season 1 and Season 2 operations. Principal deployment logistics systems, including the ACTPol Receiver Alignment Mechanism (RAM), ACTPol RAM Access Mobility Platform (RAMP), and ACTPol Critical Alignment Mount (CAM) referenced in this section correspond to the systems and their operational deployment capabilities described earlier, in Chapter 2.

5.1.1 Season 1 (2013) Operational Deployment Overview

After over 48 hours of continuous travel from NIST-Boulder to Chile at the end of February 2013, I arrived at the ACT base camp in San Pedro de Atacama (SPdA), Chile, where my academic advisor from the University of Pennsylvania, Prof. Mark Devlin was already positioned from the previous day. The next morning, along with our initial site team of Prof. Devlin, another graduate student from Penn, and two Chilean site engineers, we...
commenced initial work on the unpacking and setup of site operations at the ACT site on Cerro Toco (located at an elevation of 5190m, or 17,000 feet above sea level), which is an approximately 75 minute drive one-way from the ACT base camp in SPdA. The day before my arrival, the ACTPol 40 foot shipment container had arrived on the ACT site and its principal pallets were unloaded. For the planning and project management of this initial ACTPol PA1 deployment campaign, I was tasked with creating a Gantt chart to manage project resources, personnel, international-logistics milestones, and to optimize the work flow, from initial unpacking operations, until the beginning of first light with the ACTPol receiver on the ACT telescope superstructure again, project objectives of critical importance for efficient and successful realization of future satellite-based CMB polarization probe platforms operating at broader project scales. Figure 5.1 includes a partial initial version of this Season 1 Gantt chart that was produced prior to departure, although due to the nature and uncertainty of the work, I dynamically updated the chart structure and resource-loading during the entirety of the campaign and into our second deployment campaign in 2014, an example version of which is included for illustration in Figure 5.2 (e.g. for myself, I was originally scheduled to remain on-site until early May, although due to a variety of factors that led to the lengthening of the deployment campaign, I ended up remaining on site continuously until late June 2013).

During the first half of March, on-site operations focused on the setup of systems critical for enabling work on-site itself. Since the suspension of operations with the previous (first-generation) ACT receiver, the Millimeter Bolometer Array Camera, or MBAC, in early 2011 described earlier in this dissertation manuscript, the ACT site was nominally completely shut down (for ACT operations), during which time a new site high-bay facility was constructed for work integrating the ACTPol receiver as well as associated logistical deployment systems, which were principally described in Chapter 2. During the first days of the ACTPol deployment campaign, work was completed to complete the readiness of this high-bay facility, which ultimately, was deemed to be an extremely valuable and effective
site upgrade, as the potential for working on ACTPol integration in a standard shipping container (as was done in the case of MBAC) would have been nominally untenable, given space and infrastructure constraints.

Figure 5.3 illustrates an overview of the principal stages of ACTPol receiver deployment completed during the three seasons of optomechanical and polarimeter array package integration and CMB observation operations, spanning Austral Summer 2013 through Austral Summer 2015. The primary ACTPol receiver deployment flow began on 15 January 2013 with the shipment from North America to the ACT site in Chile of all requisite receiver, cryogenics, logistical support, and polarimeter array package systems required for the commencement of ACTPol integration at PA1 deployment levels. ACTPol integration and deployment thus began on 28 February 2013 and continued through receiver integration, on-sky testing, and integration with the ACT telescope optomechanical superstructure completed by 15 May 2013. Following on-telescope cryogenic operation and initial characterization, the ACTPol receiver was configured for initial observing operations, culminating with first light on 17 July 2013. The ACTPol first season then completed on 4 January 2014, and was followed by PA2 integration in Spring 2014, with first light with PA1 and PA2 deployed to the ACTPol receiver on 26 June 2014. The ACTPol second season continued until the close of 2014, and was immediately followed by the deployment of PA3, with full-deployment first light (with the ACTPol receiver operating with full PA1, PA2, and PA3 operation) commencing in late February 2015.

Returning to the first ACTPol operational season, work completed during the first weeks of the ACTPol PA1 site deployment included initial site setup, initial integration of selected critical site logistics systems (e.g. the ACTPol Receiver Alignment Mechanism (RAM), and installation RAMP systems), and also included pre-inspection of instrumentation integral to the operation of ACTPol itself, including evaluation of the post-shipment characteristics of the ACTPol cryostat, dilution refrigeration system, and PA1 array package. Following this initial work, during which all systems were deemed unharmed from the six-week sea
shipment, and the dilution refrigeration system was successfully tested in its test dewar (outside of the ACTPol cryostat), work shifted to the integration of the ACTPol receiver up to deployment of the PA1 optomechanical and polarimeter array systems, and ultimately, all cryogenics within the ACTPol cryostat. These integration operations lasted in duration from the second week in March until early April 2013, at which point dual milestones were reached simultaneously – namely, the first full and successful integration of the ACTPol receiver at altitude and the beginning of the first complete cooling cycle of the dilution refrigerator completed on site in the ACTPol cryostat. In point of fact, that the complete integration of the ACTPol receiver and associated systems in the ACT site high-bay lasted only approximately five weeks exceeded expectations. This was especially notable given that significant issues were encountered during testing of the PT410 pulse tube cryogenic cooling system, which is used to cool the 40K and 4K stages of the ACTPol cryostat and back the dilution refrigerator issues which were tackled in parallel to cryostat integration work in progress simultaneously on-site. Additionally, this timescale indicated increased effectiveness resulting from the extensive debugging and experience gained integrating the ACTPol cryostat at sea level prior to field-deployment in the Penn high-bay facility, which made the limited hours that could be spent integrating on site (usually 10-12 hours daily while battling the effects of altitude at 17,000 feet, as opposed to the 12-18 hour days typical during previous integration work at Penn) more efficient to keep on pace with previous integration runs in less harsh conditions.

Following work to integrate and cool down the ACTPol receiver, in mid-April 2013, the ACTPol receiver successfully reached its lowest base temperature to-date, assisted in part from low ambient site temperatures, and rapidly declining weather conditions (e.g. extreme winds cooling the site), allowing for initial on-sky testing of the ACTPol receiver, although off of the ACT telescope superstructure. These testing runs were completed on-sky with the ACTPol receiver positioned outside of the ACT on-site high bay facility, observing a patch of sky situated between the ACT ground screen and ABS experiment, roughly 45° in elevation
Figure 5.1: ACTPol Season 1 operational-deployment resource and timeline management Gantt chart.
Figure 5.2: ACTPol Season 2 operational-deployment resource and timeline management Gantt chart.
from the horizon. Nominally, all testing that was completed at Penn using test sources (e.g. cryogenic and room temperature sources) were repeated both on the sky and during dark testing (e.g. with a non-transparent window covering the ACTPol PA1 optomechanical tube input aperture), including vibroacoustical testing, I-V curve acquisition, detector wafer biasing, testing of MUXing rates, time constant measurements, beam mapping, and thermal loading measurements. Out of all of these tests, perhaps the most critical tests that were completed had to do with beam mapping and thermal loading from on-sky sources tested over a three-week period at various levels of precipitable water vapor, or PWV, which naturally changed over the course of testing due to fluctuations in atmospheric conditions over the site. Due to physical constraints associated with the length of cryogenic hosing connecting the ACTPol dilution refrigerator to its gas handling system manifold (that had to remain within the threshold of the ACT site high-bay facility) the ACTPol receiver could not be pointed in such a way to absolutely guarantee that none of its optical beam was intersecting sources of ground pickup (e.g. such as the Atacama B-Mode Search, or ABS, and the ACT telescope superstructure and ground screen). Because of this, loading slightly higher than expected could not be necessarily ruled an issue intrinsic to the system, and planning was made for further testing of ACTPol within its relevant observing environment, critically aligned in the ACT superstructure. In general, however, the results of this period of instrumental characterization was sufficiently successful to result in a decision to install the ACTPol receiver for initial operations on the ACT telescope warm optomechanical superstructure itself.

Following initial on-sky testing (off the ACT telescope) all efforts were then directed, beginning in the second week of May 2013, to the completion of site logistics hardware installation to enable the installation of the ACTPol receiver into the ACT receiver cabin on the telescope. After several days of installation and optimization of these systems, and thorough testing of the ACTPol RAM installation system with partial mechanical load, the ACTPol receiver was installed on the ACT telescope. In a significant improvement
Figure 5.3: An overview of the principal stages of ACTPol receiver deployment completed during the three seasons of optomechanical and polarimeter array package integration and CMB observation operations, spanning Austral Summer 2013 through Austral Summer 2015. The primary ACTPol receiver deployment flow began on 15 January 2013 with the shipment from North America to the ACT site in Chile of all requisite receiver, cryogenics, logistical support, and polarimeter array package systems required for the commencement of ACTPol integration at PA1 deployment levels. ACTPol integration and deployment thus began on 28 February 2013 and continued through receiver integration, on-sky testing, and integration with the ACT telescope optomechanical superstructure completed by 15 May 2013. Following on-telescope cryogenic operation and initial characterization, the ACTPol receiver was configured for initial observing operations, culminating with first light on 17 July 2013. The ACTPol first season then completed on 4 January 2014, and was followed by PA2 integration in Spring 2014, with first light with PA1 and PA2 deployed to the ACTPol receiver on 26 June 2014. The ACTPol second season continued until the close of 2014, and was immediately followed by the deployment of PA3, with full-deployment first light (with the ACTPol receiver operating with full PA1, PA2, and PA3 operation) commencing in late February 2015.
**Figure 5.4:** Illustration of the raw data response of an individual TES detector operating during a planetary test calibration observation of Saturn on 13 July 2013 under ACTPol first light operations at PA1 deployment level.
on the previous installation logistics hardware used during ACT+MBAC operations, only
90 seconds were required once in place for the motion of the ACTPol receiver from the
ground installation tracks into the ACT receiver cabin, compared with several hours for the
same motion with MBAC. This in turn allowed for initial mounting of the ACTPol receiver
on the ACT telescope within a single (12 hour) day, which proceeded without incident on
the first deployment attempt for ACTPol hence strengthening the importance of the time
spent at Penn to fully test all of these systems in as relevant an environment as could be
reproduced in central Philadelphia, during Autumn 2012, as was discussed in Chapter 2.
After installation of the ACTPol receiver on the ACTPol Critical Alignment Mount (CAM),
the next several days were utilized for the installation of all support systems for ACTPol
operations, including cryogenic and data acquisition platforms.

Shortly after completion of all hardware and support infrastructure installation to the
ACT receiver cabin, and the beginning of the first cooldown of the ACTPol receiver on the
ACT telescope, the weather on Cerro Toco, which up until that point in the deployment
campaign had cooperated favorably in terms of precipitation (e.g. in spite of consistent
sub-zero Celsius temperatures and extreme winds, no snow had impacted the site), a major
weather event was encountered across the Chajnantor Plateau region around Cerro Toco
(home to a myriad of telescopes, including ALMA), depositing enough snow that it made
transit to the site impossible for several days. Due to consistent high-winds, snow drifting
over the off-road portion of the access road to the ACT site made it essentially impossible to
reach the site other than on-foot, even with tire chains. Additionally, the highway leading
up to our offroad site access route had been officially closed off by Chilean state police due
to weather conditions, although this checkpoint was only staffed from 6AM to 6PM daily.
In spite of waiting a few days for the conditions to improve, the necessity to reach the
site to ensure the successful completion of the first on-telescope cooldown and to maintain
the potential of an on-schedule first light, the decision was made to drive around the police
barricade before it was set up very early in the day (ultimately, after receiving authorization
for this maneuver from the local authorities), to attempt to drive up the ACT access road with all-terrain chains as far as possible, and then to trek in on foot up to the site at 17,000 feet the remainder of the distance. As a result, departing before 5AM, our team was able to pass around the unstaffed police barricade, and make it to the front road by dawn, and then made it to within a few kilometers of the site, from which point a subset of the team was able to use trekking poles, snowshoes, and other equipment to climb the final few kilometers up almost 1000 feet in elevation to the ACT site. This team of 3-4 people, which during this initial weather event included myself on one trek, made various successful ascents and reached the site for four consecutive days, hence allowing for the cooling to be brought to a successful completion, such that upon opening of the road by grader crews over a week after the initial snowfall, work could proceed with the final alignment and characterization of the camera positioning within the telescope superstructure to allow for first light.

The last week in May, immediately following successful cooldown of the ACTPol receiver on the ACT telescope superstructure, work was completed with a small team from Universidad de Catholica (Santiago, Chile), as well as an expert from the private sector in photogrammetry, to complete the characterization of the alignment of the ACT telescope primary and secondary reflectors, as well as the ACTPol receiver position. The procedure associated with both precision laser-tracking and photogrammetry methods of telescope and receiver alignment was detailed in Chapter 2. The photogrammetry expert was brought in to demonstrate the proof of principle of a custom photogrammetry system for system alignment and drift diagnostics to potentially be utilized during the run of ACTPol in lieu of the current system of characterization using a Faro laser tracking system, which was utilized during MBAC operations and was also used for comparison of results to the photogrammetry system for the initial ACTPol alignment. Over two consecutive all-night sessions, the entire ACT telescope superstructure was characterized with respect to critical alignment positioning using both the laser tracker and photogrammetry system, and additionally, the ACTPol receiver was positioned using novel critical alignment mounting structure. Before
the receiver was characterized or moved into its final critical alignment position, it was already within 1 centimeter from the critical alignment position, which needed to be within a 0.5 cm tolerance of the critical alignment position. In spite of this, it still required several hours to move the cryostat into tolerance within the optical system of the telescope. One large takeaway from this work was the comparative ease by which the photogrammetry system could survey the entire instrument and telescope to the same precision as the existing Faro laser tracking system. Once the ACT primary, secondary, and receiver are fully targetized, the photogrammetry system operated with its interface software can survey the entire ACT system within tens of minutes, compared to the tens of hours required with the Faro, and additionally, the passive operation of the photogrammetry system can enable in-situ characterization of the ACT telescope during operations, hence leading to a better understanding of observing systematics across telescope scanning than was previously available.

Following this effort, and battling through several subsequent weather events, first-light was achieved for the PA1 deployment of the ACTPol receiver in mid-July 2013, in the form of initial planetary calibration tests, with the first test observation completed on 13 July 2013 with a calibration test observation of Saturn. Figure 5.4 illustrates the raw data response of an individual TES detector operating during a planetary test calibration observation of Saturn on 13 July 2013 under ACTPol first light operations at PA1 deployment level. Shortly after the commencement of initial Season one planetary calibration operations, the return of sustained severe inclement weather events at the ACT site resulted in a temporary suspension of ACT+ACTPol observing operations between 21 July 2013 and late-August 2013.

Following the resumption of site operations, nighttime planetary calibration observations continued until mid-September 2013, when ACTPol observations marked another significant Season one milestone - namely the transition to near 24-hour observing operations: the first time this continuous-operations paradigm was successfully demonstrated with a polarization-sensitive receiver coupled to the ACT telescope optomechanical superstructure.
During this period, daily operations also dynamically introduced test and then principal CMB science observing fields into the observing operations scripts with limited ACTPol CMB deep field observations completed at night. From mid-September until mid-October 2013, observations were further advanced to a state in which sufficient nighttime planetary calibration observations were completed to allow for near-continuous nighttime CMB deep field observations, with planetary calibration observations completed during the daytime. From mid-October to mid-November 2013, CMB science observations were extended to take place both overnight and in the morning, followed by afternoon galactic and planetary calibration observations. Finally, from mid-November 2013 until the end of Season one, the final, nominal science observational mode was reached, in which near 24-hour CMB deep field observations were completed, with afternoon, as-required planetary calibration observations, as well as occasional observations of Tau A, which would be used, along with galactic field observations of the Milky Way Galaxy for polarization calibration of ACTPol operations. Figure 5.5 illustrates the ACTPol Season one final observing strategy, including the ACTPol Season one nominal CMB observing strategy. Under this observing regime, each observing day would commence with a brief suspension of observations to enable dedicated site operations access of the telescope to complete any required minor maintenance and to complete the ACT site daily checklist, in which key site operations characteristics are recorded, generally taking place between 19:00-19:45 UTC. Following the completion of site access operations, ACT+ACTPol observing operations would resume, proceeding with a suite of planetary calibration observations from 19:45-22:00 UTC, ensuring that planetary targets were safely displaced from the location of the Sun to avoid damage to receiver systems associated with near-or-direct observation of solar radiation. With planetary calibration observations completed, ACTPol principal science observations would commence in two phases: between 22:00-12:30 UTC primary observations of ACTPol CMB deep fields and galactic strip fields were completed (with occasional observation of planetary calibration target Uranus), and then between 12:30-19:00 UTC continued observation of ACTPol CMB
deep fields were completed. Ultimately, this successful operational paradigm continued until the close of ACTPol Season one operations on 4 January 2014.

5.1.2 Season 2 and 3 (2014 and 2015) Operational Deployment Overview

In order to maintain and extend the momentum of research achievements associated with the ACTPol PA1 on-site deployment to the ACT site in Chile (from late-February to late-June 2013), an up-tempo, aggressive approach was taken for ramping-up PA2 site-deployment operations, and resumption of observing operations with PA2 installed, and continued throughout the conclusion of this grant period. To achieve this goal, work continued directly from that of the initial integration even during season one observing operations, toward the final integration and installation of the ACTPol PA2 polarimeter array package during ACT+ACTPol Season two deployment operations in 2014, the full-complement of PA2 optomechanical elements, as well as selected subsystem components of the ACTPol PA3 module, and eventually final deployment of all detector and cryogenics components at full-integration levels. Throughout late 2013 and into 2014, work was completed concerning instrumentation development, design work and planning with the ACTPol polarimeter array wafer fabrication team at NIST-Boulder toward the finalization of silicon mechanical wafer designs, which would constitute the waveguide interface and backshorting elements of the ACTPol PA3 polarimeter array wafer stacks. Final confirmation and release for fabrication of these elements took place in early-April 2014 during an on-site research at NIST-Boulder. Though significant progress was made between first light and early-2014 to this end, due to a Congressional impasse that resulted in a lapse in federal appropriations and a subsequent shutdown of the U.S. Government including Department of Commerce NIST-Boulder functions operating under non-appropriated or multi-year funds for much of October 2013, the entire design and fabrication effort was significantly delayed, and momentum was only regained after the NIST-Boulder fabrication effort could be fully ramped up in late-October and early-November 2013, meaning that the normal schedule for the ACTPol
Figure 5.5: ACTPol Season one final observing strategy, including the ACTPol Season one nominal CMB observing strategy. Under this observing regime, each observing day would commence with a brief suspension of observations to enable dedicated site operations access of the telescope to complete any required minor maintenance and to complete the ACT site daily checklist, in which key site operations characteristics are recorded, generally taking place between 19:00-19:45 UTC. Following the completion of site access operations, ACT+ACTPol observing operations would resume, proceeding with a suite of planetary calibration observations from 19:45-22:00 UTC, ensuring that planetary targets were safely displaced from the location of the Sun to avoid damage to receiver systems associated with near-or-direct observation of solar radiation. With planetary calibration observations completed, ACTPol principal science observations would commence in two phases: between 22:00-12:30 UTC primary observations of ACTPol CMB deep fields and galactic strip fields were completed (with occasional observation of planetary calibration target Uranus), and then between 12:30-19:00 UTC continued observation of ACTPol CMB deep fields were completed.
PA2 wafers, and thereby the ACTPol PA3 wafers were directly impacted by this act. The several week delay in this design and fabrication effort resulted in a roughly equivalent or greater setback in the overall deployment schedule for the final two ACTPol optomechanical and polarimeter array assemblies, since the detector array and silicon mechanical element wafer fabrication work at NIST-Boulder is a fundamental area in the critical path to deployment of the fully-integrated ACTPol receiver with its full complement of focal plane and optical subassemblies. Ultimately, this resulted in the decision during 2014 to forego initial planning to deploy both PA2 and PA3 polarimeter array packages during Season two, and instead move to a staged approach in which ACTPol PA2 elements were deployed during early-2014 and final integration of the PA3 multichroic focal plane within the ACTPol receiver would take place during Season three of ACT+ACTPol operations, specifically in Austral Summer 2015. Such a conclusion was arrived at to allow for science and commissioning data to be taken using ACTPol at PA1 and PA2 deployment levels on the ACT telescope optomechanical superstructure until the PA3 focal plane was prepared for final installation, and the end of the normal observing season was reached for ACTPol Season 2 observing operations at the end of 2014. Thus, the final stage of ACTPol deployment, once set to begin in early January 2014, was delayed for commencement in early 2014 (for ACTPol PA2) and early January 2015 (for ACTPol PA3).

Returning to the earlier discussion of the ACTPol Season two PA2 and associated instrumentation deployment campaign, following the season one site shutdown operations run, work shifted from the field back to Penn to commence the rapid design, fabrication, and testing of upgraded cryogenic thermal conduit components, now fabricated out of ultra-high-purity 5N grade copper, which required an extremely efficient logistical coordination between several subcontractors, allowing me to have all components to hand-carry down to the ACT site in late February 2014. With these components in hand by late-February 2014, I returned to Chile for the second time in two months, following a short shift to suspend season one observing operations in early January 2014, at which point I completed
a three-week integration campaign to modify existing systems to allow for the installation of these upgraded cryogenic components. During this run, a full polarimeter array package diagnostic sub-operation was completed. Unlike previous array-diagnostics work that was completed in the harsh conditions of the ACT site high-bay facility, given both altitude and dust considerations, the ACT collaboration leveraged a partnership that was forged with the mid-altitude ALMA Operational Support Facility (OSF) science and technical staff to allow our team to work in a high-purity cleanroom facility at the OSF. A full description of the strategic and operational advantages to operations within the ALMA OSF was included in Chapter 2. The array package diagnostics work that was completed at the OSF included effectively resolving an electrical short that had crippled a small percentage of operational detectors that would then be able to be included in the ACTPol operational detector yield continuing in Season 2, as well as replacing and upgrading the entire cryogenic clamping apparatus used to couple the detector array stacks to the Au-plated silicon feedhorn array.

The inter-season cryogenic upgrade integration campaign was completed on 12 March 2014. Ultimately, due to several potential cryogenic issues associated with the rapid integration of the ACTPol dilution refrigeration system, a second cooldown was completed following a complete receiver disintegration and re-integration between mid-April and mid-May 2014 in a third site operations run in Chile. This cryogenics run ultimately resulted in more conclusive evidence in the improvement in cryogenic performance of the ACTPol system with these improved thermal conduit components, which then allowed for the go-ahead of deployment of the ACTPol PA2 polarimeter array and optomechanical components, as well as selected ACTPol PA3 components to the ACTPol receiver for the first time. The work associated with principal receiver upgrade operations for ACT+ACTPol Season two operations occurred between mid-May and late-June 2014, on the ACT site in Chile, with the ultimate completion of the installation-phase of this PA2 deployment completed over a 12-day period from 1-12 June 2014, following a several day trip back to Philadelphia to ensure completion of modification to components critical to the ACTPol
PA2 deployment at the end of May 2014. (Aside - from an operational and international supply-chain logistics perspective, the modification of this component, the 1K optics tube extension cylinder, needed to take place in the Penn precision machine shop, from which it had originated. Given the logistical difficulty, customs challenges, and cost associated with rapid international shipment of medium-and-large-scale mechanical and electrical components between Chile and the United States, it is often best practice and most cost-effective to simply hand-carry components to and from the site for modifications via commercial airline connections).

Thus, between December and July 2014, significantly more than half of my time had been spent in Chile during four separate deployments to South America, to ensure the successful deployment of the ACTPol PA2 polarimeter array package, once again underscoring the importance of travel support to allow for the successful completion of technology development goals central to pathfinder experimental cosmology facilities like ACTPol. The work completed throughout June 2014, which included the installation of the 40K and 4K optomechanical subassemblies for PA2 and PA3, as well as the 1K and 0.1K optomechanical subassembly and polarimeter array package subassembly for PA2, allowed for the reintegration of the entire ACTPol receiver in the ACT site high-bay facility. Following this integration work, the entire ACTPol receiver was again installed over a several day period utilizing the custom ground-to-telescope integration platform utilized for Season 1 installation and disintegration from the ACT telescope superstructure. Following this effort, in mid-July 2014, first light was achieved, this time for the dual deployment of the ACTPol PA1 and PA2 polarimeter array submodules, after which season two observing operations began, and continued through the deployment of PA3 in January 2015. Given the lessons-learned throughout the deployment of ACTPol during Season one and Season two, within which PA1 and PA2 were integrated, the deployment of PA3 was ultimately required the shortest upgrade period during any individual ACTPol observing season, spanning just six weeks, with first-light and full operational deployment (e.g. ACTPol with PA1, PA2, and
PA3 integrated) taking place in late-February 2015. This deployment efficiency increase,
thus led to additional time during the season for CMB science coverage during Season
three in comparison to previous Seasons. With the commencement of full-deployment ob-
serving operations in Austral Autumn 2015, principal experimental deployment operations
associated with the ACTPol receiver was completed, and would continue through the final
completion of ACTPol operations and commencement of Advanced ACTPol operations,
which will be briefly described in Chapter 7.

5.2 ACTPol Remote Observing Operations and Efficiency

As described earlier in Chapter 2, the introduction of a number of novel integrated tech-
nologies to comprise ACTPol led to the ability of ACT+ACTPol operations to access new
and broader data sets in comparison to ACT+MBAC operations. The introduction of in-
creased sensitivity TES-based polarimeter arrays on ACTPol operating at sub-100 mK bath
temperatures allowed for access of unprecedented sensitivity in mapping of the Cosmic Mi-
crowave Background, probed now in both temperature and polarization. The inclusion of
a dilution refrigeration system, described in Chapter 3 allowed for increased data coverage
afforded by that system’s capability to provide a near-continuous base temperature without
the necessity of daily cryogenic recycling, thus opening the ability of ACT to operate on
a near 24-hour uninterrupted basis. Site logistical infrastructure, including the upgraded
high bay facility and increased collaboration with the ALMA Observatory collaboration and
shared use of the ALMA Operational Support Facility for post-shipment polarimeter array
package integration and testing also obviates the need for inter-seasonal receiver shipment
to North America for array and optical upgrade installation.

Taken together, these technology upgrades resulted in science observations under ACT-
Pol also requiring the development of an entirely new operational paradigm that shifted pri-
mary observing operations control to a remote observing, North American observer model,
rather than the principally site-centric observing model of the MBAC era. This section
describes the development of some of the integrated operational protocols developed, and continually refined and upgraded during ACTPol’s observing operations. These range from the development of a Remote Observing Coordinator (ROC) staff operating on 24-hour shifts across every continent of the Atlantic rim, to enhanced site communications and protocols, to telescope scheduling improvements, all of which allowed for a maximization of operational efficiency to allow for increased data coverage (both science and calibration data) over ACT in its previous generation. Additionally, the proliferation of new ubiquitous technologies between the final season of MBAC in 2009 and the progression of ACTPol operations between 2013-2015, most notably the prevalence of high-speed mobile internet communications on smart phone platforms, transformed ACTPol operations in surprising ways, moving from fixed control room and computer terminal platforms to continuous operations that could be monitored, and issues troubleshooting, with mobile connectivity.

5.2.1 Development of Remote Observing Operational Protocols

Following the deployment of ACTPol for Season one ACT+ACTPol observing operations, work immediately commenced in North America to continue to develop not only the calibration and CMB science targeting priorities for ACTPol Season one and beyond, but also the operational paradigm under which observational efficiency would be maximized. For this effort, several discussions and meetings were held between myself and ACTPol remote operations personnel at Princeton University, both via telecon sessions and via several in-person meetings at Princeton, in which remote observing operational efficacy was discussed. The principal initial result of these planning initiatives was the establishment, organization, and administration of a team of ACTPol collaboration members who would serve as North American Remote Observing Coordinators, often referred to as ROCs. Figure 5.6 illustrates a sample schedule of Remote Observing Coordinator shifts during ACTPol Season two operations in September 2014. The operational shift for observations from the MBAC-era,
which included a degree of on-site observations control, to ACTPol, which would be principally operated remotely for each daily observing schedule cycle meant that each Remote Observer would take 24-hour shifts on a 1-2 shift per week basis, with duties including the planning and generation of telescope control system code, coordination with the site operations team for daily maintenance and checklist work, and to resolve faults associated with observing and restart operations in the case of errors fatal to a given observing schedule. Figures 5.7, 5.8, and 5.9 provide illustrations of a shared Google document that provided observers the ability to record results for key operational parameters central to the ACT/ACTPol daily and monthly checklists, the web-based platform allowing observers to generate observing protocols for a given time range in which the schedule generator would automatically prioritize specified observing targets in a given observational window (e.g. planetary calibration vs. CMB science observations vs. galactic field), and a site remote observing observational alarms monitor, which would allow for personnel physical safety, cryogenics, and data acquisition faults to be monitored in real-time, respectively.

Since the previous generation receiver for ACT (MBAC) was operated by collaboration members directly in the field during shifts in San Pedro de Atacama, this paradigm shift for daily operations to be centralized in North America required a fair amount of infrastructure development in order for observations to run smoothly and in an organized manner that addresses the overarching goals of a given observing period during multi-week periods in which the daily observer in charge was not continuous. Additionally, given the dynamic nature of observing targeting and site operations scheduling, this infrastructure development continued until the end of operations in January 2014 (thus observing protocol development resulted in continuous work throughout ACTPol Seasons one and two), all of which assisted in the smooth operational transition to ACTPol full-deployment operations by Austral Summer 2015. Specifically, the remote observing infrastructure development included the creation of a repository of telescope robot schedule generation code and commands, standard
operating procedures, and fault resolution scenarios, all of which were ultimately posted to the ACTPol site operations wiki for new observers to use as a guide.

Additionally, skeleton schedules that give guidance toward the type of observations that should be run during any given period during a 24-hour shift was developed and updated on at least a weekly basis to ensure that ACTPol season-long observing goals are addressed, while also maintaining a level of dynamism in scheduling to allow for short term follow up on potentially interesting science results that were illuminated by concurrently working collaboration teams focused on preliminary analysis of CMB science data. To centralize communications with the site operations team, a restricted site operations Twitter feed that was utilized during nearly the entirety of Season one operations by North American Observing coordinators and site team members alike, who post the status of telescope observations and commands issued in real time, which adds a level of safety to the existing communications and control system structure for the ACT telescope superstructure (e.g. when the site team needs to access the telescope, they communicate this to the North American Observing Coordinator on duty, who then suspends telescope motion and tweets this operations state, allowing the site team to safely engage an emergency stop and access the telescope). Furthermore, the centralized nature of the site communication structure into a single feed allows for effective record-keeping in the case that future analysis must rely on a record of past operations states. The restricted site-operations Twitter feed would ultimately be upgraded to the HipChat platform during ACTPol Season two, and later the Slack platform during Advanced ACTPol operations - each operational generation of which utilized Remote observing communications protocols developed during the initial season of ACTPol operations.

Working to continuously improve this overall observing coordinator system until the suspension of Season one operations in January 2014, for example, ultimately yielded an efficient operations structure which was in place with a team of seven remote observers seamlessly handing off operations duties to one another following each 24-hour shift with
only weekly operations telecon reviews to discuss the status of remote observing. Discussions held during a collaboration meeting held at Oxford University in Spring 2014, and further discussions throughout ACTPol Season two served to evaluate this remote operations structure and yielded several changes in the manner by which operational scheduling code is generated, as well as optimization of targeted CMB field scanning, during which discussions allowed for a single, and larger merged deep field of CMB observations that had been pre-planned for the entirety of the ACTPol second observing season. During the latter half of August 2014, significant work was again completed to update all operational protocols for use with ACTPol systems upgraded for the PA1 and PA2 deployment season, as well as to robustly support revised science goals for CMB surveys taking place during the second season. Additionally, a significantly more rigorous and developed communications structure and language was developed and deployed, allowing for increased efficiency and transparency in coordinating operations running telescope observations for ACT simultaneously on two continents. The direct results of this work were directly realized, with the resumption of remote science observing operations in late-August and early-September 2014 for ACTPol Season two operations, with team of roughly 14 remote observers involved in rotating remote observing shifts for the administration of the second ACTPol observing season, which would ultimately grow to nearly 20 remote observers by ACTPol Season three operations in 2015. This remote observing operational protocol and associated remote observing infrastructure has also materially supported the efficiency of the Advanced ACTPol operations, which would follow directly from ACTPol operations. It may be interesting to also note, due to the proliferation of mobile smart devices (which were either wholly unavailable on the market, or not widely used by the close of ACT+MBAC operations), ACTPol Remote Observing Coordinators increasingly used mobile applications such as Skype, Twitter, and HipChat for site communications, while mobile web interfaces were able to be used to generate observing schedules and issue observing commands and monitor fault handling of ACT+ACTPol observing operations. Thus, observing protocol
development used in tandem with ubiquitous mobile communications technologies allowed for the command and control of what, in ACT, is the equivalent of a six-story, moveable building from one’s mobile device!

5.2.2 Example: Selected ACTPol Season Two Remote Observing Operational Protocols

This subsection provides an example of selected ACTPol remote observing operational and communications protocols, which were utilized during ACTPol Season Two operations. Given the aforementioned dynamical nature of ACTPol remote observing operational protocols developed for increased observing efficiency during the entirety of ACTPol operations (Seasons one through three) this section is by definition a snapshot of selected observing protocols rather than a definitive listing. Nonetheless, it is included to illustrate some of the best practices and operational guidelines that were developed to lead to the remote observing norms ultimately utilized during ACTPol full-deployment operations, and later adopted during next-generation Advanced ACTPol operations. That these protocols were developed and adopted over multiple stages of the ACTPol project, as well as a next-generation experimental CMB platform is again illustrative of the importance to characterize ACTPol as not only a standalone CMB science platform, but also a pathfinder experiment, with technology (hardware), software, and operational elements that can help advance requisite space technologies toward a future-generation, NASA-led CMB Inflationary Probe mission.

Ultimately, this subsection represents an overview of selected protocols, general conventions, and fault resolution guidelines that were utilized for efficient operation of the ACT+ACTPol telescope and receiver during Season one (Autumn 2013), Season two (Autumn 2014), and Season three (Spring 2015) of observing operations. Note that both the ACTPol site operations team and Remote Observing Coordinators were required to adhere to the guidelines outlined in this subsection to ensure continuity in the operations and data acquisition protocols and record-keeping in place beginning during ACTPol PA1 operations.

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Figure 5.6: Sample schedule of Remote Observing Coordinator shifts during ACTPol Season two operations in September 2014.
Figure 5.7: Shared Google document that provides observers the ability to record results for key operational parameters central to the ACT/ACTPol daily and monthly checklists.
Figure 5.8: Web-based platform allowing observers to generate observing protocols for a given time range in which the schedule generator would automatically prioritize specified observing targets in a given observational window (e.g. planetary calibration vs. CMB science observations vs. galactic field.)
Figure 5.9: Site remote observing observational alarms monitor, which would allow for personnel physical safety, cryogenics, and data acquisition faults to be monitored in real-time.
and beyond. Observing coordinators and site operations team members thus also were encour-aged to add to this repository with useful protocols to improve efficiency of ACTPol observations, where possible.

As alluded to in the previous subsection, in September 2013, to reduce the high traffic of site-communications emails (primarily regarding telescope status and initiation of daily observations), and to create a permanent log of site operations and telescope status that could be updated via a real-time interface, the ACTPol Site Operations Protected Twitter Feed was created. This feed, which was configured as a protected account so that its contents and updates were not shared on the public Twitter site or accessible via search engines, was hosted by the commercial Twitter site (http://www.twitter.com), and was used for any real-time status updates relating to telescope access, site operations (from Team Toco), and observing plan/schedule generation and status that would be beneficial for Team Toco and the ACTPol team in North America to be aware of in real-time (i.e. if Team Toco is servicing hardware on the ACT telescope superstructure it is essential that ACTPol personnel in North America are aware of this to eliminate the potential for sending a motion command with Team Toco on the telescope – of course, an emergency stop was directed to ALWAYS be pressed prior to on-site telescope access).

Beginning with ACTPol full-deployment operations (ACTPol Season 3) in Spring 2015, all primary ACT Operations communications were migrated to another protected group chat client, called HipChat. Use of HipChat enabled a consolidation of various informal site communication Skype threads concerning topics including cryogenics, housekeeping, AMCP operation, etc., into centralized chat threads for fully-logged central discussion. Separate from these threads, a site operations protocol communications thread, entitled “Obs Status Updates” was been created, and took the place of the aforementioned Protected Twitter account as a primary communications utility connecting Remote Observing Coordinators with active operations taken by Team Toco. The feed was explicitly not to be used for general discussion as in other ACTPol HipChat threads – it was be maintained free of
colloquial conversation to ensure information was clearly communicated to maintain oper-
erational safety during remote observations. A brief overview of how to use the ACTPol Site Operations HipChat Communications feed (which is intended to closely resemble the communications usage from the Protected Twitter Feed) and suggested formatting follow, where selected operations acronyms go as: ROC - Remote Observing Coordinator; NA - North America; TT - Team Toco; SPdA - San Pedro de Atacama; DE - Don Esteban; ACT - Atacama Cosmology Telescope (superstructure); CMB - Cosmic Microwave Background; E-Stop - ACT Telescope Superstructure Emergency Stop; etc.

The following list provides a brief overview of ACTPol operational protocols developed to aid in the successful completion of ACTPol science observing operations:

1. Go to ACTPol HipChat URL.

2. You will be directed to the general home page. Click on the ‘Obs Status Updates’ thread on the left sidebar of the home screen to access the ACTPol Site Operations Protocol Communications feed.

3. Here you can view all recent protocols communicated regarding the site operations status between NA and Team Toco.

4. If you want to communicate something for site ops, simply enter the communications message into the bottom text box and hit return. Your message will be posted with a time and signature stamp.

5. Done! You’ve successfully used HipChat to aid ACTPol operations!

The following provides a selection of general communications guidelines developed for ACTPol remote observing operations:
- Guideline 1: Always refer to Sisyphus schedules by their numerical schedule identifier (listed along with each verbose schedule name in Sisyphus). Format should be ‘sis-’. (e.g. ‘ACTPol planetary schedule sis-1234 executed.’)

- Guideline 2: Feed updates from Team Toco should at a minimum always give the expected schedule for the day as it progresses on-site (e.g. ‘leaving SPdA for site’, ‘arrived at site’, ‘pressed E-stop; servicing hardware or completing checklist items on telescope superstructure’, ‘telescope clear for observations’, ‘leaving ACT site’, ‘arrived in SPdA’, etc.)

- Guideline 3: Feed updates from Remote Observing Coordinators should at a minimum notify Team Toco of control status (e.g. ‘NA Observing Coordinator in control’), and provide detailed schedule and telescope status updates (e.g. ‘Sisyphus active’, ‘planetary calibration scan underway with Projected Scan Time: (time) - (time) UTC’, ‘deep field and galaxy scanning underway with Projected Scan Time: (time) - (time) UTC’, ‘all schedules completed; Sisyphus idle; telescope superstructure clear for site access’).

The following includes the desired formatting for an entire nominal ACTPol Remote Observing Operations shift, with protocols for observations under normal circumstances, with examples:

1. Indicating report-for-shift status of Remote Observing Coordinator. Identify yourself by usual initial formatting: ‘Remote Observing Coordinator BLS reports for shift.’

2. Taking control of ACT telescope superstructure from Team Toco. Indicate takeover of control and indicate planned schedules to be run for that shift: ‘Remote Observing Coordinator now in control; loading planetary and CMB schedules.’
3. Initiating planetary, polarization calibration, or CMB observing schedule. Indicate Sisyphus schedule number, and projected scan duration: ‘Schedule sis-1222 running in Sisyphus; Scan Duration: 22:00-12:30 UTC’

4. Notification of a crashed schedule that Remote Observer will resolve. Note that this should be posted immediately prior to attempting resolution protocols of any sort. Posting this will avoid the potential for multiple observers attempting simultaneous resolutions that may result in undesirable or dangerous conflicts. Indicate terminated schedule number, fault (if known), action: ‘Schedule sis-1223 crashed; Sisyphus crash and AMCP fault; recovering’

5. Notification of resolution of crashed schedule. Indicate terminated schedule number, resolution (brief): ‘Schedule sis-1223 error resolved; AMCP restarted and MCE iBootbar power cycled.’

6. Initiating a restarted schedule (CMB or calibration) following a schedule crash. Indicate terminated schedule number, resumed schedule number, and updated scan duration: ‘Schedule sis1223nowrunningassis-1224; ScanDuration : 01:30–12:30 UTC’

7. Notification of an aborted schedule by Remote Observing Coordinator. Indicate aborted schedule number, purpose of abort operation, time of abort: ‘Schedule sis-1224 aborted; TT site access required; 11:45 UTC’

8. Notification of completed schedule. Indicate final schedule number (or original schedule number, if no faults occurred to interrupt the original schedule), and final scan duration: ‘Schedule sis-1224 complete; Final Scan Duration: 01:30-12:30 UTC’

9. Relinquishing control of ACT telescope superstructure to Team Toco. Indicate completion of schedule with schedule number indicated, final observing position and state, time of transfer, notification of safe access for Team Toco: ‘Schedule sis-1224 now complete; ACT in home position and inactive at 12:40 UTC; ACT control transferred to TT’
10. Indicating resign-from-shift status of Remote Observing Coordinator. Identify yourself by usual initial formatting. ‘Remote Observing Coordinator BLS resigns from shift.’

The following includes the desired formatting for an entire nominal ACTPol Site Operations Team telescope access shift, with protocols for observations under normal circumstances, with examples:

1. Notification of departure from San Pedro de Atacama. This should be used for notification of Team Toco heading to ACT site, as well as other destinations, such as Calama, etc. Notification of departure, destination, time: ‘TT departing SPdA en route to ACT site; 14:00 UTC’

2. Notification of return to San Pedro de Atacama. This should be used for notification of Team Toco returning to San Pedro from the ACT site, as well as other destinations, such as Calama, etc. Notification of return, travel origin, time: ‘TT arrives at SPdA from ACT site; 22:00 UTC’

3. Notification of arrival on ACT site. Notification of arrival, travel origin, time: ‘TT arrives at ACT site; 15:30 UTC’

4. Taking control of ACT telescope superstructure from NA Observing Coordinator. Indicate taking control from previous-shift NA Observing Coordinator (indicate initials of that coordinator), current telescope state, time of transfer, initiation of e-stops: ‘TT now in control of ACT; ACT in home position and inactive at 16:45 UTC; e-stops initiated’

5. Notification of planned action(s) and duration of ACT telescope superstructure site access period. Indicate telescope maintenance action(s), projected duration, time of beginning of access and maintenance action: ‘TT completing standard daily checklist in RC; 90 minutes required beginning at 16:55 UTC’
6. Notification of extension of expected duration of ACT telescope superstructure site access period. Indicate telescope maintenance action change, revised projected duration, time of extension of access and maintenance action(s): ‘TT will additionally swap MCE crate cards; 30 minutes additional required beginning at 18:25 UTC’

7. Notification of completion of action(s) and duration of ACT telescope superstructure site access period. Indicate telescope maintenance action(s) completed, final site access duration, time of completed access and maintenance action(s): ‘TT completed standard daily checklist; 90 minutes required; site access complete at 18:25 UTC’

8. Relinquishing control of ACT Telescope Superstructure to Remote Observing Coordinator. Indicate transfer of control to next-shift Remote Observing Coordinator (indicated initials of that coordinator), current telescope state, time of transfer, release of e-stops: ‘ACT site access period complete; ACT in home position and inactive at 18:45 UTC; e-stops released; ACT control transferred to ROC’

The following operational protocols, which give an overview of selected steps in the ACTPol schedule generation and execution process for both planet-observation-centric and deep-field-and-galaxy-centric observing schedules are intended were specifically used in Autumn 2014 for ACTPol second-season PA1 and PA2 observing operations. As ACTPol PA1 and PA2 Season Two operations progressed to full operational deployment in 2015, these procedures continued to evolve, though the following general protocol was still the basis for full deployment operations observing. During ACTPol Season two, occasional planetary calibration (i.e. beam profile) measurements were performed, which took place on an occasional basis outside of CMB deep field scans for rising planets (usually Saturn, as of September 2013), and setting planets prior to nighttime CMB deep field and Galactic Strip observations (usually a few observations of Venus, followed by 8-10 observations of Saturn). As schedules for individual planets can be generated, it was useful to generate separate schedule files of, e.g., Venus and Saturn over roughly overlapping time periods as
both planets rise/set, and then stitch them together, with current emphasis as previously described (2-4 observations of Venus followed by 8-10 observations of Saturn). Depending on the state of telescope operation and site operations status, it was not always possible to achieve this weighting, but targeting a maximum number of Saturn observations before setting was a general rule.

1. To generate schedules for planetary calibration, an ACT Collaboration generated planetary schedule generator was utilized, located at: http://actexperiment.info:81

2. Under ‘Planet-Sched.py’ heading, find prompt for entering parameters.

3. Enter the name of the planetary target, and select ‘submit’.

4. For each planetary schedule generated, you will be supplied with a verbose version of this schedule (appearing in the left-hand-box), followed by a condensed, executable version (appearing in the right-hand-box).

5. As an example, in early-September 2013, we had generally run planetary calibration observations for Venus and Saturn setting from 21:00-23:30 UTC. Thus, forming a single planet schedule for these two planets to run in Sisyphus following the weighting guidelines above, we thus create a condensed planetary schedule for both Venus and Saturn.

6. Next, it was generally preferred to put the telescope into position for the first scan as early as possible in the schedule for efficiency and to test telescope slewing. Usually, we place this line of code.

7. We now have generated a viable planetary calibration schedule for use in Sisyphus.

Next we move our attention to loading and executing CMB deep field and galactic field schedule files in Sisyphus, the control software package capable of executing observing schedule files for ACTPol operations:

2. Click on the ‘+’ button under the ‘Pending’ section of the left-hand-side vertical toolbar. This will bring up a ‘New Script’ generation/loading page.

3. Since we already have our planetary schedule for making observations of Venus and Saturn from the previous section, let’s begin by loading this schedule. Copy and paste your final planetary schedule script into the ‘Script:’ dialogue box.

4. Enter a descriptive title and author for this script such that it is easy to identify in the future. E.g. The schedule above could be called – ‘pre-field-saturn-and-venus-fest-13-Sep-2013’

5. Add any additional notes that might be relevant in the 'Notes' dialog box.

6. When complete, click the ‘Load Schedule’ button to place this script into the executable queue.

7. Before clicking ‘Run’, which will load the next pending schedule script and begin executing telescope commands, double check the site operations status on Twitter for safety, and make a final check for any potential syntax or timing errors. Note that one should always leave at least 15-20 minutes prior to the first ‘wait until...’ command line time to ensure that all startup commands are fully completed prior to the end of the first planet observing scan. If all startup commands do not complete by this time, there is a potential that the first planetary observation would be missed, which often causes Sisyphus to crash, and an amended schedule would be required.

8. When satisfied with schedule, click ‘Run’, and then approve this command in the prompt that will request confirmation to run the pending script(s). Note that the queue order can not be changed other than reloading scripts according to a certain desired order, so make sure to plan ahead.
9. If all progresses properly, there should be a large green box at the top of the Sisyphus page, stating ‘sisyphus is busy’ and highlighting the current command line from the executed script.

10. With our planetary schedule now running, one can then generate nightly CMB schedule directly in Sisyphus. Again click on the ‘+’ button to open the ‘New Script’ generation/loading page.

11. To generate schedules for CMB operations, we use the ACTPol online CMB schedule generator. Navigate to this schedule generation page: http://actexperiment.info:81

12. Keeping in mind the ending time of the last schedule in the queue, in this case our planetary schedule, enter a ‘starting’ and ‘ending’ time for the CMB deep field/galactic strip schedule to be created. Note that all times are in UTC. Generally, 20-30 minutes is included between the end of the last planet scan observation and the beginning of the CMB schedule to ensure that all ending commands are completed prior to the beginning of the next schedule in the queue. The idea is also to make sure the schedule has completed in time for telescope maintenance and daily checklist tasks by Team Toco each day.

13. After entering the start and end times of the schedule, click the ‘submit’ button, and a generated script will autopopulate the window field.

14. Copy and paste resultant CMB schedule into Sisyphus ‘Script’ dialogue box.

15. Rename the ‘Title’ and ‘Author’ fields with a similar format to that used for planetary schedules. E.g. a CMB deep field/galactic strip schedule could be called – ‘cmb-deep-field-gal-obs-13-Sep-2013.’
16. When satisfied with schedule, click ‘load schedule’ to load this CMB field/galactic strip schedule into the active queue, review, and click ‘Run’, followed by approving this command in the prompt that will request confirmation to run the pending script.

17. Once all nightly planetary and CMB deep field/galactic strip schedules are in the active queue, no further action is required for schedule execution – Sisyphus will continue to run and complete all schedules in the active queue in order until an abort command, exception, or failure mode is encountered (some that cause Sisyphus operation of the telescope to crash), or all schedules are successfully completed, in which case, the status bar at the top of the page will return to grey and state ‘sisyphus is idle’.

Finally, during ACTPol Season two, due to in-season contamination of the ACTPol Dilution Refrigeration system, a protocol was initiated to recycle the entire cryogenic system roughly every eight days to preempt an unanticipated warm up or cryogenic fault during observations. During these cycling periods, nominal science observing operations are suspended and the following ‘lock-out’ protocol was deployed:

1. Penn cryogenics team will assess status of cryogenic performance and make a decision for a system recycle (usually 12-24 hours before recycle will take place).

2. Penn cryogenics team will contact Team Toco directly to notify site crew of the schedule for the next scheduled cryogenic recycle. Team Toco continues to Tweet/HipChat status and location as usual during entire process.

3. Penn cryogenics team will then contact remote observing coordinator on duty to notify of next scheduled cryogenic recycle.

4. Prior to scheduled beginning of recycle, remote observing coordinator suspends nominal science observing operations and moves telescope to home position.
5. Penn cryogenics team reports for shift via site operations Twitter/HipChat interface.

6. Remote observing coordinator resigns from shift via site operations Twitter/HipChat interface.

7. Penn cryogenics team runs a schedule in Sisyphus with a single ‘wait until...’ operation, naming this Sisyphus schedule ‘cryo-recycle-lock-out’ and proceeds with recycle procedure. This schedule is run to ensure that remote observing coordinators (such as the next ROC on the schedule) recognize that a cryogenic recycle is underway and not to initiate telescope motion or run an observing schedule.

8. When recycle process is nearing completion, usually 3-4 hours before reaching base operation temperature, Penn cryogenics team will contact next remote observing coordinator and Team Toco to notify that operations may resume soon.


10. Penn cryogenics team verifies completion of recycle procedure, and that all systems are left ready for observations (e.g. MCEs on), and aborts ‘cryo-recycle-lock-out’ schedule in Sisyphus.

11. Penn cryogenics team notifies remote observing coordinator of transfer of control to resume observing operations via site operations Twitter/HipChat interface.

12. Penn cryogenics team resigns from shift via site operations Twitter/HipChat interface.

13. Remote observing coordinator proceeds through normal site operations communications structure, ensuring that Team Toco and any physical obstructions are removed from telescope with e-stops released (by virtue of continuing to Tweet/HipChat status updates, Team Toco should be aware of cryo status and have already informed Penn cryogenics team and ROCs of telescope clear status).
14. Remote observing coordinator resumes science observing operations via generation and execution of CMB observing schedule.

5.2.3 Overview of ACTPol Observational Efficiency

Throughout the previous subsection, protocols were described that would, in addition to the ultimate technology performance of the ACTPol receiver itself as a system (e.g. cryogenic, readout, etc.), allow for the consistent and predictable science operations of the ACT+ACTPol system. As described earlier in this Chapter, the fully-integrated ACTPol receiver, in addition to its logistical deployment support infrastructure, is the assemblage of a wide array of critical space technology systems, including high-purity silicon optics with novel anti-reflective coatings, transition-edge-sensor-based polarimeter array focal planes, multi-channel electronics readout, and a field-deployable dilution refrigeration system. Coupled with existing and updated operations for the ACT telescope optomechanical superstructure itself, and the introduction of a novel set of remote observing protocols, the operation of the ACT+ACTPol system over its entire observing lifetime was remarkably effective, and is a testament to the long-term hardware, software, and operations development campaign that allowed for synchronous operation of this broad array of disparate technical systems.

The result of this effort was a high-efficiency experimental cosmology platform in ACTPol, which was continually operated during its observational lifetime to maximize CMB science yield, while ensuring that the system was operated in a safe, resilient, and well-characterized/calibrated manner. Given the introduction of a dilution refrigeration system to provide ACTPol’s requisite sub-100mK cryogenic bath temperature, the theoretical maximum efficiency for CMB operations could be thought to be at or near 100 percent on a daily basis, given that a primary operational advantage of the dilution refrigeration system is its continuous operational mode at base temperature, theoretically obviating the need for thermal cycling. Of course, due to requirements for the ACT site operations team to
physically access the ACT telescope optomechanical superstructure for routine maintenance and system monitoring, as well as the need during observations for planetary calibration observations, detector tuning and calibration, and nominal telescope slewing between observational fields, CMB science observations did not reach 100 percent (full 24 hour CMB science operations) during the lifetime of ACTPol. These technical realities notwithstanding, the resultant operational efficiency of the ACT+ACTPol experiment was generally superior. This is especially evident when compared to the previous-generation ACT+MBAC experiment, which, due to MBAC’s requirement for cryogenic cycling once per day with a maximum of roughly 12 hours of possible observing operations in a given day, could only reach roughly 50 percent of ACTPol’s theoretically-achievable scientific efficiency.

ACT+ACTPol’s operational efficiency results are illustrated for ACTPol Season one operations in Figure 5.10, and for ACTPol Season two operations generally in Figure 5.11, and including a detailed breakdown of specific observing operations for Season two in Figure 5.12. During ACTPol Season one, Figure 5.10 illustrates the manner by which, aside from a small number of dropouts due to site inactivity associated with weather events, the ACT+ACTPol experiment operated nearly continuously throughout the entire season, with overall operational efficiency increasing across the course of the season, culminating with operations reaching greater than 90 percent efficiency for nearly the entire final month of observations. This high-efficiency period corresponded to the full-deployment of the previously-described suite of remote observing operations, operating under final, nominal CMB science-optimized observing modes for ACTPol season one, with the only fully-inactive periods each day limited to telescope access lockout periods (for safety) by ACTPol site operations personnel. Within this period, CMB science data in particular was generally acquired for greater than 70 percent of a given 24-hour period. Overall, ACTPol Season one generated 1427 integrated hours of CMB science observations, with a primary focus on ACTPol CMB Deep Fields 5 and 6, which will be further characterized in the following Chapter. During ACTPol Season two, Figure 5.11 and Figure 5.12 illustrate an
increase in observing discontinuities, especially in comparison to ACTPol Season one, with entire observing inactivity periods occurring generally on 8-10 day intervals. This periodic dynamic was ultimately the result of suspected contamination within the dilution refrigeration system, which would have resulted in a cryogenic fault or possible failure, were the system run in continuous mode (overpressuring monitored in various locations in the DR and its associated gas-handling system indicated the potential that a leak had led to contamination of the system, with a pronounced risk of creating an ice plug in a DR system capillary or general cryogenic performance degradation, were the system not pre-emptively thermally cycled during the season). Ultimately, the periodic recycling protocol resulted in the ACTPol receiver to not be required to be fully-removed from the ACT telescope optomechanical superstructure during the season, which could have been detrimental to the overall time on-sky and thus resultant science data yield for PA1 and PA2 deployment. In spite of these challenges presented by system cryogenics, while at base temperature during ACTPol Season two, the entire experiment continued to consistently reach greater than 90 percent efficiency on many days from October 2014 to the end of the second season, with CMB science field coverage consistently exceeding 60 percent of a given observing day. Overall, in spite of the reduced continuity of operations in 2014, ACTPol Season two operations generated 1584 integrated hours of CMB science observations, exceeding the ACTPol Season one CMB science data yield.

5.3 ACTPol Observational Data Coverage

As described at the close of Chapter 2, ACT+ACTPol observing coverage was planned to focus on three distinct observational regimes, enabled by the system’s new capability for near-continuous operation at cryogenic base temperature. These regimes, in priority order of scientific objectives, include ACTPol CMB Deep, ACTPol CMB Wide, and ACTPol CMB Ultra-Wide. For the first two seasons of ACTPol operations, calibration targets (planetary, galactic, and Tau A) were also included in nominal observing operations, and
Figure 5.10: Operational Efficiency for ACTPol Season One Observations. Aside from a small number of dropouts due to site inactivity associated with weather events, the ACT+ACTPol experiment operated nearly continuously throughout the entire season, with overall operational efficiency increasing across the course of the season, culminating with operations reaching greater than 90 percent efficiency for nearly the entire final month of observations. This high-efficiency period corresponded to the full-deployment of the previously-described suite of remote observing operations, operating under final, nominal CMB science-optimized observing modes for ACTPol season one, with the only fully-inactive periods each day limited to telescope access lockout periods (for safety) by ACTPol site operations personnel. Within this period, CMB science data in particular was generally acquired for greater than 70 percent of a given 24-hour period. Overall, ACTPol Season one generated 1427 integrated hours of CMB science observations, with a primary focus on ACTPol CMB Deep Fields 5 and 6, which will be further characterized in the following Chapter.
Figure 5.11: Operational Efficiency for ACTPol Season Two Observations. Observable is an increase in observing discontinuities, especially in comparison to ACTPol Season one, with entire observing inactivity periods occurring generally on 8-10 day intervals. This periodic dynamic was ultimately the result of suspected contamination within the dilution refrigeration system, which would have resulted in a cryogenic fault or possible failure, were the system run in continuous mode. Ultimately, a periodic recycling protocol was utilized and resulted in the ACTPol receiver to not be required to be fully-removed from the ACT telescope optomechanical superstructure during the season, which could have been detrimental to the overall time on-sky and thus resultant science data yield for PA1 and PA2 deployment. In spite of these challenges presented by system cryogenics, while at base temperature during ACTPol Season two, the entire experiment continued to consistently reach greater than 90 percent efficiency on many days from October 2014 to the end of the second season, with CMB science field coverage consistently exceeding 60 percent of a given observing day. Overall, in spite of the reduced continuity of operations in 2014, ACTPol Season two operations generated 1584 integrated hours of CMB science observations, exceeding the ACTPol Season one CMB science data yield in terms of integrated hours on CMB fields.
Figure 5.12: Operational Efficiency for ACTPol Season Two Observations (with annotated breakdown of CMB Observations, Detector Tuning and Calibration, Planetary Calibration Observations, Telescope Motion, and Idle Periods.)
comprise the full yield of ACTPol’s targeted data coverage during these two seasons. Figure 5.13 illustrates ACTPol Season one planetary (beam characterization) calibration targets, which included Mercury, Venus, Mars, Jupiter, Uranus, Saturn, and Neptune, in addition to Tau A, which would ultimately be utilized for polarization calibration. Figure 5.14 illustrates ACTPol Season one CMB Deep Field targets and locations (with an emphasis on deeper observations of the ACTPol Deep 5 and 6 fields illustrated), weighted by duration of observation, in addition to galactic strip and center fields, selected results of which will be shown for the first time in the next Chapter. Figure 5.15 illustrates CMB Deep Field results for ACTPol Deep 1, 2, 5, and 6, acquired over the period of 11 September 2013 to 23 December 2013, which will also be discussed further in the next Chapter. Finally, Figure 5.16 illustrates science targets during ACTPol Season two, including a merged field covering ACTPol Deep 5 and 6, and observation of the BOSS region, weighted by duration of observation. Both preliminary and final galactic and CMB field results acquired during ACTPol’s first season will be discussed the the Chapter, which follows.

5.4 Summary

Over the course if this Chapter, we have highlighted the timeline, characteristics, and selected challenges overcome during the deployment of ACTPol during its three initial seasons, from PA1-only operations through its fully-deployed and operational state. As might be expected for the deployment and operation of a fully-experimental pathfinder platform such as ACTPol, the journey from site shipment to full-deployment in just over two years time, including periods of semi-deployed receiver science operations was non-linear. Physical challenges associated with operating in a harsh, arid, high-altitude, and remote environment of the Cerro Toco based site, coupled with the technical complexities of fully integrating the receiver in a new on-site facility and resultant deployment to the ACT telescope superstructure for the first time in the field provided unforeseen hurdles that needed to be overcome to reach each stage of operational deployment, however given the
Figure 5.13: ACTPol Season One planetary (beam characterization) calibration targets, which included Mercury, Venus, Mars, Jupiter, Uranus, Saturn, and Neptune, in addition to Tau A, which would ultimately be utilized for polarization calibration.
Figure 5.14: ACTPol Season One CMB Deep Field targets and locations (with an emphasis on deeper observations of the ACTPol Deep 5 and 6 fields illustrated), weighted by duration of observation, in addition to galactic strip and center fields, selected results of which will be shown for the first time in the next Chapter.
Figure 5.15: CMB Deep Field results for ACTPol Deep 1, 2, 5, and 6, acquired over the period of 11 September 2013 to 23 December 2013, which will be discussed further in the next Chapter.
Figure 5.16: Science targets during ACTPol Season Two, including a merged field covering ACTPol Deep 5 and 6, and observation of the BOSS region, weighted by duration of observation.
significant planning, simulation, and pre-deployment development work completed in the years prior to initial shipment, none of the temporary roadblocks proved insurmountable. The development and success of a capable and reliable team of remote observers around the four continents of the Atlantic rim also allowed for continuous improvements in operational efficiency of the ACT+ACTPol platform, and thus a larger and scientifically richer data set was able to be acquired during ACTPol operations compared to previous experiments. The next chapter explores this resulting data and selected early ACTPol science results, with an brief overviews of key Cosmic Microwave Background mapping and power spectra results (in both temperature and polarization), as well as an early look at data analysis and results performed to map and probe the polarization characteristics of the ACTPol galactic field dataset, which have been heretofore unreported in publication prior to development of this dissertation.
Chapter 6

ACTPol Early Science

Yes, press my eyelids close, 'tis well,
yes, press my eyelids close, 'tis well,
but far the rapid fancies fly
to rolling worlds of wave and shell,
and all the land where corals lie.

Thy lips are like a sunset glow,
thy smile is like a morning sky,
yet leave me, leave me, let me go
and see the land where corals lie.
The land, the land, where corals lie.

from Edward Elgar’s “Sea Pictures: Where Corals Lie”

Over the course of the preceding Chapters, a robust overview has been provided regarding the site, instrumentation, and operational protocol development that would enable the realization of ACTPol as a fully-integrated, well-characterized, and operational system that
would result in, when coupled with the Atacama Cosmology Telescope, detailed mapping and characterization of the Cosmic Microwave Background, in both temperature and polarization. Broadly speaking, the development, integration, and qualification testing of ACT-Pol and its constituent subsystem technologies, described heretofore, might be considered reflective of a capable space technology system developed to a NASA Technical Readiness Level definition of TRL 6. In this case, using the NASA TRL definitions provided earlier in Chapter 3, this reflects ACTPol’s level of development as a “System or subsystem model or prototype demonstration in a relevant environment (ground or space).” Particular subsystems were furthermore tested to certain relevant qualification levels reflective of operation in a space-bourne environment (or, in some cases, the particular physical dynamics of a space launch payload), including the vibroacoustic qualification testing suite completed for the ACTPol 150 GHz sensitive transition-edge-sensor (TES) based polarimeter array package completed at NASA’s Goddard Space Flight Center, described earlier, which could arguably push the level of technology qualification into the TRL 7 regime, which would be reflective of a “system prototype demonstration in a space environment.” Of course, the relevance of vetting ACTPol within a framework of TRL’s for integrated space technologies is clear when viewing ACTPol within a continuum of ground-based pathfinder CMB observatory platforms to culminate in a future-generation, seminal, space-bourne NASA Inflationary Probe mission. However, as we have seen earlier, ACTPol can be viewed definitionally in the context of three principal space technology rationale: (i) ACTPol as a fully-integrated, standalone science platform capable of millimeter-wavelength imaging of the Cosmic Microwave Background in both temperature and polarization; (ii) ACTPol as a pathfinder experiment, allowing for the development of incremental space technology systems and subsystems contributing to the development of a seminal Inflationary Probe mission; and (iii) ACTPol as a platform to support system- and subsystem-level development of cross-cutting, allied-field instrumentation development, such as providing proven core component and sub-system technologies for the NIST 350 GHz imager (known generally as ‘The THz Project’),
a security imager capable of passive, video-rate sensitivity monitoring of concealed threats at standoff distances for portal and military security applications.

With these technology-development considerations in mind, however, can one fully qualify ACTPol as supporting any of the preceding three definitions without also demonstrating that when operating coupled to the Atacama Cosmology Telescope, the receiver is able to effectively achieve its own core science objectives? Furthermore, if the requirements for probing inflationary physics in a future space-borne mission will ultimately necessitate technologies of increasing sensitivity and efficiency to characterize both CMB temperature and polarization anisotropies while simultaneously constraining foreground signals (e.g. low-frequency channel synchrotron emission, and high-frequency channel dust emission) can ACT+ACTPol be fully considered as satisfying a TRL 6 system-level technology qualification without demonstrating that its operational yield and analysis protocols also contribute to these core objectives? Certainly not! Throughout this Chapter, we will provide a brief overview of early science results produced though ACTPol’s first season of operations (2013), with a particular focus on three main areas: (i) demonstration of ACTPol’s ability to map and characterize the Cosmic Microwave Background in both temperature and polarization at millimeter wavelengths; (ii) demonstration of ACTPol’s ability to detect galaxy clusters via the Sunyaev-Zel’dovich effect through wide and unbiased surveys; and (iii) demonstration of ACTPol’s ability to probe polarization characteristics of the Galactic Plane in millimeter wavelength sensitivity at high-resolution. While early results for science objectives (i) and (ii) are briefly reported and have been published by the ACTPol collaboration, early results of objective (iii) have not yet been published and thus will be presented publicly for the first time ever in this work.

6.1 Review of Principal ACTPol Cosmology Objectives

In Chapter 1, we presented the fundamental science motivation underpinning the drive toward ACTPol as a next-generation integrated experimental cosmology platform. Broadly
speaking, ACTPol as a probe of the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) measured at small-angular scales allows for the characterization of a wide-array of fundamental cosmology and modern physics objectives. With first light achieved in July 2013, ACTPol has thus become a critical probe of CMB polarization science. In particular, mapping and characterization of the CMB at high-sensitivity, such as achievable from ACTPol, in both temperature and polarization allows for critical constraints on cosmological parameters central to probe and constrain $\Lambda$CDM cosmology. This section will provide a brief review of the two most central primary ACTPol science area objectives, namely, those related to probes of the CMB in temperature and polarization, at high-sensitivities and small-angular-scales at multipole $\ell > 200$, and second, ACTPol galaxy cluster science through observation of the Sunyaev-Zel’dovich effect.

6.1.1 Observing the CMB in Temperature and Polarization at Multipole $\ell > 200$

As covered in Chapter 1, high-sensitivity temperature and polarization mapping of the CMB allow for constraints to be placed on CMB power spectra, and therefore enable constraints to be placed on key cosmological parameters that can describe and further constrain $\Lambda$CDM cosmology. This will therefore allow instruments like ACTPol to enable a better understanding of the characteristics and shape of the Universe, the nature of the baryonic matter, the characterization of the growth of structure of the Universe, and as probes of primordial dark energy. Of course, in comparison to previous-generation CMB experimental cosmology platforms, like the Millimeter Bolometer Array Camera (MBAC) which preceded ACTPol as the primary receiver for the Atacama Cosmology Telescope and was only capable of mapping the temperature anisotropies of the CMB at small-angular-scales, the introduction of a polarization-sensitive receiver like ACTPol to the ACT telescope extends the scope of achievable CMB science. Viewed broadly, the characterization of CMB temperature and polarization anisotropies require knowledge of three quantities for any given observed point
on the sky. These three quantities are: the observed temperature of the CMB blackbody spectrum \( T \), the degree of polarization, or polarization intensity \( P \), and the angle between the direction of polarization and a given coordinate system on the sky, denoted as \( \alpha \). \( P \) and \( \alpha \) are traditionally parametrized in terms of the Stokes Parameters, \( Q \) and \( U \), defined in Equations 6.1 and 6.2 as:

\[
Q = P \cos(2\alpha) \tag{6.1}
\]

\[
U = P \sin(2\alpha) \tag{6.2}
\]

When an instrument like ACTPol makes a polarization-sensitive map of a given field of the CMB, we measure the Stokes Q and U polarization on the sky and then decompose them into two linear orthogonal bases, which have: (i) curl-free E-mode polarization, which arises from plasma accelerating into and out of overdense regions of the early Universe; and (ii) divergence-free B-modes, which, if directly detected, would provide evidence of gravitational waves propagating through space and a verification of inflationary cosmology. As described by Kaminkowski in (Kamionkowski 2002), the two-point statistics of a combined CMB temperature and polarization map is described by six power spectra, given in Equation 6.3 as:

\[
C_{KL}^{\ell}; \text{for } K, L = T, E, B
\tag{6.3}
\]

However given constraints of parity invariance, \( C_{\ell}^{TB} \) and \( C_{\ell}^{EB} \) are trivial, leaving four relevant power spectra to describe CMB maps in temperature and polarization: \( C_{\ell}^{TT}, C_{\ell}^{TE}, C_{\ell}^{EE}, \) and \( C_{\ell}^{BB} \). For the purposes of this Chapter, we shall simplify notation for \( C_{\ell}^{TT}, C_{\ell}^{TE}, C_{\ell}^{EE}, \) and \( C_{\ell}^{BB} \), to TT, TE, EE, and BB, respectively. (Kamionkowski 2002) Whereas previous experimental cosmology platforms such as MBAC were able to better constrain characteristics of the primary temperature anisotropy, or TT, power spectrum of the CMB...
to good agreement with $\Lambda$CDM cosmology models (as did the early temperature results from the Planck mission), next generation, polarization-sensitive instruments like ACTPol would then be able to further probe the other three characteristic power spectra for temperature and polarization maps of the CMB, the temperature-polarization cross power spectrum, TE, and the so-called E-mode, and B-mode power spectra, EE and BB, respectively. In particular, ACTPol will be able to further probe the EE power spectrum to break degeneracies between parameters, and probe the EE power spectrum at small angular scales, while also utilizing gravitational lensing to begin to constrain the BB power spectrum as probes of dark energy, as well as inflationary constraints if extended to larger angular scales. For direct probes of the BB power spectrum future-generation instrumentation will be required at higher sensitivities with very well-understood systematics, as well as constraint on both low-frequency channel synchrotron radiation, and high-frequency channel dust emission.

Ultimately, primary ACTPol observational surveys will measure intrinsic CMB temperature and polarization anisotropies, probing $\Lambda$CDM cosmology through constraint of the TT, EE, and BB (via gravitational lensing) power spectra. First, ACTPol will measure the TT power spectra across observed fields for multipole $200 < \ell < 9000$ with increased sensitivity over its predecessor instrument, MBAC. Second, ACTPol will measure the TE and EE power spectra across observed fields to roughly $\ell < 3000$. Finally, ACTPol will attempt to constrain the BB power spectrum generated by gravitational lensing. Figure 6.1 illustrates the expected contribution to the constraint of the EE power spectrum by the introduction of a high-sensitivity, polarization-sensitive receiver in ACTPol. Previous generation EE power spectrum measurements can be seen in the left panel, which constrain $\Lambda$CDM cosmology predictions to good agreement, though operating at small-angular scales, ACTPol (right panel), will be able to probe further down the Silk damping tail at higher $\ell$ than those experiments, given that at smaller angular scales, as achievable by ACTPol, the polarization fraction arising from foregrounds at higher $\ell$ is lower for the EE power spectrum than at larger-angular scales.
Figure 6.1: The expected contribution to the constraint of the EE power spectrum by the introduction of a high-sensitivity, polarization-sensitive receiver, ACTPol. Previous generation EE power spectrum measurements can be seen in the left panel, which constrain $\Lambda$CDM cosmology predictions to good agreement, though operating at small-angular scales, ACTPol (right panel), will be able to probe further down the Silk damping tail at higher $\ell$ than those experiments, given that at smaller angular scales, as achievable by ACTPol, the polarization fraction arising from foregrounds at higher $\ell$ is lower for the EE power spectrum than at larger-angular scales. Figure courtesy M. Niemack.
6.1.2 ACTPol Galaxy Cluster Science with the Sunyaev-Zel'dovich Effect

As described in more depth in Chapter 1, galaxy clusters are the largest virialized structures in the Universe, and can act as important cosmological probes. Additionally, the observation and characterization of galaxy clusters are fundamentally important to physics more broadly, exhibiting physical phenomenon, e.g. shocks and cold fronts, that are of crucial importance to other areas of physics and the characterization of astrophysical dynamics. Galaxy clusters form from the collapse of dark matter halos, and range in mass from $10^{14}$ to $10^{15}$ solar masses. Galaxy clusters were observed throughout the CMB fields of ACT+MBAC and will also be detected in ACTPol CMB fields, via the Sunyaev-Zel'dovich effect. The Sunyaev-Zel'dovich effect occurs when low-energy photons from the CMB inverse Compton scatter when interacting with a cloud of high-energy electrons, such as those comprising hot cluster gasses. As a result, CMB photons become blue-shifted through the Sunyaev-Zel'dovich effect, and, more pertinent to ACTPol, in the observable band of frequencies (90 GHz and 150 GHz channels), a decrement is observed in the CMB intensity allowing for surveys of galaxy clusters to be acquired from ACTPol CMB maps. As discussed earlier in this dissertation, the number counts of Sunyaev-Zel'dovich galaxy clusters are sensitive to various cosmological models, including $\Lambda$CDM, therefore galaxy cluster survey and detection is fundamental for the constraint and verification of cosmological models. Observation of Sunyaev-Zel'dovich galaxy clusters also allows for further constraints to test $\sigma(8)$ and the dark energy equation of state parameter $w$, and enable a better understanding of the nature of dark matter and dark energy densities. Like its predecessor instrument, MBAC, ACTPol will be an effective Sunyaev-Zel'dovich galaxy cluster survey instrument and will again employ a multi-stage approach to Sunyaev-Zel'dovich measurements, by: detecting Sunyaev-Zel'dovich galaxy clusters in CMB surveys, determining cluster redshifts via optical follow-up, use x-ray, optical, and Sunyaev-Zel'dovich data to determine the mass selection function, calculating the number distribution, finally allowing for further constraint of $\sigma(8)$ and $w$. Throughout the operational lifetime of the ACTPol instrument,
taking into account the projected ACTPol Deep, ACTPol Wide, and ACTPol Ultra-Wide surveys operationally described in the previous chapter, roughly 1000 Sunyaev-Zel’dovich effect detected galaxy clusters are expected by the close of ACTPol operations.

6.2 ACTPol Early Science: CMB Polarization Measurements for $200 < \ell < 9000$ and Early ACTPol Galaxy Cluster Survey Results

To confirm that ACTPol has been able to demonstrate the capability to achieve two of its science goals with respect to measurement of CMB polarization at millimeter-wavelengths at small-angular scales, as well as its ability to survey galaxy clusters via the Sunyaev-Zel’dovich effect, we provide a brief summary of early ACTPol science results, concentrating on outcomes from the first two seasons of ACTPol observing. ACTPol Season 1 CMB polarization results are detailed in (Naess et al. 2014a), while early ACTPol Sunyaev-Zel’dovich effect galaxy cluster survey results are found in (Hilton et al. 2018). Considering first the early CMB polarization mapping and power spectrum results, we recall from the previous Chapter that ACTPol Season 1 CMB science operations focused integration time on six deep fields (‘Deep 1,’ ‘Deep 2,’ ‘Deep 3,’ ‘Deep 4,’ ‘Deep 5,’ ‘Deep 6’), with a particular focus concentrated on mapping the Deep 1, Deep 2, Deep 5, and Deep 6 fields, with highest observing time dedicated to Deep 5 and Deep 6. Taken together, those four deepest fields represent 1030 hours of total integration time, with 29 and 31 percent of the total CMB science integration time taken during ACTPol Season 1 CMB science operations, which spanned from 11 September 2013 to 24 December 2013, focused on the Deep 5 and 6 fields, respectively. The area on the sky covered by the Deep 1, 2, 5, and 6 fields were 73, 70, 63, 70 square degrees, respectively. Figure 6.2 illustrates the locations of the four deepest ACTPol Season 1 CMB science fields on a full-sky map. The locations of these fields provide the potential for enhancing ACTPol’s data richness due to significant overlap with other sur-
veys including SDSS, BOSS, XMM-XXL, Herschel, HSC, DES, GAMA, and others. (Naess et al. 2014a)

Although the observation of these fields allowed for the integration of both daytime and nighttime data enabled by the introduction of ACTPol continuous operation dilution refrigeration system, given the the current superior characterization of the behavior of the ACTPol nighttime beam, nighttime data was exclusively used in the CMB mapping and power spectrum results presented in (Naess et al. 2014a). That notwithstanding, we provide Figure 6.3, which illustrates a test that was performed in which ACTPol Deep 1 daytime and nighttime data were separated (the data coverage for Deep 1 was in fact 50 percent taken during the daytime and 50 percent during the nighttime), and EE power spectrum calculated for the day- and night-partitioned data sets. As illustrated, the daytime and nighttime results are in good agreement with one another, which is encouraging for future ACTPol CMB science analysis, which will attempt to integrate both daytime and nighttime data into science results. For this early CMB science data, however, data taken outside of the ACTPol-defined nighttime range, defined as data taken between 0000hrs-1100hrs UTC, was removed. This characteristic, along with others described later in this Chapter, formed the cuts package for the ACTPol Season 1 CMB science data set. For the purposes of this work, data selection criterion and mapping procedures for ACTPol’s polarized data set, which follow those set forth in (Dünnen et al. 2013) and (Naess et al. 2014a), are described in the following section, in which original mapping and polarization characterization analysis is provided for the ACTPol galactic field data set.

Figures 6.4 and 6.5 provide highlights of the successful demonstration of ACTPol’s primary science goals, as an adept imager of CMB temperature and polarization characteristics. Figure 6.4 shows CMB mapping results for the central subregion of the Deep 6 field, with mapping results in I (shown as T in the map), Q, U, E, and B shown. Additionally, a detail region of the intensity map is expanded to reveal both Sunyaev-Zel’dovich effect signal decrement in the map indicating the detection of a galaxy cluster via the Sunyaev-Zel’dovich
Figure 6.2: Illustration of the locations of the four deepest ACTPol Season 1 CMB science fields on a full-sky map. The locations of these fields provide the potential for enhancing ACTPol’s data richness due to significant overlap with other surveys including SDSS, BOSS, XMM-XXL, Herschel, HSC, DES, GAMA, and others. Taken together, these four deepest fields (Deep 1, 2, 5, 6) represent 1030 hours of total integration time, with 29 and 31 percent of the total CMB science integration time taken during ACTPol Season 1 CMB science operations, which spanned from 11 September 2013 to 24 December 2013, focused on the Deep 5 and 6 fields, respectively. The area on the sky covered by the Deep 1, 2, 5, and 6 fields were 73, 70, 63, 70 square degrees, respectively.
Figure 6.3: Results of a test that was performed to compare the daytime and nighttime EE power spectrum results for the ACTPol Deep 1 CMB science field. Here, ACTPol Deep 1 daytime and nighttime data were separated (the data coverage for Deep 1 was in fact 50 percent taken during the daytime and 50 percent during the nighttime), and EE power spectrum calculated for the day- and night-partitioned data sets. As illustrated, the daytime and nighttime results are in good agreement with one another (daytime vs nighttime EE power spectrum is shown in the upper panel, and daytime vs nighttime difference in the lower panel), which is encouraging for future ACTPol CMB science analysis, which will attempt to integrate both daytime and nighttime data into science results. (Naess et al. 2014a)
effect, as well as the detection of a point source (signal increment on intensity map). As we perform for the filtering of the ACTPol galactic field maps later in this Chapter, the maps are filtered in ℓ such that the noisiest ℓ ranges for a small-angular scale polarization-sensitive receiver like ACTPol are minimized. In this case, the ACTPol Deep 6 subregion I map is shown after applying a high-pass filter for multipole ℓ > 240, while the ACTPol Deep 6 polarized Q and U maps are shown following the application of a bandpass filter for 260 < ℓ < 1370. Also shown in the bottom panel, are the corresponding difference maps generated for the intensity, E, and B maps. A jack-knife method was used here to calculate the ACTPol Deep 6 subregion I,E,B difference maps using two-way splitting of the ACTPol galactic field I,E,B data set (split by odd and even pairs of days of observation). Similar to the results that will be shown for the ACTPol galactic field I,Q,U difference maps later in this Chapter, we observe correlated noise in the I,E,B maps aligned with the dominant scanning direction of ACTPol, which similar to that shown in the galactic field data sets, is also diagonal for the ACTPol CMB science fields. From these maps, we can clearly see that our intensity maps are of excellent precision and high-resolution to show structures of both point sources and galaxy clusters in addition to primary CMB signal. Additionally, our Q and U maps show that we have a good response to the polarized signal of the CMB. The E-mode polarization map shows a much greater signal-to-noise, corresponding to our ability to make an accurate calculation of the E-mode power spectrum at small-angular scales with this early data, however no direct detection of B-mode polarization signal is yet observed, as expected for the ACTPol results. The map sensitivity shown correspond to 11-17 μK arcminute for the four deepest regions.

Figure 6.5 shows the ACTPol TT, TE, EE, and BB power spectra results for the ACTPol Season 1 CMB deep field data set. Here we see that TT, TE, and EE power spectra results for the ACTPol Season 1 data set are in good agreement with ΛCDM cosmology and analogous power spectra measurements form the WMAP and Planck missions. Furthermore, ACTPol results show TT, TE, and EE power spectrum results competitive with constraints
placed on these power spectra at high angular scales by other contemporary small angular scale experiments, out to $\ell$ of roughly 9000 in TT and 3000 for TE and EE, as was stated as a primary CMB science goal of the ACTPol receiver. Of course, while no B-mode power spectrum is detectable by ACTPol, the introduction of multiple operating wavelengths, able to detect and constrain both low-frequency (synchrotron), and high-frequency (dust emission) foregrounds, and the extension of ACTPol science to larger angular scales, as will be described in the next Chapter as central to the planned science and technology development goals of the Advanced ACTPol receiver, will continue the push toward direct probes of primordial gravitational waves. It should be noted that these results, that only consist of a subset of data taken over a roughly three month span in 2013, yield results that are comparable to three years of MBAC operational data with only one 150 GHz polarimeter array package deployed. The ACTPol Season 1 CMB science data set was also tested for systematic pathologies by conducting null tests in which differencing of the data set was performed in a number of ways, splitting the data into various detector, observing field, temporal, and daytime vs nighttime data sets and performing null testing. Ideally, map-based null tests should yield zero. In reality, however, differences from zero are found which place constraints on which to probe systematics. For ACTPol, the differenced values for the various null testing regimes were found to be consistent with expectations when compared to ideal $\chi^2$ statistics, where for map based statistics, we define $\chi^2$ in Equation 6.4, for pixel values $d_{m1}$ and $d_{m2}$ and corresponding pixel variances $\sigma_{m1}$ and $\sigma_{m1}$. So ultimately, when we consider the number of map pixels as the number of degrees of freedom (dof), for ACTPol we then consider $\chi^2/(dof)$ where $\chi^2$ is from the map data, so ideally we want $\chi^2/(dof) = 1$, but find in (Naess et al. 2014a) that this actually ranges from 0.55 to 1.6. From this, a table is then used to find the probability of exceeding (PTE) $\chi^2$ for a given degree of freedom, and doing this we find that the outlier behavior corresponds to the $\chi^2$ extremes, where $\chi^2$ of 1.6 corresponds to a PTE of 0.003 and $\chi^2$ of 0.55 corresponds to a PTE of 0.997. Ultimately, (Naess et al. 2014a) confirms that these results are not
unexpected and therefore the ACTPol Season 1 CMB data set indeed does not appear to be dominated by error resulting from systematic sources.

\[ \chi^2 = \sum \frac{(d_{m1} - d_{m2})^2}{\sigma_{m1}^2 + \sigma_{m2}^2} \]  

(6.4)

Given that the next section will discuss in detail the polarization characterization of the ACTPol galactic field data set, we provide here Figures 6.6 and 6.7 which illustrate the polarization structure of ACTPol’s observation of Tau A, as well as the predicted TT power spectrum for thermal dust emission across the ACTPol Season 1 CMB deep fields. For the observation of Tau A, a polarization intensity (mathematically defined later in the ACTPol galactic field analysis section), peaked at roughly 6800 \( \nu \)K, corresponding to the highest polarization intensity range of the ACTPol galactic field maps shown later (6000-8000 \( \nu \)K maximum polarization intensity). Measured at the central pulsar of Tau A, the ‘Crab Pulsar,’ the polarization angle found in the ACTPol measurement of Tau A agrees well with observations made on the IRAM 30 meter telescope using the XPOL polarimeter operating with a central frequency of 89.2 GHz, in which the IRAM result corresponded to a polarization angle of \( \gamma = 149.9 \pm 0.2 \) degrees, with ACTPol measuring a polarization angle offset from the IRAM result by \(-1.2 \pm 0.2 \) degrees, with both data sets smoothed to a 5 arcminute gaussian beam (Aumont et al. 2010) (Naess et al. 2014a).

Furthermore, using the results for the extrapolation of galactic dust emission at 100 microns for CMB frequencies using the FIRAS instrument as described in (Finkbeiner et al. 1999) as a template, ACTPol Season 1 CMB deep field results were correlated to this dust emission template. From this, as shown in 6.7 which illustrates the predicted TT power spectrum for thermal dust emission across the ACTPol Season 1 CMB deep fields Deep 1, 5, and 6, it is shown that using the (Finkbeiner et al. 1999) results as a template it is expected that above \( \ell \) of 2000, dust foreground emission in these fields should only add less than \( 2^2 \) to the TT power spectrum. Furthermore, using results presented for dusty foreground maps measured by the Planck mission in (Planck Collaboration et al. 2015a), which we will use extensively...
in the ACTPol galactic field analysis found in the next section, the polarization fraction expected for ACTPol Deep Fields 1, 5, and 6 are roughly 5 percent, which is consistent with polarization fraction results calculated for fields on and off of the ACTPol galactic field data set. Thus, using these expectations predicted by the Planck mission for the ACTPol deep field regions for polarization fraction, (Naess et al. 2014a) states that even for a possible maximum polarization fraction of 10 percent for these regions (and as we will see for the ACTPol galactic field data set, maximum polarization fraction was often 10 percent or below, however exceeded 20 percent in a number of measured subregions), above \( \ell \) of 2000 dust foreground emission in these fields should only add less than 0.02 \(^2\) to the TT power spectrum.

Finally, Figures 6.8 and 6.9 illustrate recently-released early galaxy cluster survey results from the first two seasons of ACTPol operation. Recall that for ACTPol Season 1, the receiver was populated with a single polarization-sensitive array package operating at 150 GHz, before a second, twin, 150 GHz polarimeter array package was added for operation for ACTPol Season 2 operations (ACTPol PA1 and PA2, respectively). These results report that 182 galaxy clusters were detected by observation of signal decrement resulting from the Sunyaev-Zel-dovich effect across a single 987.5 deg\(^2\) field that was assembled through a combination of the so-called equatorial strip field observed during ACT+MBAC operations and CMB science fields observed during the first two ACT+ACTPol observing seasons. Notably, of the entire set of 182 galaxy cluster detections (with signal-to-noise ratio greater than 4) in this combined MBAC and ACTPol data set, 28 clusters are newly discovered. For the entire dataset, detected clusters have a median redshift of 0.49, and span the range \(0.1 < z < 1.4\), and furthermore consistency is found between the mass distribution of this MBAC+ACTPol dataset and the mass distribution measured by the South Pole Telescope for clusters that have \(M_{500c}>4\times10^{14}M_{\text{solar}}\). Figure 6.8 provides an example set of these SZ cluster detections for the 15 clusters with highest signal-to-noise ratio in the dataset, where compared to the entire ACT+MBAC only cluster catalog, the 15 highest signal-to-noise
ratio detections including ACT+ACTPol data exceed the signal-to-noise ratios for all but two of the clusters in the ACT+MBAC only dataset. The scale for these images ranges from -150 $\mu$K for the black regions to 50 $\mu$K for the white regions. Figure 6.9 provides optical imagery of six galaxy clusters in the MBAC+ACTPol SZ galaxy cluster survey from SDSS, in which the location of the central cross in each image (each square regions of 6 arcminute sides) indicates the location of the MBAC+ACTPol SZ cluster detection with contours indicating the decrement signal in the 148 GHz MBAC+ACTPol dataset. (Hilton et al. 2018) Analysis and multiwavelength follow-up observation campaigns are currently ongoing for the full three-season ACTPol dataset, however, these early results again confirm that ACTPol has met its science goals as an effective survey instrument for the detection of galaxy clusters via the Sunyaev-Zel’dovich effect.

6.3 ACTPol Galactic Field Observations

In the previous Chapter, we provided an overview of observational data coverage for ACTPol Season 1 operations during 2013, completed with the ACTPol receiver deployed to the ACT telescope optomechanical superstructure with a single 150 GHz TES-based polarimeter array package deployed. In particular, this season focused on six deep CMB science fields, with a particular emphasis on two of the six fields (e.g. ACTPol CMB Deep 5 and ACTPol CMB Deep 6) during science integration operations. In addition to planetary calibration targets, which for ACTPol Season 1 included Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune, two additional operational fields were targeted for potential polarization calibration purposes: Tau A, or ‘Crab Nebula,’ and a section of the galactic field. As discussed earlier in this Chapter, ultimately the observation of Tau A was utilized as an initial polarization calibration source for ACTPol, but nonetheless during ACTPol Season 1, in addition to the 1427 integrated CMB science hours completed, 73.82 integrated hours of galactic field observations were performed. In this section, we discuss early map-
Figure 6.4: CMB mapping results for the central subregion of the Deep 6 field, with mapping results in I (shown as T in the map), Q, U, E, and B shown. Additionally, a detail region of the intensity map is expanded to reveal both Sunyaev-Zel’dovich effect signal decrement in the map indicating the detection of a galaxy cluster via the Sunyaev-Zel’dovich effect, as well as the detection of a point source (signal increment on intensity map). As we perform for the filtering of the ACTPol galactic field maps later in this Chapter, the maps are filtered in $\ell$ such that the noisiest $\ell$ ranges for a small-angular scale polarization-sensitive receiver like ACTPol are minimized. In this case, the ACTPol Deep 6 subregion I map is shown after applying a high-pass filter for multipole $\ell > 240$, while the ACTPol Deep 6 polarized Q and U maps are shown following the application of a bandpass filter for $260 < \ell < 1370$. Also shown in the bottom panel, are the corresponding difference maps generated for the intensity, E, and B maps. A jack-knife method was used here to calculate the ACTPol Deep 6 subregion I,E,B difference maps using two-way splitting of the ACTPol galactic field I,E,B data set (split by odd and even pairs of days of observation). Similar to the results that will be shown for the ACTPol galactic field I,Q,U difference maps later in this Chapter, we observe correlated noise in the I,E,B maps aligned with the dominant scanning direction of ACTPol. (Naess et al. 2014a)
Figure 6.5: ACTPol TT, TE, EE, and BB power spectra results for the ACTPol Season 1 CMB deep field data set. Here we see that TT, TE, and EE power spectra results for the ACTPol Season 1 data set are in good agreement with ΛCDM cosmology and analogous power spectra measurements from the WMAP and Planck missions. Furthermore, ACTPol results show TT, TE, and EE power spectrum results competitive with constraints placed on these power spectra at high angular scales by other contemporary small angular scale experiments, out to ℓ of roughly 9000 in TT and 3000 for TE and EE, as was stated as a primary CMB science goal of the ACTPol receiver. Of course, while no B-mode power spectrum is detectable by ACTPol, the introduction of multiple operating wavelengths, able to detect and constrain both low-frequency (synchrotron), and high-frequency (dust emission) foregrounds, and the extension of ACTPol science to larger angular scales, as will be described in the next Chapter as central to the planned science and technology development goals of the Advanced ACTPol receiver, will continue the push toward direct probes of primordial gravitational waves. (Naess et al. 2014a)
Figure 6.6: The measured polarization structure map of the ACTPol observation of Tau A (the Crab Nebula). For the observation of Tau A, a polarization intensity (mathematically defined later in the ACTPol galactic field analysis section), peaked at roughly 6800 $\nu$K, corresponding to the highest polarization intensity range of the ACTPol galactic field maps shown later (6000-8000 $\nu$K maximum polarization intensity). Measured at the central pulsar of Tau A, the ‘Crab Pulsar,’ the polarization angle found in the ACTPol measurement of Tau A agrees well with observations made on the IRAM 30 meter telescope using the XPOL polarimeter operating with a central frequency of 89.2 GHz, in which the IRAM result corresponded to a polarization angle of $\gamma = 149.9 \pm 0.2$ degrees, with ACTPol measuring a polarization angle offset from the IRAM result by $-1.2 \pm 0.2$ degrees, with both data sets smoothed to a 5 arcminute gaussian beam (Aumont et al. 2010) (Naess et al. 2014a).
Figure 6.7: The predicted TT power spectrum for thermal dust emission across the ACTPol Season 1 CMB deep fields Deep 1, 5, and 6. Here, it is shown that using the (Finkbeiner et al. 1999) results as a template (plotted beneath the TT power spectrum results for these fields), it is expected that above $\ell$ of 2000, dust foreground emission in these fields should only add less than $2^2$ to the TT power spectrum. Furthermore, using results presented for dusty foreground maps measured by the Planck mission in (Planck Collaboration et al. 2015a), which we will use extensively in the ACTPol galactic field analysis found in the next section, the polarization fraction expected for ACTPol Deep Fields 1, 5, and 6 are roughly 5 percent, which is consistent with polarization fraction results calculated for fields on and off of the ACTPol galactic field data set. (Naess et al. 2014a)
Figure 6.8: An example set of for the 15 clusters with highest signal-to-noise ratio in the MBAC+ACTPol dataset of galaxy clusters detected via the Sunyaev-Zel’dovich effect. Compared to the entire ACT+MBAC only cluster catalog, the 15 highest signal-to-noise ratio detections including ACT+ACTPol data exceed the signal-to-noise ratios for all but two of the clusters in the ACT+MBAC only dataset. The scale for these images ranges from -150 $\nu$K for the black regions to 50 $\nu$K for the white regions. (Hilton et al. 2018)
Figure 6.9: Optical imagery of six galaxy clusters in the MBAC+ACTPol SZ galaxy cluster survey from SDSS, in which the location of the central cross in each image (each square regions of 6 arcminute sides) indicates the location of the MBAC+ACTPol SZ cluster detection with contours indicating the decrement signal in the 148 GHz MBAC+ACTPol dataset. (Hilton et al. 2018)
ping and polarization analysis associated with the ACTPol Season 1 galactic field dataset, initial results of which appear for this first time in this dissertation manuscript.

6.3.1 Motivation for ACTPol Galactic Field Observations

A propensity of modern experimental cosmology facilities focusing on the mapping and characterization of the Cosmic Microwave Background at small-angular-scales is to avoid intersecting CMB science fields with (or at declinations near) the plane of the Milky Way Galaxy, which for the purposes of the following section will be referenced interchangeably as the galactic field, galactic plane, or galaxy. While such a strategy may result in CMB observations that minimize confusion with foreground emissions in comparison to fields intersecting or near the galactic plane, it is equally important that polarization-sensitive, millimeter-wavelength experimental cosmology facilities, including ACTPol, at least include the galactic plane as a tertiary science objective. This is due to the fact that, polarization-sensitive observation of the galactic plane at millimeter wavelength regimes can be vital to serve as a polarization calibration data source between observational platforms (e.g. between ACTPol and Planck). Additionally, and perhaps most important for the drive toward future-generation facilities probing inflationary physics via a direct observation of the B-mode power spectrum at large angular scales, it will be necessary to well understand and characterize foregrounds, both from synchrotron and dust emission, where, in particular, polarization signal from dust emission can dominate lower intensity CMB science targets, including the B-mode power spectrum. Performance of joint analysis of, for example, multiwavelength Planck data with other multiwavelength polarized data sources can aid in the characterization and constraint of dust emission signals that will need to be understood to analyze possible inflationary regimes. Additionally, polarized galactic dust emission is physically interesting in its own right, and resultant millimeter-wavelength polarized galactic maps made available for use in supporting galactic science in the larger community can,
e.g., support probes of magnetic field structures of high column density galactic filamentary molecular clouds.

Throughout this section, a framework is built-out, currently using only ACTPol Season 1 data, that is, 150 GHz temperature and polarization results for the galactic field, to coadd and compare to corresponding sky map areas from the Planck 143 GHz channel temperature and polarization results. Ultimately, the framework and methods performed in this single frequency joint analysis, will enable rapid future analysis and understanding of, e.g., Advanced ACT (AdvACT) multifrequency data sets in both the mid-frequency CMB channels, as well as high-frequency dusty foreground emission, and low-frequency synchrotron emission channels at larger angular scales (to be achieved on AdvACT through the introduction of a ambient-temperature, rapid-rotating, half-wave-plate at the entrance aperture of the to-be-upgraded receiver).

Thus, for AdvACT further constraints could potentially be placed on the tensor-to-scalar ratio $r$, and hence, move toward next-generation probes of inflationary physics. At a minimum, introduction of multiwavelength polarimeter arrays will allow for a better characterization (and ultimate removal from CMB signal) of foreground emission regimes in nominal CMB fields, with lower dust column densities than fields at or near the galactic plane. (Dunkley et al. 2009) provides a CMBPol (Inflationary Probe) mission concept study focusing on the prospects for removing polarized foregrounds including synchrotron and dust emission. In that discussion, four distinct mechanisms are expected to provide polarized foreground challenges for the observation of the B-mode power spectrum, namely, polarized synchrotron emission, polarized thermal dust emission, secondary polarization resulting from free-free or bremsstrahlung emission, and excess polarization signal from anomalous emission sources. Free-free emission is defined as emission resulting from electron-scattering resulting from interaction with warm ionized gas within the interstellar medium, however it should be noted that given that scattering directions for this mechanism are randomly oriented, free-free emission does not exhibit inherent polarization signal. With that in mind,
however, as indicated in (Keating et al. 1998) for ionized hydrogen regions, Thompson scattering by electrons in these regions will result in the (secondary) polarization of the free-free emission signal, tangential to the limits of these regions. For nominal CMB field observations, however, polarization resulting from this mechanism is expected to be polarized at the 10 percent level within the galactic plane when observing at high angular resolutions, and less than 1 percent at low angular resolutions off of the galactic plane. Explicitly, (Keating et al. 1998) predicts that the polarized free-free emission signal will be manifest itself for frequencies greater than roughly 10 GHz at a level of at least an order of magnitude lower than synchrotron emission in the analogous frequency range. Similarly, anomalous emission sources, including from so-called “spinning dust” resulting from polarized emission from rotating polycyclic aromatic hydrocarbons with dipole moments described in (Lazarian and Finkbeiner 2003), or the mechanism described in (Draine and Lazarian 1998) in which magnetic dipole radiation is emitted as thermally vibrating dust grains undergo magnetic fluctuation. In spite of this, WMAP results, including those described in (Battistelli et al. 2006) indicate that the polarized excess from anomalous emission remains less than roughly 5 percent. In particular, (Battistelli et al. 2006) describes the measurement of Q and U polarization maps made of anomalous emission in the perseus molecular complex with the Cosmosomas experiment. This measurement resulted in a detection of polarized anomalous emission signal with measurements of Q and U polarization in which, $Q = -0.2 \pm 1.0\%$ and $U = -3.4^{+1.8}_{-1.4}\%$, corresponding to a total polarization of $3.4^{+1.5}_{-1.3}\%$. (Dunkley et al. 2009)

Therefore, although a robust understanding of the magnitude and physical processes leading to both excess polarization signals from both free-free and anomalous emission signals are vital, these mechanisms are subdominate to the two primary sources of excess polarization foreground signals that can limit CMB polarization observations, and in particular future measurements of the B-mode power spectrum: synchrotron emission from relativistic electrons, and thermal dust emission. Figure 6.10 illustrates predicted polarized foreground spectra for the wavelength regime 10-1000 GHz relevant for polarization-sensitive, millime-
ter wavelength CMB experiments, such as ACTPol and AdvACT. Here, we observe that predicted free-free, or Bremsstrahlung, emission is subdominate to synchrotron emission over analogous frequency ranges. In general, signal from synchrotron and thermal dust emission mechanisms are minimal from roughly 70-100 GHz, with synchrotron emission dominating below 70 GHz, and thermal dust emission dominating as a polarized foreground signal source above 100 GHz. (Planck Collaboration et al. 2015a) (Keating et al. 1998) The source of observed polarized synchrotron emission is described in the text of (Rybicki and Lightman 1979). In general, synchrotron emission arises from the acceleration of relativistic electrons within the galactic magnetic field, in which synchrotron emissivity is dependent on the density of relativistic electrons in a region, as well as the magnetic field strength of that region, with intensity given by 6.5, where is the given observational frequency, \( L \) refers to the depth of emission, \( B \) is the local magnetic field strength, \( N_0 \) refers to the relativistic electron density, and furthermore, the relativistic electron energy spectrum is given by \( (dN/dE) = (N_0)(E^{-p}) \), as given in (Davies and Wilkinson 1998). Furthermore, (Rybicki and Lightman 1979) states that partial polarization of the galactic synchrotron emission arises, such that for electron energies distributed according to a simple power law, fractional linear polarization, aligned orthogonal to the galactic magnetic field, is given by Equation 6.6, with frequency dependence given according to \( T(\nu) \propto \nu^\beta \) for spectral index \( \beta = -(p+3)/2 \) (Rybicki and Lightman 1979), (Dunkley et al. 2009).

\[
I(\nu) = (\text{constant})(L)(N_0)(B^{(p+1)/2})(\nu^\beta - (p-1)/2) \tag{6.5}
\]

\[
f_{\text{synch}} = ((p+1)/(p+7/3)) \tag{6.6}
\]

An understand of polarization signal from thermal dust emission also is required for characterization of CMB polarization, in the case of dust for frequencies above 100 GHz. In this frequency range characteristic for CMB polarization experiments in which dust emission is prevalent, e.g. between 100 - 1000 GHz, all-sky mapping reveals galactic emission
Figure 6.10: Predicted polarized foreground spectra for the wavelength regime 10-1000 GHz relevant for polarization-sensitive, millimeter wavelength CMB experiments, such as ACTPol, Planck, and AdvACT. Here, we observe that predicted free-free, or Bremstrahlung, emission is subdominate to synchrotron emission over analogous frequency ranges. In general, signal from synchrotron and thermal dust emission mechanisms are minimal from roughly 70-100 GHz, with synchrotron emission dominating below 70 GHz, and thermal dust emission dominating as a polarized foreground signal source above 100 GHz. (Planck Collaboration et al. 2015a) Figure courtesy (Keating et al. 1998)
that is dominated by thermal emission by dust grains corresponding to the thermal emission propagated via the thermal fluctuation of the electric dipole moment of a given dust grain (Dunkley et al. 2009), with grain temperatures ranging between 10 and 100 K. Astronomical spectroscopic analysis shows that dust grains comprising the interstellar medium have a composition primarily consisting of silicates, and carbonaceous materials, including the aforementioned polycyclic aromatic hydrocarbons, discussed in the description of anomalous sources of polarized foreground emission (Draine and Fraisse 2009). The presence of dust in the galactic interstellar medium provides for linear starlight polarization, as first discussed in (Hiltner 1949), and led to the characterization of the galactic dust grain population, a significant fraction of which are non-spherical and in which a significant fraction of silicate dust grains are in alignment with the galactic magnetic field. Thermal dust emission has linear polarization produced through this alignment with the galactic magnetic field, in which for non-spherical dust grains, both emission and absorption occur readily along the major axis of the grain in which the major grain axis is aligned orthogonally to the galactic magnetic field structure present in a given region. This will therefore give rise to the aforementioned characteristic of dusty foreground polarization, in which polarization vectors associated with thermal dust emission will exhibit alignment orthogonal to the galactic magnetic field structure present in a given region, with polarization vectors parallel to the galactic magnetic field structure present in a given region when absorption occurs (Dunkley et al. 2009). Broadly, thermal emission from dust grains becomes polarized since aligned, spinning dust grains exhibit inherent anisotropies (Matthews et al. 2009). Polarization intensity also has a strong wavelength dependence when viewing multi-wavelength observations of dense cloud structures comprising the galactic plane, in which a minimum polarization intensity is observed in these structures at a frequency of roughly 850 GHz (Dunkley et al. 2009), (Draine and Fraisse 2009). Additionally, the fractional polarization exhibited through observations of galactic structures and in high-galactic-latitude mapping of thermal dust polarization, such as conducted by the SCUBA and Planck experiments in
the 350 GHz frequency regime, often exhibit a polarization fraction on the range of 0.5-10% (Matthews et al. 2009), (Planck Collaboration et al. 2015a).

Ultimately, given the broad parameter space within the galactic plane, consisting of, among other properties, dust grain composition and morphology, dust grain population mixing, far-infrared grain radiation, thermal dust polarization measurable in the millimeter and submillimeter wavelength regimes, and polarization dependence on the galactic magnetic field structure, characterization of dusty foregrounds can provide a rich understanding of dynamical galactic and astrophysical phenomenon in their own right. A comprehensive overview of the nature of thermal dust emission and the thermal dust polarization foreground mechanism can be found in (Draine and Fraisse 2009). It is also important to mention that thermal dust intensity overall does not always proportionally scale to its corresponding polarization intensity, therefore a robust mapping of dust polarization intensity is important to have a greater understanding of polarized foreground characteristics on a given patch of sky to ensure that an excess of dust polarization signal is not confused for CMB polarization signal, similar to the initially mistaken confirmation of B-mode polarization in early data sets of the BICEP experiment. An understanding of the importance of a proper characterization of dominant synchrotron and thermal dust emission polarized foreground mechanisms is further illustrated in Figure 6.11, which depicts the challenge posed by both mechanisms when attempting to measure the BB power spectrum (of tensor-to-scalar ratio $r = 0.01$) at 90 GHz, even in regions of estimated minimal foreground signal. In this plot, we observe that for observation of 0.75 of the entire sky, one would predict that the polarization signal from thermal dust emission would dominate B-mode power spectrum signal even on the range of polarization fractions expected from experimental observation (0.5-10%), in which the lower and upper solid red line represents the polarized dust emission signal assuming a polarization fraction of 1.5% and 5%, respectively (Dunkley et al. 2009).

Clearly, astrophysical observation of galactic thermal dust emission, both in the complex galactic plane and within the galactic halo, can shed light on the fundamental properties
Figure 6.11: Illustration of the challenge posed by both synchrotron and dust emission polarization mechanisms when attempting to measure the BB power spectrum (of tensor-to-scalar ratio $r = 0.01$) at 90 GHz, even in regions of estimated minimal foreground signal. In this plot, we observe that for observation of 0.75 of the entire sky, one would predict that the polarization signal from thermal dust emission would dominate B-mode power spectrum signal even on the range of polarization fractions expected from experimental observation (0.5-10%), in which the lower and upper solid red line represents the polarized dust emission signal assuming a polarization fraction of 1.5% and 5%, respectively (Dunkley et al. 2009)
of the galactic magnetic field itself, given aforementioned dependencies on the alignment of dust grains with the galactic magnetic field, which exists in both the galactic plane and halo at the level of a few microgauss, and, as described in (Planck Collaboration et al. 2015a), is responsible for the nature of fundamental galactic dynamics and processes as the structure and morphology of the interstellar medium, the acceleration of relativistic electrons (resulting in the aforementioned synchrotron emission polarized foreground mechanism), and star formation, among others. Observing campaigns performed on leading radio observatories have allowed for a more comprehensive characterization of the galactic magnetic field, though characteristic processes observed in radio surveys have dependency on thermal and relativistic electron densities, on which it is difficult to place a constraint - therefore, the addition of thermal dust polarization characteristics and mapping obtained via polarization-sensitive, millimeter wavelength instruments such as ACTPol and AdvACT can have a real benefit to the broader galactic radio astronomy community by complementing data sets obtained by radio telescopes (Planck Collaboration et al. 2015a).

Pertinent to the science goals of next-generation millimeter-wavelength, polarization-sensitive instruments probing the Cosmic Microwave Background polarization spectra, if foregrounds can be removed with the introduction of multiwavelength channels required for component analysis to allow foreground constraint and removal, the field will be enabled to measure the B-mode power spectrum. When this occurs, the result it will provide significant evidence for primordial gravitational waves, and thus confirmation of the predicted inflationary model of the early universe. Therefore, the stakes of understanding, characterizing, and constraining foreground behavior couldn’t be higher. The two sections that follow will briefly look at data reduction and analysis methods and procedures that will ultimately support next-generation multi-wavelength component analysis of CMB polarized foregrounds, though given that this utilizes single wavelength data, in a complex, non-gaussian galactic field region, this will only touch upon broad concepts that a future foreground component analysis would address. The first section illustrates the statistical overview of the ACTPol
Season 1 galactic field data set, followed by the steps (and resulting plots) that allowed raw galactic field maps to be moved through the process of data reduction, ultimately allowing for ACTPol 146 GHz galactic field data to be coadded with Planck 143 mapping results in the same region, along with power spectra of the ACTPol I, Q, and U maps of this region. The next section conducts a similar statistical analysis as performed in (Planck Collaboration et al. 2015a), in which the ACTPol+Planck coadded data is compared to Planck-only data in the same region, both with regard to qualitative field structure stemming from resolution improvements associated with the addition of small-angular-scale data from ACTPol, and in characterizing the resulting polarization intensity, angle, and fraction properties of the entire high-statistic ACTPol+Planck coadded galactic field and the corresponding Planck-only maps, both for the full field and for on- and off-galactic-plane subregions.

### 6.3.2 Overview of Statistics, Mapping, Reduction, and Analysis of ACTPol 146 GHz + Planck 143 GHz Coadded Galactic Field Maps

The data set comprising the ACTPol 146 GHz galactic field data set was taken during ACTPol Season 1 Operations, which ranged from first light in July 2013 until suspension of ACTPol Season 1 operations in early-January 2014. Given that galactic field data was taken strictly during Season 1 operations, in which ACTPol was integrated with a single TES detector-enabled polarimeter array package operating with 150 GHz sensitivity, the ACTPol data set only contains data from this single frequency channel. Although ACTPol Season 3 operations included a fully-integrated receiver operating with dual 150 GHz sensitive polarimeter array packages, in addition to a single multichroic polarimeter array package operating with simultaneous 90 GHz and 150 GHz sensitivity, further data taking within the ACTPol galactic field was deprioritized for latter ACTPol observing seasons in favor of increasing integration time for CMB science field operations (interspersed with planetary calibration and polarization calibration targets). The need for this field as a potential polarization calibration target was furthermore obviated by the use of Tau A, or the Crab
Nebula, as the primary polarization calibration target for ACTPol operations. As described in the preceding chapter, even during ACTPol Season 1 operations, observing time dedicated to the ACTPol galactic field was deemed a tertiary priority, again to maximize planetary targeting for beam and systematic characterization early in Season 1, with a progression to near-continuous operations (daytime and nighttime) for CMB science ‘Deep Fields’ 1, 2, 3, 4, 5, and 6, with a particular emphasis of maximizing depth in fields 5 and 6.

In spite of this, the ACTPol galactic field was provided enough integration time in ACTPol Season 1 observing operations for high-fidelity mapping, able to provide a rich, if areally-limited, dataset, which we will find even as a tertiary science field target, has been able to make significant resolution contributions at small-angular scales to analogous maps obtained by the Planck mission at larger angular scales. Figures 6.12 and 6.13 provide an overview of primary statistical attributes of the ACTPol galactic field data set ultimately used for the analysis described in this section. Nominal telescope observing altitudes for the data set ranged from 45-60 deg, with nominal observing azimuthal coverage for the primary data set ranging from roughly 30-70 deg. The data set nominal observing hours during daily ACTPol Season 1 operations ranged from 14-01 hours UTC, and the data set was fully obtained between September and December 2013, with the majority of integration time concentrated in November 2013. The highest number of TODs for the ACTPol galactic data set were obtained within the range of 16-01 hours UTC, corresponding to a range of 1300-2200 hours Chilean local time. Furthermore, in 6.13 we find that the final ACTPol galactic field data set consisted of TODs taken when the ambient precipitable water vapor (PWV) ranged from roughly 0.5-2.5 mm, where the mean PWV for the data set was 1.17 mm with a standard deviation of 0.55 mm. The average per TOD observing duration for the ACTPol galactic field data set was 8.53 minutes with a standard deviation of 3.36 minutes given that most TODs in the data set were between 10 and 12 minutes in duration. The entire ACTPol galactic field data set presented here corresponds to a total analysis-grade observing integration time of 73.82 hours. For comparison, the integrated data set duration
for the deepest two ACTPol CMB observing fields, namely ACTPol ‘Deep 5’ and ‘Deep 6,’
corresponded to field observing durations of 311 and 305 hours, respectively, for ACTPol
Season 1 operations (Naess et al. 2014a).

With these data set statistical characteristics now in hand, the reader should be re-
minded that the attributes of the ACTPol galactic field data set presented here correspond
those TODs that ultimately survived data cuts to be included in the map-making proce-
dures and resulting science-grade maps for this analysis. The creation of the data cuts
package for the ACTPol galactic field data set follows the criterion and procedures de-
scribed in (Dünner et al. 2013), which illustrated the cuts procedure for ACT+MBAC
operations, and in (Naess et al. 2014a), which extended that procedure and set criterion
for polarization-sensitive data obtained during ACT+ACTPol operations. While an entire
reproduction and description of the ACTPol cuts package generation, data selection, and
map making process will not be reproduced in this manuscript, a few reminders of core pro-
cedures and characteristics used for ACTPol science-grade data should be provided from
(Dünner et al. 2013) and (Naess et al. 2014a). For ACTPol data selection, the final cali-
bration procedure was extended from that described in (Dünner et al. 2013) given that a
higher number of detectors utilized for ACTPol observing operation perform near saturation
than was the case during MBAC operations. (Naess et al. 2014a) describes this challenge
as addressed by determining an absolute calibration for a subset of detectors that have
stable operational characteristics during oscillations in loading and focal plane operating
temperature characteristics. To minimize issues introduced to the science data stream by
low-frequency drifts, a lower-order polynomial is then removed from these data files, before
flat-fielding is completed for detectors comprising each TOD using the atmospheric common
mode (Naess et al. 2014a). With this calibration in hand, data selection then occurs on
both a detector-characterization basis, and then a subsequent TOD data file basis. First,
for a given data file, detector performance characterization, including attributes described
earlier in this dissertation such as vibroacoustic response, time-constant characteristics, sat-
Figure 6.12: An overview of primary statistical attributes of the ACTPol galactic field data set. Nominal telescope observing altitudes for the data set ranged from 45-60 deg, with nominal observing azimuthal coverage for the primary data set ranging from roughly 30-70 deg. The data set nominal observing hours during daily ACTPol Season 1 operations ranged from 14-24 hours UTC, and the data set was fully obtained between September and December 2013, with the majority of integration time concentrated in November 2013.
Figure 6.13: Precipitable water vapor (PWV) and time ordered data (TOD) attributes of the ACTPol galactic field data set. The final ACTPol galactic field data set consisted of TODs taken when the ambient precipitable water vapor (PWV) ranged from roughly 0.5-2.5 mm, where the mean PWV for the data set was 1.17 mm with a standard deviation of 0.55 mm. The average per TOD observing duration for the ACTPol galactic field data set was 8.53 minutes with a standard deviation of 3.36 minutes where most TODs in the data set were between 10 and 12 minutes in duration. The entire ACTPol galactic field data set presented here corresponds to a total analysis-grade observing integration time of 73.82 hours.
uration power, noise characteristics, optical efficiency, sensitivity, and more are taken into account to set set thresholds for categorizing detectors into three sets. Those sets include ‘live’ or ‘effective’ detectors, which exceed minimum threshold performance criterion for inclusion into science grade maps, ‘dark’ detectors, which are either intentional dark pixels included on the focal plane for systematic performance purposes or else do not couple to the sky or are defective in some way yet exhibit some useable operational attributes, and ‘broken’ detectors which either do not meet a sufficient operational threshold (e.g. such as an unacceptably large time constant) or can not be properly read out or are entirely non-responsive.

For the ACTPol galactic field data set, for example, only detectors classified as ‘effective’ were ultimately were included into usage within the final science-grade TODs for the set. Furthermore, as described in (Dünner et al. 2013), broad observing data set factors influence selection criterion for data included for science-grade analysis. These include the rejection of any data file taken during poor atmospheric observing conditions corresponding to data taken when PWV conditions exceeded 3.0 mm, data files for which a significant number of constituent detectors were deemed to have insufficient performance characteristics for characterization as ‘effective’ (e.g. less than 400 effective detectors in a single data file), poor cryogenic performance attributes in which the base temperature exhibited instability (variation by greater than 1 mK within a given TOD) or was higher than 7 mK greater than the required nominal base temperature, or exhibited poor calibration or corruption in the readout or analysis pipeline for that given file (Dünner et al. 2013). Extending the cuts criterion further than that described in (Dünner et al. 2013) for ACT+MBAC operations, however, for ACT+ACTPol operations, we no longer reject data taken more than one hour before or after sunrise or sunset. This criterion was included for ACT+MBAC operations both because cryogenic performance often degraded toward the end of a given observing night prior to cryogenic recycling in that era, as well as the drive to avoid data taken when the ACT telescope optomechanical superstructure exhibited thermal deformation related...
to daytime heating. However, given that ACTPol's operation with a continuous-operation
dilution refrigeration system allowed for the introduction of daytime operations, and im-
provements in optomechanical alignment and associated characterization by the ACTPol
non-contact photogrammetry system for daytime alignment paradigms, these cut criterion
were removed for the ACTPol galactic field data set, especially relevant given that the nom-
inal data acquisition for this set took place in a daily time range, 1300-2200 hours Chilean
local time, which straddled both daytime and nighttime operational characteristics.

In the end, utilizing these procedures for science-grade data selection, the final ACTPol
cuts package is generated, with both the ACTPol CMB and galactic field data sets utilizing
data from well-characterized, commonly-calibrated detectors, with superior noise perfor-
ance, and $f_{3db} > 20\text{Hz}$, residing within the aforementioned broader data file selection
criterion (Naess et al. 2014a). With this cuts package then applied to the ACTPol galactic
field data set, we then have the subsequent final data set characteristics as described earlier
in 6.12 and 6.13. With this subset of science-grade galactic field TODs then well defined,
these data streams are then processed into maps using the procedure for projection onto
the sky described in (Dünner et al. 2013). Here, a given ACTPol map takes the form of the
generic mapping definition found in Equation 6.7 where for a given per-pixel TOD vector
d, we have:

$$d = Px + n$$  \hspace{1cm} (6.7)

where $P$ goes as the pointing matrix defining the location at which a given pixel was
pointed at a given time, $n$ is the ACTPol noise vector, and $x$ is the sky map being solved
for. The using an estimate for the noise covariance matrix, given in Equation 6.8, where

$$N \equiv <n|n^T>$$  \hspace{1cm} (6.8)

we can then consider that the model to maximize the likelihood function will go as
defined in Equation 6.9, where,
The maximum likelihood solution for $x$ can then be written as in 6.10. Given that computational limitations do not allow for the direct inversion of $(P^TN^{-1}P)$, a precondition Conjugate Gradient algorithm is used to iteratively solve a linear least-squares equation for $x$ as described in (Press 2007) and thereby yield ACTPol science grade mapping products that is able to project science-grade-selected TODs into a raw mapping product for analysis use (Swetz 2009) (Newburgh 2010) (Dünner et al. 2013) (Naess et al. 2014a). Additional details of the pre-processing and characterization of the noise solution that leads to final ACTPol mapping products, can be found in (Dünner et al. 2013).

$$x = (P^TN^{-1}d)/(P^TN^{-1}P)$$

The ACTPol galactic field data set was, similar to the ACTPol polarized CMB mapping products, computationally mapped using the Ninkasi mapmaking code operating on the GPC supercomputer of the SciNet HPC Consortium. As described in (Dünner et al. 2013), the mapping algorithm explicitly solves for gaps in a given time stream resulting from data removed via the cuts package criteria, point source models are removed directly from each given detector time stream, detector correlated noise is included in the noise matrix instead of solving directly for detector-correlated noise characteristics, and an initial map is generated to allow for the removal of signal-induced bias in the noise estimation, after which the noise is estimated a second time (Dünner et al. 2013). Figure 6.14 illustrates the raw full-field I,Q,U mapping results for the ACTPol galactic field data set taken during ACTPol Season 1 operations with a single ACTPol 146 GHz polarization-sensitive polarimeter array package prior to point-source analysis. Following raw-mapping of the ACTPol galactic field, inspection of resultant initial maps, including those shown in 6.14, it was discovered that using nominal ACTPol CMB cuts package criteria, significant structure was removed from the galactic plane, with holes in map data apparent. These artifacts were determined
to be the result of removal of point sources or high-intensity galactic structures falsely-characterized ‘glitch’ events, which are defined in (Dünner et al. 2013) as regions of dramatic spiking in a given data stream that are greater than 10 times the ambient noise RMS, which can be generated by a variety of causes, including incident cosmic rays. Cuts are nominally applied to remove the event plus data 0.5 seconds to either side of the ‘glitch’ event and in regions of multiple detected ‘glitches’ less than 5 seconds apart these events are then combined into a single cut applied to that region of the map corresponding to the offending glitches (Dünner et al. 2013). While this is indeed a wise data selection criterion to be set for CMB science mapping, with the ACTPol galactic field existing as a non-gaussian field with characteristic high-intensity structures, these glitch removal criterion resulted in unnecessary data cutting (especially in the central regions of high-intensity galactic structures) and caused streaking and distortion effects in the original raw galactic field maps. To overcome this, the raw maps were then analyzed to determine the coordinates of high-intensity regions in the galactic field maps, targeting strong and fast variations in the data, which, for the purposes of this field, included both point sources and data in the galactic field with characteristics strong intensity gradients. Figure 6.15 illustrates the point source and high-intensity gradient finding protocol which was run on the raw ACTPol galactic field maps, generating a list of coordinates of high-intensity structures within nine overlapping subregions of the central galactic field map region. These structures were then introduced to allow for their removal from the original ‘glitch’ catalog, which allowed for a final cuts package to be generated for the ACTPol galactic field and remapping with these identified structures included.

The resulting final full-field mapping results for the ACTPol galactic field following updated ‘glitch’ removal data selection criterion can be found in 6.15 along with corresponding weight maps for full-field I,Q,U mapping results. For comparison, the Planck mission year 2 HFI I,Q,U mapping results for Planck 100 GHz, 143 GHz, 217 GHz, and 353 GHz channels mapped over the same region of sky as the ACTPol full-field galactic data set can be
found in 6.17 (Planck Collaboration et al. 2015a). Given the relatively limited integration time spent on the ACTPol galactic field data set during Season 1, statistical coverage over the full-field was non-uniform, as shown by the ACTPol 146 I,Q,U full-field weight maps - therefore for coadding with Planck and further polarization-analysis purposes described here, the ACTPol galactic field data set was reduced to a high-statistic central region, of 45.5 sq. deg., with coordinates of RA = [-73.0, -80.0] and DEC = [-2.0, 4.5]. Figure 6.18 and Figure 6.19 illustrate the resulting high-statistic ACTPol galactic field maps and multiwavelength Planck results over the same region of sky. A jack-knife method was then used to calculate ACTPol 146 GHz galactic field I,Q,U difference maps using two-way splitting of the ACTPol galactic field I,Q,U data set (split by odd and even pairs of days of observation), shown in 6.20. The signal-to-noise for the high-statistic region of the ACTPol galactic field data set is also shown in 6.20, calculated by dividing the ACTPol galactic field I,Q,U high-statistic signal maps by their corresponding I,Q,U residual maps, which confirm that the ACTPol galactic field high-statistic region data set is indeed signal dominated. Similar to the results cited earlier for the ACTPol Season 1 CMB deep field data sets, we observe correlated noise in the I,Q,U maps aligned with the dominant scanning direction of ACTPol, which like for the CMB data sets, is also diagonal for the ACTPol galactic field sets. This correlated noise is analogous to the correlated noise in the TODs previously described, only expressed in terms of map space (Naess et al. 2014a).

With the initial mapping, statistical, and noise properties of the ACTPol galactic field maps now characterized, we can proceed with the creation of a coadded map of ACTPol 146 GHz and Planck 143 GHz frequency channel results. As a reminder, ACT+ACTPol operate with arcminute angular resolution in its 146 GHz band, while the 143 GHz band of the Planck mission operates with a resolution of 7.1 arcminutes. Using a method similar to that used for CMB deep subregions shown in (Naess et al. 2014a), Figure 6.21 shows the ACTPol 146 GHz I,Q,U bands for the high-statistic galactic field region defined earlier filtered to maximize signal-to-noise across the relevant bands. In this case, the ACTPol galactic field
Figure 6.14: The raw full-field I,Q,U mapping results for the ACTPol galactic field data set taken during ACTPol Season 1 operations with a single ACTPol 146 GHz polarization-sensitive polarimeter array package prior to point-source analysis.
Figure 6.15: Selected subregion maps from the point source and high-intensity gradient finding protocol run on the raw ACTPol galactic field maps. This generated a list of coordinates of high-intensity structures within nine overlapping subregions of the central galactic field map region. These structures were then introduced to allow for their removal from the original ‘glitch’ catalog, which allowed for a final cuts package to be generated for the ACTPol galactic field and remapping with these identified structures included.
Figure 6.16: Final full-field mapping results for the ACTPol galactic field following updated ‘glitch’ removal data selection criterion, with corresponding weight maps for full-field I,Q,U mapping results.
Figure 6.17: Planck mission Year 2 HFI I,Q,U mapping results for Planck 100 GHz, 143 GHz, 217 GHz, and 353 GHz channels mapped over the same region of sky as the ACTPol full-field galactic data set. (Planck Collaboration et al. 2015a)
Figure 6.18: ACTPol galactic field data set reduced to a high-statistic central region, of 45.5 sq. deg., with coordinates of RA = (-73.0, -80.0) and DEC = (-2.0, 4.5) in I,Q,U.
Figure 6.19: Planck mission Year 2 HFI I,Q,U mapping results for Planck 100 GHz, 143 GHz, 217 GHz, and 353 GHz channels mapped over the same region of sky as the ACTPol high-statistic central region reduced data set. (Planck Collaboration et al. 2015a)
Figure 6.20: ACTPol 146 GHz I,Q,U high-statistic galactic field region data set difference and signal-to-noise (S/N Ratio) maps. A jack-knife method is used to calculate ACTPol 146 GHz galactic field I,Q,U difference maps (above) using two-way splitting of the ACTPol galactic field I,Q,U data set (split by odd and even pairs of days of observation). The signal-to-noise maps (below) for the high-statistic region of the ACTPol galactic field data set is also shown, calculated by dividing the ACTPol galactic field I,Q,U high-statistic signal maps by their corresponding I,Q,U residual maps, which confirm that the ACTPol galactic field high-statistic region data set is indeed signal dominated. Similar to the results cited earlier for the ACTPol Season 1 CMB deep field data sets, we observe correlated noise in the I,Q,U maps aligned with the dominant scanning direction of ACTPol, which like for the CMB data sets, is also diagonal for the ACTPol galactic field sets. This correlated noise is analogous to the correlated noise in the TODs previously described, only expressed in terms of map space. (Naess et al. 2014a)
I map is shown after applying a high-pass filter for multipole $\ell > 240$, while the ACTPol galactic field polarized Q and U maps are shown following the application of a bandpass filter for $260 < \ell < 1370$. The I, Q, and U maps are noticeably smoothed and structural features enhanced following the filtering away of parts of the relevant $\ell$ range for which maps are noisiest. Figures 6.22 and 6.23 prepare for the first stage of coadding the ACTPol 146 GHz and Planck 143 GHz channel galactic field intensity maps, in which again we focus on the maximization of the signal-to-noise for both experiments in temperature mapping. In particular, given the efficacy of ACTPol as a small-angular scale imager, and Planck at larger-angular scales, a high-pass filter was applied to the ACTPol data for $\ell > 1500$ and a low-pass filter was applied to the Planck data for $\ell < 1500$. Additionally shown in 6.22 is a high-pass filter for $\ell > 260$ for the ACTPol Q and U bands. 6.23 culminates with a view of the coadded ACTPol 146 GHz and Planck 143 GHz galactic field map, which results from stacking the high- and low-passed mapping results from each experiment, respectively.

From the high- and low-passed ACTPol and Planck intensity mapping results, along with the first stage of coadding of the data, we find that while the introduction of ACTPol small-angular scale data to the Planck galactic field map improves the resultant map resolution and indicates intensity gradients and structures that are not resolvable on the map utilizing Planck-only data, both the experiment-specific filtered maps and their resultant map following stacking exhibit significant ringing near high intensity regions and at the boundaries of the map. This is in part due to this rough stacking method using a ‘hard cut’ at the edge of the $\ell$ range for both experiments. For this reason, we then proceed to the second stage coadding of the ACTPol and Planck intensity data taking into account beam matching of both experiments prior to data stacking. In this case, we note that when the maps for each experiment are filtered separately and then directly stacked, the effective beam for the map will have a discontinuity, and if the beam has a strong discontinuity, this discontinuity will be manifested in the map space as artifacts such as ringing effects. Ultimately, in order to eliminate this discontinuity, beam-matching is performed and ap-
plied to the combined map, in which input maps are appropriately weighted to result in an continuous output beam. For the purposes of the ACTPol and Planck beam-matched coadded map, given white noise properties it should be noted that it is optimal to select the beam corresponding to the highest resolution map, which of course, corresponds to the ACTPol beam in this case. To achieve this, we first define functions that are curves fit to the beam transformations for both ACTPol and Planck, characteristics of which are available on Lambda for ACTPol and on the Planck website for Planck. These definitions will result in the beam for each experiment defined at any particular $\ell$. With these definitions, we then begin with the ACTPol map data and apply a filter such that for the defined ACTPol beam, $B_{ACTPol}$ and the defined Planck beam, $B_{Planck}$ the filter goes as in Equation 6.11. The beam is then altered from $B_{ACTPol}$ to $B_{ACTPol} - B_{Planck}$. Then, as the calibration for the ACTPol and Planck maps is effectively the same save for beam effects, when the two galactic field maps are then stacked, the beam takes the form of the ACTPol beam for the map given Equation 6.12. Therefore, the resultant second stage coadded map has a continuous beam adding ACTPol data to the Planck map, such that weighted appropriately, the resultant map has a continuous ACTPol beam, which can be observed in 6.24. Thus, we can see from this resulting map that the ringing effects associated with simple coadding of the hard-filtered data for each experiment have been largely eliminated, and the resolution gain associated with the addition of ACTPol small-angular scale data to Planck larger-angular scale data for this field is noted with increased intensity gradients and structures evident. It should be noted that the beam used for this ACTPol galactic field analysis is the same as the beam that, as described earlier, has been well characterized for ACTPol Season 1 nighttime operations. Of course, given the data coverage noted earlier in this section, the data set was taken both during the afternoon and evening, so in future analysis we will need to expand on this usage of the nighttime beam as a first-order approximation for the entire galactic field dataset. Nonetheless, this approach is reasonable for these results given that the galactic plane is high signal and has extended non-gaussian structures and that there
are times that daytime and nighttime beams exhibit roughly the same good performance characteristics. Closing this section, we view the ACTPol 146 GHz galactic field power spectrum for I, Q, and U bands (performed over the aforementioned high-statistic region of the data set), and also include intensity power spectra for the Planck 100 GHz, 143 GHz, 217 GHz, and 353 GHz channels, found in Figures 6.25 and 6.26, respectively. Clearly, to even attempt to recover relevant CMB power spectrum data from these regions of the respective maps, for example, by looking at a subregion with maximum angular separation from the primary structures inherent to the galactic plane while still in the field, a better understanding of foreground signal contributions, such as synchrotron and dust emission signals described earlier in the Chapter, will be needed to be well characterized. The polarization properties of the ACTPol and Planck corresponding galactic field maps will be considered in the following section.

\[
\frac{(B_{ACTPol} - B_{Planck})}{B_{ACTPol}} = 1 - \frac{B_{Planck}}{B_{ACTPol}} \quad (6.11)
\]

\[
B_{ACTPol} = (B_{ACTPol} - B_{Planck}) + B_{Planck} \quad (6.12)
\]

### 6.3.3 Characterizing the Polarization Properties of the ACTPol 146 GHz Galactic Field with Corresponding Planck 143 GHz Data

In this section, we will characterize the polarization properties of the ACTPol 146 GHz galactic field combined with corresponding Planck 143 GHz data, the final coadding process of which was described in the previous section. For this we will correspondingly analyze key polarization characteristics of both the second stage ACTPol 146 GHz plus Planck 143 GHz galactic field map as shown in 6.24 as well as the corresponding Planck 143 GHz data set alone over the same field. In doing this, it will again be shown that the addition of ACTPol small-angular scale data taken at higher resolution than Planck will
Figure 6.21: The ACTPol 146 GHz I,Q,U bands for the high-statistic galactic field region filtered to maximize signal-to-noise across the relevant bands. In this case, the ACTPol galactic field I map is shown after applying a high-pass filter for multipole $\ell > 240$, while the ACTPol galactic field polarized Q and U maps are shown following the application of a bandpass filter for $260 < \ell < 1370$. 
Figure 6.22: Preparation for the first stage of coadding the ACTPol 146 GHz and Planck 143 GHz channel galactic field intensity maps. Here, we focus on the maximization of the signal-to-noise for both experiments in temperature mapping. In particular, given the efficacy of ACTPol as a small-angular scale imager, and Planck at larger-angular scales, a high-pass filter was applied to the ACTPol data for $\ell > 1500$ and a low-pass filter was applied to the Planck data for $\ell < 1500$. Additionally shown are mapping results for the application of a simple high-pass filter for $\ell > 260$ for the ACTPol Q and U bands.
Figure 6.23: First stage coadding of the ACTPol 146 GHz and Planck 143 GHz channel galactic field intensity maps. On the left, we see the resultant map following the application of a low-pass filter applied to the Planck data for this field for $\ell < 1500$. On the right, we see the view of the coadded ACTPol 146 GHz and Planck 143 GHz galactic field map, resulting from stacking the high- and low-passed mapping results from each experiment, respectively.
**Figure 6.24:** Second stage coadded galactic field map for corresponding ACTPol 146 GHz and Planck 143 GHz data, following application of beam-matching for ACTPol and Planck beams to eliminate beam discontinuities observed in the first stage coadded map and again filtering (high-pass for $\ell > 1500$ for ACTPol and low-pass for $\ell < 1500$ for Planck).
Figure 6.25: ACTPol 146 GHz galactic field power spectrum for I, Q, and U bands (performed over the aforementioned high-statistic region of the data set). To even attempt to recover relevant CMB power spectrum data from these regions of the respective maps, for example, by looking at a subregion with maximum angular separation from the primary structures inherent to the galactic plane while still in the field, a better understanding of foreground signal contributions, such as synchrotron and dust emission signals described earlier in the Chapter, will be needed to be well characterized.
Figure 6.26: Intensity power spectra for the Planck 100 GHz, 143 GHz, 217 GHz, and 353 GHz channels performed over the aforementioned ACTPol high-statistic region of the galactic field data set.
allow for further understanding of the central polarization properties of this region, both overlapping with principal galactic plane structures and subregions angularly separated from these structures while still in the field. This analysis will closely follow the statistical analysis of the all-sky polarization analysis properties described in (Planck Collaboration et al. 2015a), “Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust.” As defined earlier in the Chapter, ACTPol’s millimeter-wavelength, polarization-sensitive focal plane is able to generate maps in intensity (temperature), as well as polarization, hence providing maps, shown in the previous section, for intensity (I), as well as the Stokes Parameters (Q and U). From these three parameters, we are able to calculate and map the polarization intensity, polarization angle, and polarization fraction across the field, while also analyzing and representing in map space the polarization structure of the ACTPol galactic field region. Equation 6.13 and 6.14 represent Stokes Q and U represented in terms of the intensity I, polarization angle p, and polarization angle $\gamma$. Ultimately, the polarization intensity, polarization angle, and polarization fraction are defined in Equations 6.15, 6.16, and 6.17, respectively, where angles calculated using Equation 6.16 allow for resultant angles to be represented in terms of IAU notation, defined where to the north $\gamma = 0$ degrees and proceeds positively to the east (Planck Collaboration et al. 2015a) (Hamaker et al. 1996).

\[ Q = (p)(I)\cos(2\gamma) \] (6.13)

\[ U = (p)(I)\sin(2\gamma) \] (6.14)

\[ P = (Q^2 + U^2)^{1/2} \] (6.15)

\[ \gamma = \frac{1}{2}\arctan(-U, Q) \] (6.16)
\[ p = ((Q^2 + U^2)^{1/2}) / I \]  

(6.17)

\[ \Delta \gamma^2(x, \delta) = (1/N) \sum_{i=1}^{N} \Delta \gamma_{x_i}^2 \]  

(6.18)

With these definitions now in hand, we proceed by calculating these polarization parameters for both the coadded ACTPol 146 GHz + Planck 143 GHz galactic field map, as well as the Planck 143 GHz only map over the same field. The resultant data is then re-mapped over the same field dimensions, and associated histograms are generated. Figures 6.27 and 6.28 present the polarization results for the full field of the ACTPol+Planck coadded galactic field map, including polarization intensity, polarization angle, polarization structure, and polarization fraction in map space, and then present the corresponding histograms for each parameter, respectively. While the broad characteristics of the polarization intensity, angle, and fraction are evident from these full-field maps, given the resolution added by the inclusion of ACTPol data, polarization structure can be more readily viewed for smaller structures along and off of the galactic plane. Figure 6.29 defines nine individual subregions of equal dimension, each a square subregion of covering an area of 0.25 sq. deg. for which polarization analysis was performed to describe the polarization characteristics of regions both on and off of the galactic plane, in which selection attempted to cover both some of the highest-gradient and structural elements of the galactic plane, as well as a few regions of the field separated by a few degrees from the galactic plane. Selected regions on the galactic plane include subregions 03, 05, 06, 08, and 09, while regions representing structures and sky to varying degree from the galactic plane include subregions 01, 02, 04, 07.

Figures 6.30 through 6.36 show the results for the polarization intensity, polarization angle, and polarization fraction maps for each subregion, the histograms for each polarization parameter within each subregion, and the polarization structure (polarization intensity/vector maps) for each subregion. Table 6.1 then provides the polarization characteristics.
for ACTPol 146GHz galactic field map coadded with Planck 143 GHz galactic field map. Provided are full high-statistic field and subregions (column 1), galactic coordinates for each region (columns 2-5), the mean, median, and standard deviation of the polarization intensity (P) in δT (columns 6-8), the mean, median, and standard deviation of the polarization angle (columns 9-11), and the mean, median, standard deviation, maximum, and minimum of the polarization fraction (columns 12-16). Figure 6.37 illustrates detail views of the polarization structure of subregions 05, 07, 08, and 09 providing a visual comparison for the polarization structure associated with selected structures on and off of the galactic plane. Figures 6.38 through 6.44 show the Planck 143 only results for the polarization intensity, polarization angle, and polarization fraction maps for each subregion, the histograms for each polarization parameter within each subregion, and the polarization structure (polarization intensity/vector maps) for each subregion. Figure 6.35 is provided to illustrate the manner by which the inclusion of high-resolution, small-angular scale data acquired by ACTPol allowed for significant resolution improvements compared to Planck-only data, and the manner by which polarization results agree between the coadded data and Planck-only data, however revealing more detail of the polarization structure viewed both on and off of the galactic plane, illustrated by subregion 05 and 04 comparisons, respectively. Finally, Table 6.2 includes polarization characteristics for the Planck 143 GHz galactic field map. Provided are full high-statistic field and subregions (column 1), galactic coordinates for each region (columns 2-5), the mean, median, and standard deviation of the polarization intensity (P) in δT (columns 6-8), the mean, median, and standard deviation of the polarization angle (columns 9-11), and the mean, median, standard deviation, maximum, and minimum of the polarization fraction (columns 12-16).

By inspecting the mapping, histogram, and statistical data results for the ACTPol 146 GHz + Planck 143 GHz data set and the analogous Planck 143 GHz only set, it is readily apparent that the introduction of ACTPol data at high-resolution enhances our understanding of the overall morphological and polarization structure and characteristics of
this galactic field region compared to looking at large-angular scale data from Planck alone. Furthermore, the mapping and polarization statistical products for the combined data set continue to agree with the major data trends apparent in the Planck-only data set, and correspond to many of the characteristics of galactic foreground emission described earlier in this Chapter. Given our earlier discussion in which we provided the characteristics of the various foreground emission mechanisms that require characterization to extend the drive to measure B-mode CMB polarization, we can be certain that the ACTPol 146 GHz and Planck 143 GHz galactic field maps and their coadded result in this region are dominated by foreground contributions sourced from galactic dust emission. Considering the utility of this data set for studying overarching properties of the galactic magnetic field, we recall from earlier that for dusty foreground polarization, such as those observed in our coadded galactic field maps, polarization vectors associated with thermal dust emission will exhibit alignment orthogonal to the galactic magnetic field structure present in a given region (Dunkley et al. 2009). Thus, our polarization structure and angle maps and associated statistics are really showing us not only the polarization properties of these regions, but are in fact representing the distribution of the magnetic field direction across both the full field and subregions of this data set - rotating polarization vectors by 90 degrees would thus give the localized magnetic field orientation across various structures of the data set.

From both (Ferrière 2011) and (Planck Collaboration et al. 2015a) it is predicted that the galactic magnetic field direction ought to be aligned statistically with (parallel to) the galactic plane, especially as one observes the field characteristics near the center of the galactic plane. Given the orthogonal relationship between magnetic field orientation and our calculated polarization vectors, it would thus be expected that the average polarization angle for structures along the galactic plane correspond to a polarization angle of 0 degrees. This prediction is indeed confirmed by the full-field polarization angle map provided in Figure 6.27, in which the region corresponding to the galactic plane displays a mean polarization angle approaching 0 degrees. Furthermore, comparing the set of subregions residing on or
near the galactic plane (03, 05, 06, 08, 09), with the subsequent off galactic plane subregions, it is again confirmed in 6.33 that histograms for the polarization angles of the distribution of subregions near the galactic plane are, as expected, roughly gaussian distributed with central peak at or near 0 degrees, whereas subregions off of the galactic plane exhibit a wider, non-gaussian distribution of polarization angles. Further analysis of the polarization angle (and therefore magnetic field orientation) properties of this data set would prioritize a study of the polarization angle dispersion function, as defined in Equation 6.18.

Ultimately, characterization of the polarization dispersion function enables a further characterization of the distribution of the galactic magnetic field as well as its orientation, by yielding statistical results on the degree of inhomogeneity of the polarization angle distribution across a given field (Planck Collaboration et al. 2015a). Across this data set we also yield expected results for the relationship between measured galactic field intensity and the associated polarization fraction at a corresponding location. In particular, the ACTPol 146 GHz + Planck 143 GHz galactic field exhibits polarization fraction trends similar to those described in (Planck Collaboration et al. 2015a), in which observed sky regions of lower intensity correspond to higher polarization fraction results. Here, Figure 6.27 exhibits this property, with highest intensity map regions (e.g. those nearest the highest-intensity structures close to the galactic plane) corresponding to lower polarization fraction levels than those regions further from the galactic plane and exhibiting lower intensity. Likewise, 6.35 exhibits this trend, in which higher-polarization fraction levels are exhibited in histograms associated with lower-intensity regions further from the galactic plane, in particular, for subregions 01, 02, 04, 07. Polarization fraction results for the full-field and subregion also generally exhibit results that match expectations from (Planck Collaboration et al. 2015a), where wider histogram distributions are found for polarization fraction results for mid-latitude data, with histograms peaking at roughly 4 percent - for our results, we find a similar wider distribution for subregions off of the galactic plane (01, 02, 04, 07), with a mean polarization fraction for these subregions of roughly 5.8 percent. Conversely, we also
find more compact distributions associated with higher intensity regions on or near the
galactic plane, where it was expected that histograms peak at a 1-2 percent levels, and our
results for these regions (03, 05, 06, 08, 09) corresponding to a mean polarization fraction
of 1.6 percent. Comparable to the results from (Planck Collaboration et al. 2015a) and the
dust polarization fraction levels predicted earlier in the Chapter, ignoring spurious pixel
values exhibiting extremely high polarization fractions (a few of these are illustrated in the
p(max) columns of Tables 6.1 and 6.2), the maximum polarization fraction for the subre-
gions typically range from several percent to just over 20 percent. As described in (Planck
Collaboration et al. 2015a), characterization of the maximum polarization fraction associ-
ated with a given region of the galactic field is a vital characteristics since it will provide
for an upper limit on the amplitude of polarization emission from dusty foregrounds, which
is necessary for proper foreground component analysis of CMB fields, ultimately necessary
to enable the future detection of B-mode polarization and confirmation of the inflationary
model of the early universe.
Figure 6.27: Polarization results for the full field of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map, including polarization intensity, polarization angle, polarization structure, and polarization fraction in map space.
Figure 6.28: Histograms corresponding to polarization results for the full field of the ACT-Pol 146 GHz + Planck 143 GHz coadded galactic field map, including polarization intensity, polarization angle, and polarization fraction.
Figure 6.29: Definition of nine individual subregions of equal dimension of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map, each a square subregion of covering an area of 0.25 sq. deg. for which polarization analysis was performed to describe the polarization characteristics of regions both on and off of the galactic plane, in which selection attempted to cover both some of the highest-gradient and structural elements of the galactic plane, as well as a few regions of the field separated by a few degrees from the galactic plane. Selected regions on the galactic plane include subregions 03, 05, 06, 08, and 09, while regions representing structures and sky to varying degree from the galactic plane include subregions 01, 02, 04, 07.
Figure 6.30: Polarization intensity maps for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.31: Polarization intensity histograms for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.32: Polarization angle maps for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.33: Polarization angle histograms for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.34: Polarization fraction maps for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.35: Polarization fraction histograms for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.36: Polarization structure maps for the nine subregions defined in 6.29 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map.
Figure 6.37: Detail views of the polarization structure of subregions 05, 07, 08, and 09 of the ACTPol 146 GHz + Planck 143 GHz coadded galactic field map, providing a visual comparison for the polarization structure associated with selected structures on and off of the galactic plane.
Figure 6.38: Polarization intensity maps for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.39: Polarization intensity histograms for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.40: Polarization angle maps for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.41: Polarization angle histograms for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.42: Polarization fraction maps for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.43: Polarization fraction maps for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
Figure 6.44: Polarization structure maps for the nine subregions defined in 6.29 represented for the Planck 143 GHz only galactic field map.
| Region | RA$_I$ [deg] | RA$_{II}$ [deg] | DEC$_I$ [deg] | DEC$_{II}$ [deg] | mean(P) [μK] | σ(P) [μK] | mean(γ) [deg] | med(γ) [deg] | σ(γ) [deg] | mean(p) [%] | med(p) [%] | σ(p) [%] | max(p) [%] | min(p) [%] |
|--------|--------------|----------------|---------------|----------------|-------------|---------|-------------|----------|--------|-----------|---------|--------|--------|---------|---------|
| FULL   | -73.0        | -80.0          | -2.0          | 4.5            | 98.01       | 56.68   | -2.88       | -4.66    | 47.16  | 5.30      | 9.40    | 99.91  | 0.01   |         |
| 01     | -75.2        | -74.7          | 1.5           | 2.0            | 91.06       | 48.58   | -5.01       | -11.86   | 56.06  | 3.10      | 2.87    | 1.72   | 13.39  | 0.05    |
| 02     | -75.2        | -74.7          | 0.0           | 0.5            | 92.85       | 48.52   | 0.94        | 3.06     | 52.58  | 8.47      | 7.58    | 4.86   | 37.90  | 0.03    |
| 03     | -76.8        | -76.3          | 1.0           | 1.5            | 138.32      | 100.56  | -4.38       | -4.16    | 32.58  | 1.89      | 1.76    | 1.05   | 7.59   | 0.01    |
| 04     | -79.5        | -79.0          | 2.0           | 2.5            | 69.26       | 36.25   | 5.13        | 10.67    | 52.15  | 7.19      | 6.73    | 3.82   | 29.61  | 0.04    |
| 05     | -75.0        | -74.5          | 4.0           | 4.5            | 133.13      | 66.66   | -10.59      | -11.51   | 28.00  | 1.76      | 1.67    | 0.90   | 6.04   | 0.03    |
| 06     | -75.5        | -75.0          | 3.0           | 3.5            | 135.84      | 54.73   | -10.28      | -10.41   | 17.50  | 2.64      | 2.56    | 1.11   | 7.89   | 0.04    |
| 07     | -74.5        | -74.0          | 0.0           | 0.5            | 96.16       | 50.20   | -3.33       | -8.18    | 53.30  | 15.78     | 14.44   | 8.97   | 72.32  | 0.26    |
| 08     | -78.3        | -77.8          | -2.0          | -1.5           | 180.67      | 185.38  | 2.33        | 2.07     | 42.00  | 1.36      | 1.15    | 0.99   | 10.95  | 0.03    |
| 09     | -77.0        | -76.5          | 1.0           | 1.5            | 142.9       | 101.06  | -2.12       | -3.12    | 34.58  | 2.11      | 1.91    | 1.22   | 9.83   | 0.05    |

**Table 6.1:** Polarization characteristics for ACTPol 146GHz galactic field map coadded with Planck 143 GHz galactic field map. Provided are full high-statistic field and subregions (column 1), galactic coordinates for each region (columns 2-5), the mean, median, and standard deviation of the polarization intensity (P) in δT (columns 6-8), the mean, median, and standard deviation of the polarization angle (columns 9-11), and the mean, median, standard deviation, maximum, and minimum of the polarization fraction (columns 12-16).
Table 6.2: Polarization characteristics for the Planck 143 GHz galactic field map. Provided are full high-statistic field and subregions (column 1), galactic coordinates for each region (columns 2-5), the mean, median, and standard deviation of the polarization intensity (P) in $\delta T$ (columns 6-8), the mean, median, and standard deviation of the polarization angle (columns 9-11), and the mean, median, standard deviation, maximum, and minimum of the polarization fraction (columns 12-16).
6.4 Summary

The early science results discussed and presented in this Chapter provide robust justification for an assessment of ACTPol as not only a pathfinder platform for the development of integrated space technologies in support of a future-generation inflationary probe mission, but also as a successful standalone millimeter-wavelength CMB polarization imager that has extended our understanding of CMB polarization physics. ACTPol met or exceeded all of its core CMB cosmology goals via polarization mapping and power spectrum measurements, while displaying its merits as an effective survey instrument for the detection of galaxy clusters via the Sunyaev-Zel’dovich effect. Additionally, ACTPol observations of the galactic plane, presented for the first time in this work, allowed for an exploration of polarization characteristics in this field, and provided further understanding of the nature of foreground emission mechanisms (as well as galactic physics) that will be necessary to further constrain via multiwavelength component analysis for any future inflationary probe mission. The Chapter, which follows, provides an overview of the scientific motivation for next-generation probes of inflation, the early technology development work performed for the predecessor instrument to ACTPol, called Advanced ACTPol, and provides a brief overview of the outlook for the field of polarization-sensitive CMB experimental cosmology projected over the next few years.
Part IV

Outlook
Chapter 7

Advanced ACTPol, CMB Stage IV, and Beyond

With short, sharp, violent lights made vivid,
    to southward far as the sight can roam;
     only the swirl of the surges livid,
the seas that climb and the surfs that comb.
Only the crag and the cliff to nor’ward,
     the rocks, receding, and reefs flung forward,
waifs wrecked seaward and wasted shoreward
 on shallows sheeted with flaming foam.

A grim, grey coast and a seaboard ghastly,
    and shores trod seldom by feet of men -
where the battered hull and the broken mast lie,
they have lain embedded these long years ten.
Love! Love! When we wander’ed here together,
Hand in hand! Hand in hand through the sparkling weather,
from the heights and hollows of fern and heather
God surely loved us a little then.  

The skies were fairer, the shores were firmer -
the blue sea over the bright sand rolled;
babble and prattle, and ripple and murmur,
Sheen of silver and glamour of gold -
Sheen of silver and glamour of gold.

from Edward Elgar’s “Sea Pictures: The Swimmer”

By June 2015, over a year had passed since the ACTPol collaboration had gathered in a lecture hall at Oxford University, joined by global CMB researchers connected remotely around the globe, to witness a press conference hosted by the Harvard-Smithsonian Center for Astrophysics, in which potentially ground-breaking results were released from the South Pole Station’s BICEP2 experiment team, suggesting the first direct telescopic detection of excess B-mode power at large angular scales. The period between this announcement in Spring 2014 and June 2015 was dominated by heated and sometimes public scientific debate regarding the validity of the BICEP2 results, including concerns, supported within the 2014 data release of the Planck satellite, that the excess B-mode signal identified in the BICEP2 results were actually the result of yet uncharacterized high-frequency, highly-polarized foreground dust emission. However, when the global CMB community again convened in late-June 2015, this time in person at Princeton University, the occasion was marked not by an adversarial narrative, but a celebratory one - at a three-day conference convened to recognize the 50th anniversary of the first detection of the Cosmic Microwave Background radiation by Arno Penzias and Robert Wilson, which was detailed in Chapter 1 of this dissertation manuscript. Figure 7.1 highlights the proceedings of the conference that took place between 10 and 13 June 2015, while 7.2 shows the several hundred faculty,
researchers, and students from the global CMB community that convened for the event. (University 2015)

During the event, a series of seminal panel discussions provided a historiographic account of the development of the theoretical work leading to the prediction of a Cosmic Microwave Background radiation and hot Big Bang model of the Universe, as well as an overview of the initial discovery of the CMB radiation by experimental means, provided by Robert Wilson himself, who, nearly 80 years old at the time of the event, was able to provide unique insight into remarkable course that the field had taken in its five decades of existence since its humble beginnings at Bell Laboratories in 1964. These early histories were succeeded by an overview of the development of the modern field of precision experimental cosmology, most recently led by polarization-sensitive observations of the CMB by instruments developed by modern researchers, including through the ACTPol, SPTPol, POLARBEAR, and BICEP2 collaborations. The discussion proceeded to highlight the contemporary status of CMB observational results and their implications to verify theoretical cosmological and astrophysical models on both large- and small-angular-scales, including a robust discussion of the BICEP2 B-mode detection outlook, which had been rolled-back by that time following joint analysis of BICEP2 results with high-frequency data from Planck. Rather than a portent of a bleak future for global CMB science, in particular at large-angular-scales, the subsequent tone of the meeting was rather reflective of a reignition of the quest to detect primordial B-mode polarization in CMB observational results, not through increased divisions among CMB research collaborations, but the creation of new strategic partnerships between once rival supranational experimental cosmologists, through discussions of the trajectory of the field from current-generation CMB polarimeters, to next-generation receivers and arrays, including Advanced ACTPol, CLASS, SPT-3G, and others through the second-half of this decade, culminating with the global-scale observational CMB collaborative effort, CMB-S4, and, eventually, a seminal, NASA-led Cosmic Inflationary Probe Imager satellite platform.

This is not to imply that each of the panel discussions of the conference were met with
universal consensus. In the concluding keynote panel, renown theoretical cosmologist and mathematician (and lifelong colleague of Professor Stephen Hawking) Sir Roger Penrose took the stage, giving his own assessment of a field that he, at age 83, had helped to lead for the entirety of his professional career. In particular, Penrose explained his outlook that the field must not only look toward the goal of confirming the inflationary model of the Universe through the direct detection of primordial B-mode polarization signals in next-generation CMB observational data sets, but also toward more peculiar, and difficult to detect circular anomalies of low-temperature variance in the primordial CMB signal, which, in the assertion of Penrose, could have implications to describe the physical dynamics of supermassive black holes in a pre-Big Bang universe, in a model of cosmology Penrose refers to as “Conformal Cyclic Cosmology.” (Gurzadyan 2013)

While the it is not in the scope of this dissertation to discuss the validity of the Penrose assertion or the subsequent debate over the potential for a method to experimentally verify its basis that followed at the conference, it does underscore the very human spirit of discovery that underpins the endeavor of experimental cosmology. Just as the assertion by Albert Einstein a century ago led to implications of the presence of gravitational waves existing at a variety of scales throughout the observable universe, the theoretical models forwarded by Einstein would need to wait until the twenty-first century for experimental physics technology development to achieve a maturity to enable the verification of this prediction. And indeed, within the past twelve months, the Laser Interferometer Gravitational-Wave Observatory’s (LIGO) dual detector facilities simultaneously detected a transient gravitational-wave signal in a form predicted by Einstein’s general relativity for the merger of a massive binary black hole system, confirming that the horizontal theory postulated by Einstein after the turn of the twentieth century, was indeed an observable phenomenon. (Abbott et al. 2016) Thus, the era of gravitational-wave astronomy was ushered in by the success of the decades of technology development that was integrated into LIGO, and in this manner next-generation CMB instrumentation development may yield
verification of directly-detected primordial gravitational waves in the next decade, and even, perhaps through disruptive advances in future-generation CMB detector technologies, an experimental verification of Penrose’s theory.

In this chapter, we highlight this basic human spirit of exploration that will be undertaken by the global experimental cosmology community, to probe the CMB with at an ever wider range of angular-scales and frequencies, and deeper sensitivities within the next decade. The goal of this effort will be to make a direct-detection of primordial B-mode polarization in confirmation of inflationary cosmological models a reality. To this end, we will move forward from the immediate next-generation CMB technology development platforms, highlighting one such system, Advanced ACTPol in Section 7.1, to those in future-generations, including the CMB Stage IV (CMB-S4) Program in which immediate next-generation experimental cosmology platforms, including CLASS, BFORE, and a next-generation, multi-latitude BICEP array, are included in this context as examples of proposed systems, which could enable the broad successes of a future global CMB Stage IV Program. Finally, we discuss the prospects and outlook for a future-generation seminal inflationary probe satellite, CMBPol.

### 7.1 Advanced ACTPol (AdvACT)

Even as instrumentation comprising the second of three planned stages of deployment for the ACTPol instrument were undergoing final pre-shipment preparations in North America in late-2013 (namely, laboratory polarimeter characterization testing of the second ACTPol 150 GHz polarimeter array package, ACTPol PA2), the ACT collaboration began preparations for a next-generation instrument to immediately succeed the ACTPol receiver, following the completion of proposed ACTPol full-deployment operations in early-2016. Central to this proposal, which was submitted to the 2014 National Science Foundation Mid-Scale Innovation Program (MSIP) proposal call, was an ACTPol receiver upgrade, which would allow ACT to not only enhance its present ability to conduct precision CMB-polarization...
science at small-angular scales, but to simultaneously extend the scope of ACTPol science to a larger-angular-scale regime of CMB polarimetry, at a wider range of effective frequencies. Whereas the transition from MBAC CMB temperature characterization science to ACTPol CMB polarization characterization science required the design of an entirely new receiver system to integrate a myriad of new polarization-measurement-enabling technologies, including high-purity silicon reimaging optics with novel anti-reflective coatings, liquid-cryogen-free continuous-operation cryogenics systems, and transition-edge-sensor (TES) polarimeter arrays, the next-generation project would utilize the unique modularity framework of the ACTPol receiver design, within which to deploy an upgraded portfolio of detector and optical technologies, which would allow for the rapid realization of the extended experimental cosmology science goals at both small-and-large angular scales motivating the upgraded instrument.

On 15 September 2014 this next generation project, known simply as Advanced ACT-Pol (AdvACT) was officially funded by the U.S. National Science Foundation under the MSIP framework, extending ACT operations under AdvACT through 2020 for an award of $7,269,979.00, including funding for both AdvACT instrumentation development, laboratory integration, site deployment, and seasonal CMB science operations and analysis. (AdvACT 2014) The section, which follows, discusses the principal science drivers underscoring the motivation for the AdvACT program, most notably, a drive toward ACT science operations at frequency and angular-scale regimes commensurate with enabling probes of inflationary cosmology, as well as early work, completed under the auspices of the NASA Space Technology Research Fellowship that supported the completion of the research detailed throughout this dissertation, toward the development of higher-pixel density, multi-chroic polarimeter arrays at a variety of operational frequency bands to enable this next phase of ACT science.
7.1.1 Toward Empirical Verification of Inflationary Cosmological Models

As we have highlighted throughout this dissertation, one of the most important physical discoveries over the past half-century, which profoundly enhanced our fundamental understanding of the universe has been the detection of the Cosmic Microwave Background (CMB) radiation. Since its initial experimental discovery by Penzias and Wilson in 1964, observation of the CMB has been the foremost transformational element in the study of physical cosmology, as well as providing broad scientific impact across a myriad of scientific areas, from particle physics to astronomy. (Penzias and Wilson 1965) Within the past two decades, key advances in receiver technologies operating on telescope facilities dedicated to observational cosmology at a wide range of angular scales (from entire sky to arcminute resolution), have resulted in cosmic-variance limited measurements of the temperature anisotropies of the CMB, as well as significant progress in the measurement of CMB polarization anisotropies. (Ade et al. 2014) These measurements have improved constraints of cosmological parameters describing ΛCDM cosmology, and allowed for the precise characterization of the spatial curvature of the universe, the nature of the baryonic matter, sum of neutrino masses, and primordial helium abundance, as well as probes of the mysterious primordial dark energy. Additionally, mapping of the CMB at small angular scales has been proven to serve as an effective detection mechanism for galaxy clusters via the Sunyaev-Zeldovich effect (SZE), interpretation of which has provided insight to the nature of the dark energy, in addition to key advances in the characterization of astrophysical phenomena via x-ray, infrared, and optical follow-up observations of confirmed SZE clusters. (J. E. Carlstrom 2002) In spite of this remarkable scientific yield, the CMB still has much to tell us, primarily in the measurement of its polarization anisotropies, now unlocked across ever-larger areas of the sky by present-generation CMB instruments, including ACTPol.

Perhaps the most compelling area among the rich portfolio of CMB polarization science, and primary drivers of current expansions in active research within observational cosmology, lies in the effort to directly probe a possible epoch of inflation in the primordial Universe.
Inflation describes a period spanning $10^{-32}$ seconds following the Big Bang, in which the early universe is predicted to have undergone exponential expansion, producing gravitational waves, which imprint a distinct signature in the polarized CMB, the mechanism for which was described along with temperature anisotropies and polarization manifest in the CMB from baryonic acoustic oscillation at the outset of this manuscript. Detection, confirmation, and cosmological constraints from a measurement of the inflationary CMB polarization signal at appropriate scales will require the development of next-generation receiver technologies, including advanced cryogenics, efficient and low-loss optics, and higher-density arrays of high-sensitivity polarimeters, as well as novel analysis paradigms to address the removal of CMB foregrounds, which currently limit efforts to observationally verify inflationary physics.

To provide context on the underlying drivers toward probes of inflationary cosmology, we recognize from earlier Chapters that when referring to the CMB, we describe a relic light produced 380,000 years after the universe began, where the existence of the CMB provides indisputable evidence of a hot Big Bang. (Ade et al. 2014) The CMB was generated at the point during the evolution of the early universe, when the universe expanded and cooled to transition from a hot, opaque, dense primordial plasma of coupled photons and baryons, to an environment of decoupled photons and neutral hydrogen. The decoupling process allowed photons to stream away, forming the CMB signal that we observe. Observationally, the CMB is optimally observed in the millimeter, as it has a thermal blackbody spectrum that peaks in the millimeter and is roughly flat between a few tens to a few hundreds of GHz in frequency. This sets the useful window for CMB measurements. However, considering all-sky survey results from satellite-borne observational platforms, such as WMAP and Planck, one readily observes synchrotron emission from the galaxy at the lowest frequency interval of this window, while dust begins to dominate at the highest frequency interval of this window. Thus, primary CMB signal measurements are typically conducted between roughly 60 and 150 GHz in frequency sensitivity.
According to the standard cosmological model, small over-densities in the primordial plasma formed temperature anisotropies in the CMB, where these over-densities resulted in the growth of the large-scale structure present in the universe today. Linear polarization of the CMB signal resulting from Thompson scattering is present, and is generated from two sources: motion in the plasma accelerating in and out of overdense regions of the universe, and possibly from the gravitational wave background produced during an inflationary epoch. Inflationary models predict a background of gravitational waves existing purely as tensor perturbations, with amplitude corresponding to the energy scale of inflation. These tensor perturbations (gravity waves) are fully distinct from scalar perturbations. The two sources of CMB polarization can be distinguished by their polarization pattern: curl-free E-modes that have recently been measured and are sourced by scalar perturbations (the same anisotropies which produce the CMB temperature power spectrum), and divergence-free B-modes generated from gravitational waves (tensor perturbations), which have not yet been directly detected. (Naess et al. 2014a) Furthermore, while characterization of the tilt and scale dependence of the E-mode power spectrum of the polarized CMB can offer constraints on inflationary dynamics, direct detection of a cosmological B-mode excess in the power spectrum at large angular scales enables direct probes of primordial gravitational waves and, hence, strong evidence supporting inflationary theory. It also offers an investigation of physics at grand unified theory (GUT) energy scales that are a trillion times higher than those accessible in terrestrial accelerator facilities. With this, the importance of observations utilizing high-sensitivity detector arrays capable of polarimetry to measure the CMB polarization is readily apparent, as it can offer a direct method to constrain and confirm inflationary models with a broad impact across all areas of physics.

Detection of the B-mode signal via observation of the CMB polarization is a formidable task: with the polarized signal resulting from inflation projected to be just $10^{-9}$ of the 2.725K isotropic CMB, robust programs to develop and conduct CMB observational operations with high-sensitivity receivers having extremely well-characterized instrumental
systematics are vital. The primordial B-mode amplitude constrains the amplitude of tensor perturbations present during inflation, which we parametrize by the term $r$, the ratio of tensor-to-scalar perturbations. Because $r$ is directly related to the energy scale of inflation, measurement of $r$ can allow for a differentiation between inflationary models with various initial conditions; i.e. if GUT-scale inflation is to explain the current structure of the universe, this would suggest a constraint of the B-mode amplitude of $r < 0.01$. (Wollack 2014) Upper limits have been placed on $r$ both by a combination of BAO, $H_0$, and WMAP 9-year temperature anisotropy data, as well as by the Planck mission, while recent results from the South Pole Stations BICEP2 experiment suggest detection of excess B-mode power at large angular scales. (Ade et al. 2014; Hinshaw et al. 2013; Planck Collaboration et al. 2014)

Were it verified, the BICEP2 result would have been a definitive and revolutionary confirmation of inflationary theory in its own right. In spite of the significant progress toward direct confirmation of inflationary models represented by these results, concerns were subsequently realized that the excess signal was in fact related to highly-polarized foreground dust emission suggested by more recent Planck results, which were unknown at the time of the BICEP2 publication. (Planck Collaboration et al. 2015b) The Planck results strongly emphasize the importance of measuring and characterizing high-frequency dusty foreground emission (in addition to low-frequency synchrotron foregrounds) at high signal-to-noise in order to deconfuse CMB observations at large-angular scales, enabling systematic probes of inflationary physical models. A first study of highly polarized foreground emission manifest in the ACTPol Season 1 galactic field data set was presented in the previous chapter.

In spite of this result, the BICEP2 experiment should not be characterized with failure: rather, not only was it a highly-precise large-angular-scale CMB data set in its own right, but it further underscored the forward-looking structural requirements for the inflationary cosmology community to support programs of instrumentation development favoring
higher-sensitivity polarimeter arrays within primary CMB frequency channels, as well as the addition of simultaneously sensitive foreground monitor channels to current and future instruments. In addition to this wider range of CMB observational channels within future instruments, both below and above CMB frequency windows to mitigate confusion with synchrotron and dust emission signals, next-generation programs would also benefit from measurement and analysis of a variety of independent data sets overlapping with multi-wavelength coverage from complementary instruments, as will be possible under the myriad of programs fostered by broad research initiatives like the U.S. Department of Energy-led CMB-S4 program, all in support of further constraint and confirmation of existing and forthcoming B-mode measurement datasets.

7.1.2 Extending the Scope of ACTPol Science to Large Angular Scales

As has been fully demonstrated during discussion of the robust distributed portfolio of space technology development and cosmological physics results throughout the entirety of this dissertation, the ACT collaboration has demonstrated a well-established tradition toward the development of critical technologies, observational strategies, and innovative analysis techniques that have enabled precision observations of the temperature and polarization anisotropies of the CMB at small-angular-scales, across two generations of receiver deployment and operation during the past decade; first probing temperature anisotropies with the Millimeter Bolometer Array Camera (MBAC), and then characterizing the CMB polarization with ACTPol, a high-resolution, millimeter-wavelength polarimeter currently in operation on ACT that has been the principal instrumentation-development focus of this dissertation. (Naess et al. 2014a; Swetz et al. 2011a)

In the development and operation of a next-generation receiver, Advanced ACTPol (AdvACT), the ACT collaboration will continue its community-wide leadership in small-angular-scale CMB polarization science, including a broad-impact science portfolio probing the growth rate of structure, the redshift and duration of reionization, constraints on the
Figure 7.1: Selected overview of proceedings from the Cosmic Microwave Background at 50 conference, which was held between 10 and 13 June 2015, at Princeton University, Princeton, New Jersey. The conference, which assembled the global CMB research community in celebration of the 50th anniversary of the first detection of the CMB radiation by Arno Penzias and Robert Wilson focused on the historiography, status, strategic planning, and horizontal outlook for the field entering the second half-century of CMB research. (University 2015)
Figure 7.2: A group image of the several hundred faculty, researchers, and students forming the global CMB research community that was convened for the Cosmic Microwave Background at 50 conference, held between 10 and 13 June 2015, at Princeton University, Princeton, New Jersey. (University 2015)
age, composition, and geometry of the universe, constraints on key cosmological parameters, as well as dark energy science via the detection of $\gtrsim 20,000$ galaxy clusters via the thermal- and kinetic-SZE (tSZE and kSZE, respectively) across half of the sky. (Hand et al. 2012; Hasselfield et al. 2013a) In addition, the introduction of a novel polarization modulator on AdvACT, in this case a non-cryogenic, rapidly-spinning (2.5 Hz), broad-band half-wave plate (HWP), will allow for transformational stability and sensitivity to CMB polarization at large-angular-scale regimes (greater than $1^\circ$), possibly enabling direct measurement of inflationary cosmology inaccessible to the previous-generation ACTPol experiment. (Niemack 2014) In particular, the addition of the HWP polarization modulation system will enable AdvACT to access larger-angular-scale regions of the CMB angular power spectrum, generating CMB maps at angular scales of $10 < \ell < 10,000$ over half of the sky, all at arcminute angular resolution (1.3 arcminute angular resolution at the 145 GHz band), which will allow for probes of inflationary gravitational waves if $r \gtrsim 0.01$.

Additionally, AdvACT will address the other central requirement of next-generation inflationary cosmology platforms set forth by the BICEP2 result, namely, simultaneously “cleaning” CMB channel maps through the deployment of high-pixel-density multichroic focal planes across five bands (between 30–230 GHz) including low-frequency multichroic polarimeters to address synchrotron foreground signals, and high-frequency multichroic polarimeters to address foreground dust emission signals, all developed using staged deployment approach. The staged-deployment multichroic polarimeter arrays, whose early development is discussed throughout the remainder of this section include: a low-frequency (LF) array design with simultaneous 28 GHz and 48 GHz operational sensitivity (for constraint of synchrotron emission signal), a mid-frequency (MF) array design with simultaneous 90 GHz and 150 GHz operational sensitivity (for coverage of primary CMB channels), and a high-frequency array design with simultaneous 150 GHz and 230 GHz operational sensitivity (for primary CMB and dusty foreground emission constraint), which will also be analyzed in tandem with Planck 230 GHz and 353 GHz channel datasets over the same observational
survey range, for further constraint and subtraction of dusty foregrounds. Moreover, the AdvACT multifrequency datasets also benefit from a strategic overlap with a wide range of multiwavelength observational data sets, to improve data richness across the $> 25,000$ deg.$^2$ accessible from ACT’s mid-latitude, southern-hemisphere physical location, including future survey results from the Large Synoptic Survey Telescope (LSST). (LSST 2015)

Thus, in its unparalleled capability to address a wide range of vital topics in modern cosmology through high-sensitivity measurements of the polarized CMB at both small- and large-angular scales, AdvACT directly addresses a majority of the central science objectives set forth by the Astrophysics Division of NASA’s Science Mission Directorate (SMD) within the framework of its Physics of the Cosmos Program (PCOS), including programs to “expand our knowledge of the dark energy...[and] precisely measure the cosmological parameters governing the evolution of the universe and test the inflation hypothesis of the Big Bang. (PCOS 2012) Additionally, the polarimeter, optical, and cryogenic development that will enable the successful deployment of AdvACT, will not only support revolutionary breakthroughs in CMB polarization measurements with standalone science impact, but will also allow AdvACT to serve as a fully-integrated, ground-based pathfinder experiment to significantly enhance the state-of-the-art in CMB polarimeter development, which will be a central enabling technology for a seminal, future-generation Inflationary Probe mission (CMBPol), which was recommended as a high-priority of the recent National Research Council (NRC) Astro2010 decadal survey. Furthermore, NASA’s PCOS program office has directly identified instrumentation development of high-sensitivity, high-pixel density multichroic focal planes, such as those to be designed and operated on AdvACT, as well as novel multiwavelength approaches to constraining the signature of inflationary cosmology, as essential to realize the Astro2010 decadal survey recommendations.
7.1.3 Development of Improved Site Logistics for the Advanced ACTPol Era and Beyond

Earlier in this dissertation, we described the development of site logistics facilities and equipment, which was able to increase operational efficiency of the ACT site over its first two generations of operations. The ACT+MBAC era marked the initiation of the ACT site as a premier experimental cosmology facility, including the development of the principal site infrastructure (e.g. ACT telescope optomechanical superstructure, retrofitted shipping containers for site control systems, a container for mechanical and electrical maintenance and limited receiver integration, and diesel fuel tanks feeding associated generators enabling primary site power generation). The ACT+ACTPol era extended the operational efficiency over the ACT+MBAC era, by introducing an on-site high bay facility which enabled for the first time in situ receiver integration capabilities, and obviated the need for the return of the ACTPol receiver for integration with the next stage of optical and polarimeter array package deployment, as was the operational paradigm utilized in the MBAC era. This facility, along with the establishment of a strategic partnership with the ALMA Operations Support Facility to allow for clean room usage for in-field polarimeter array package inspection and validation prior to integration with the ACTPol receiver, enabled for higher overall operational efficiency compared to the MBAC era, a dynamic additionally aided by the introduction of continuous-operation cryogenics in the ACTPol dilution refrigeration system (enabling near 24-hour continuous operation) and remote observing protocols that increased the percentage of time utilized for primary ACTPol CMB science operations. Additionally, improved systems for receiver integration with the ACT warm optomechanical superstructure (e.g. ACTPol Receiver Alignment System, ACTPol Critical Alignment Mount, and related systems) and the development of new alignment diagnostics systems, including a custom photogrammetry platform, reduced the interval between receiver high-bay integration and first light over previous generation ACT operations. Further detail on these developments were described further in earlier sections.
In spite of these clear improvements in logistical support systems enabling improved science operational efficiency across the MBAC and ACTPol eras of ACT operations, acute challenges remain that must be addressed for a continued improvement in operational efficiency into the Advanced ACTPol era and beyond. In order to continue to move toward an operational mode for the ACT site in which remote operations dominate a given 24-hour observing period, it will be necessary to continue to work with Chilean federal authorities to fund and install high-bandwidth fiber optic communications cables, perhaps bootstrapping efforts underway for this improvement on the ALMA experiment, which would enable not only improved reliability for site communications, but also moving toward an operational mode in which experimental housekeeping and CMB cosmology data can be directly migrated to analysis facilities in Chile, South Africa, and North America, obviating the need for data transported via hard drives. Weather events described earlier in this dissertation continue to be a periodic issue for site access, thus, further work with Chilean federal authorities on the improvement of road access and public works activities for route clearing both on the Paso de Jama and the access routes on the front slope of Cerro Toco will be required. Additionally, these weather events are not only an issue for site access and operations, but general road conditions coupled with these weather events also present an issue for delivery of diesel fuel for power generation at the ACT site.

For future site operations, a potential solution for improved continuity in site power generation could be the introduction of a small-scale, permanent gas-fired power plant, situated at mid-altitude, between San Pedro de Atacama and the ACT site on Cerro Toco. The selection of natural gas as a fuel source is specifically selected to allow for operational improvements for not only the ACT site, but perhaps the wider array of sites in the Chajnantor Plateau region, by bootstrapping off of nearby permanent natural gas transport infrastructure. In particular, sourcing gas as a fuel for power generation from a 20 inch diameter natural gas transmission pipeline, called GASATACAMA, could be an appealing option. GASATACAMA was constructed and brought into operation in 1999, and was
initially aimed at exporting supplies of natural gas from the Argentinian northwest, for use in Northern Chile, in particular by the robust mining industry of the Northern Atacama, which was detailed in Chapter 2. GASATACAMA runs from Jujuy in Argentina, enters Chile parallel to the Paso de Jama road, before traversing San Pedro de Atacama and Calame en route to the Chilean coast. Energy security in northern Chile was challenged both by geopolitics (due to sometimes strained political relations with neighboring Argentina), as well as market and supply dynamics, which led to gas supply interruptions from Argentina in the mid-2000s. Given the relative isolation of the northern Atacama region and its dependence on Argentina as a supply country, these dynamics challenged the overall energy security of the region. When one studies dynamics to ensure energy security worldwide, the most fundamental model to ensure regional or national energy security is to ensure that a diversification of supply routes, fuel types, and source countries are present - an increasingly important dynamic given the migration of energy security theory from previous-generation drives for so-called “energy independence” to work to strive for “energy security” models given the increasingly interconnected global energy market.

Thus, stressing the importance of cyber and physical security of energy infrastructure, policies and regulatory regimes central to the completion of a well-functioning, open, and diversified energy market, and fundamental diversification of energy infrastructure, represent three central pillars to ensuring energy security in a relatively geographically isolated region as is manifest in Northern Chile. Given that the GASATACAMA pipeline was increasingly operated on an intermittent basis given supply dynamics from northern Argentina, the deployment of an LNG terminal at the port of Mejillones, north of Antofagasta, Chile, enabled a diversity of supply options for the northern Atacama region, and increased reliability of volumetric bookings on transmission pipeline infrastructure like GASATACAMA, while interconnecting the region to global LNG markets. Additional supply options for these pipelines, for example, from the introduction of mid-scale floating storage and regasification units (FSRUs) along the Chilean coast could lead to additional supply security
for the region. According to the 2014 International Energy Agency energy security country profile for Chile, the GASATACAMA trunkline operates nominally at a transit rate of 15.6 MCM/d (million cubic meters per day), providing a reliable fuel source, which is both easily accessible, and within a few tens of kilometers from the ACT site, and other experimental cosmology facilities operating across the Chajnantor Plateau, most of which currently operate using independent diesel generator models similar to the ACT site. To ensure increased operational continuity and security of supply to the ACT site, an easement for a small area near the GASATACAMA trunkline off of the Paso de Jama could be acquired. A small-capacity secondary distribution pipeline could then interface with GASATACAMA, and supply the operation of power plant operating a gas fired turbine. Depending on the extent of sites needing supply from the plant, the turbine could be designed to operate in single stage mode, in which the turbine simply runs of natural gas combustion, venting exhaust heat capacity into the atmosphere, or in dual stage mode, in which this expelled heat capacity is then recaptured to power a coupled steam turbine. With the gas fired power plant permanently deployed, an interconnection electricity cable trunkline then could be buried along the shortest possible route to the ACT site. In terms of cost effectiveness, running a facility in this configuration would minimize the need for an extensive distribution pipeline to transport gas volumes from GASATACAMA to the Chajnantor plateau itself, and running the facility at a lower altitude, in particular below an altitude at which weather events typically reduce site access, would increase the ability to ensure continuous power to the site, meaning that remote operations could in practice continue further even when the site itself is inaccessible (of course, within the boundaries of safety protocols developed for nominal ACT site CMB science operations). The use of natural gas as a fuel source would also reduce the carbon dioxide emission footprint of the ACT site (and others), especially useful to demonstrate the commitment of the global science community to combat the detrimental effects of anthropomorphic climate change, and furthermore appropriate given that the ACT site resides within the the Atacama ecoregion
reserve described in earlier chapters. Figure 7.3 provides an overview of LNG import and natural gas transmission pipeline infrastructure located in the Northern Atacama region, including the GASATACAMA pipeline, which runs near the ACT site (Agency 2014).

7.1.4 Introduction of a Novel Polarization Modulator: A Rapidly Rotating Half Wave Plate

As discussed in the previous section, in order for an AdvACT-generation receiver upgrade to integrate probes of inflationary cosmology into ACT’s already-robust science profile, a distributed-portfolio of enabling space technologies must be developed and integrated as upgraded subsystems into the existing ACTPol receiver design. While some of the technologies required for this next-generation of the receiver have already been deployed and demonstrated in earlier chapters of this dissertation manuscript, including (multichroic) TES-based polarimeters, low-loss, wide-bandwidth cryogenic silicon optics, and a field-deployed dilution refrigeration system providing a 100 mK bath temperature to the detector arrays, or else are intrinsic to the design of the ACT telescope optical superstructure itself, including providing a 1.3’ optical beam, two principal subsystem-level technology upgrades are needed to achieve inflationary science targets. At the forefront of this development effort is the design of TES-based feedhorn-coupled multichroic polarimeter arrays at wider frequency ranges and higher pixel densities than present in the ACTPol focal planes (enabled by a novel geometric design and photolithographic fabrication procedure, discussed in the next section). However, without the introduction of a subsystem technology that would allow AdvACT to reach large-angular-scale sensitivities requisite for direct detection of excess primordial B-mode signal in the AdvACT data stream, the instrument would be confined to achieving a similar distributed portfolio of cosmological science goals at small-angular-scales as achieved with the ACTPol instrument, albeit with higher-sensitivities over both foreground and primary CMB frequency channels.
Figure 7.3: An overview of LNG import and natural gas transmission pipeline infrastructure located in the Northern Atacama region, including the GASATACAMA pipeline, which runs near the ACT site. (Agency 2014)
In order to extend the scope of ACTPol science to large-angular-scales in the AdvACT generation of the ACT experiment, the design, fabrication, integration, field-deployment, and operation of a novel polarization modulation system is necessary. To this extent, AdvACT will ultimately deploy three (one for each optomechanical subassembly) rapidly-rotating, broad-bandwidth half-wave-plates (HWPs). Figure 7.4 illustrates the design of the fully-integrated ACTPol HWP assembly installed at the input aperture windows of the three ACTPol optomechanical subarray assemblies, and the relative scale and position of the HWP system-level assembly within the ACT+ACTPol telescope superstructure mechanical environment.

\[ d_m = I + \epsilon \text{Re}[(Q + iU)m(\chi)] + A(\chi) + \nu \quad (7.1) \]

These HWPs will rotate at 2.5 Hz within individual air-bearing rotator subsystems mounted at the input aperture of each of the three AdvACT windows, and allow the AdvACT polarimeter arrays to operate with performance sensitivity on angular scales larger than 1° following modulation of the input polarization at roughly 8 Hz (Henderson et al. 2016). Equation 7.1 refers to the demodulated signal response observed by individual ACTPol polarimeter array pixels (TES pairing for coverage of Q and U Stokes Parameter signal response), where the modulation function is defined as \( m(\chi) = e^{-i4\chi} \), the HWP synchronous signal is defined as \( A(\chi) \), incident intensity is defined as \( I \), noise is defined as \( \nu \), and the polarization demodulation modulation efficiency is given by \( \epsilon \) (Essinger-Hileman et al. 2016).

The use of a similar rapid-rotating HWP system on the Atacama B-Mode Search (ABS) presented a test-bed for the Advanced ACTPol HWP system, where, ultimately, the ABS HWP system was able to reduce low-frequency noise following demodulation by a factor of roughly 500 with only 0.1 percent leakage from incident intensity to the polarization signal (Henderson et al. 2016). The principal improvement in the AdvACT system in comparison to the ABS demodulation system is the use of high-purity silicon with micromachined
**Figure 7.4:** The design of the fully-integrated ACTPol HWP assembly installed at the input aperture windows of the three ACTPol optomechanical subarray assemblies, and the relative scale and position of the HWP system-level assembly within the ACT+ACTPol telescope superstructure mechanical environment.
metamaterial antireflective coatings, following the methods described earlier for the ACTPol silicon lenses, which will allow for a significant reduction in loss by providing nearly twice the birefringence as the sapphire HWPs used for ABS (Henderson et al. 2016). Figure 7.5 indicates initial laboratory testing with a polarized source in which the power spectrum for incident polarization signal is compared with and without the operation of the ACTPol HWP system. In this case, we see that low frequency $1/f$ noise is reduced to 0.1 Hz when using the ACTPol HWP system compared to the power spectrum results for the raw unmodulated signal. On the right side of the figure, the initial test installation of the rapid rotator HWP system on the ACTPol receiver is shown during initial mechanical and test operation during ACTPol Season 3 operations (Ward 2015).

7.1.5 Development of Higher-Pixel-Density Multichroic Focal Planes

In addition to the introduction of a rapid-rotator half wave plate signal, allowing for Advanced ACTPol to reach lower-frequency, larger-angular-scale regimes required to probe inflationary physics compared to the ACTPol receiver, Advanced ACTPol will benefit from the deployment of high-pixel-density multichroic focal planes across five bands. These bands are categorized into three frequency ranges: LF (‘low frequency’), MF (‘mid frequency’), and HF (‘high frequency’). The LF frequency channels will have central frequencies of 28 GHz and 41 GHz and will allow for characterization of foreground signals originating from synchrotron emission. The MF frequency channels will cover the ACTPol CMB science bands, with central frequencies again targeted at 90 GHz and 150 GHz. Finally, the HF frequency channel will cover 230 GHz, and will be used along with Planck 353 GHz intensity and polarization data (described in the previous chapter), to enable Advanced ACTPol to make small angular scale measurements of foregrounds sourced from galactic dust emission. In this respect, the Advanced ACTPol instrument will extend not only its scientific yield by enabling probes of inflationary physics, but also enable further synergistic science goals,
Figure 7.5: Initial laboratory testing with a polarized source in which the power spectrum for incident polarization signal is compared with and without the operation of the Advanced ACTPol HWP system. In this case, we see that low frequency $1/f$ noise is reduced to 0.1 Hz when using the ACTPol HWP system compared to the power spectrum results for the raw unmodulated signal. On the right side of the figure, the initial test installation of the rapid rotator HWP system on the ACTPol receiver is shown during initial mechanical and test operation during ACTPol Season 3 operations (Ward 2015).
such as providing a useful data set to study the galactic magnetic field structure via polarization analysis of dust emission in both the galactic plane and dusty halo of the Milky Way Galaxy, hence providing a data set to extend the initial foreground polarization analysis completed for the ACTPol galactic field data set, with results presented for the first time in the previous chapter.

As we recall from our earlier characterization of the two ACTPol single-frequency polarimeter array packages operating with 150 GHz sensitivity (ACTPol PA1 and PA2), these arrays were comprised of three hexagonal polarimeter array stacks and three semihexagonal polarimeter array stacks coupled to a single monolithic corrugated silicon feedhorn array. The detector wafers in the semihexagonal and hexagonal wafer stacks had 47 and 127 polarimeter pixels each, respectively, such that each of these polarimeter arrays were comprised of 1044 TES bolometers measuring the response of 522 feedhorn-coupled polarimeters. For comparison, the Advanced ACTPol 150 GHz polarimeter array package is projected to consist of 2718 TES bolometers. As we recall, while segmenting each array package focal plane into six distinct subarrays for ACTPol did have the advantage of enhanced modularity (e.g. an inefficient or non-functional wafer stack could in principal be replaced without impacting the remainder of the array assembly), this segmentation was driven in part by fabrication limitations, in which polarimeter fabrication efficiency was optimized for photolithographic techniques across 3-inch and 4-inch silicon wafers, used to fabricate the semihexagonal and hexagonal detector wafers, respectively. The ability to fabricate monolithic detector wafers across 6-inch arrays for Advanced ACTPol represents a significant improvement, which, along with using lessons-learned from the fabrication of ACTPol PA3, which was a multichroic polarimeter array package operating with simultaneous 90 GHz and 150 GHz sensitivity, allows Advanced ACTPol to field significantly more detectors compared to ACTPol. In order to optimize the use of a monolithic polarimeter array for Advanced ACTPol, various polarimeter geometries were explored, ultimately allowing for the numerology of these various design splits to yield the highest pixel density
for a detector wafer in which three-fold rhomboidal geometric symmetry was selected, thus fully populating a single monolithic hexagonal polarimeter wafer for each multichroic array package comprising Advanced ACTPol.

This geometry enabled for increased pixel density over the ACTPol detector stacks, increased the geometric efficiency and packing density of readout traces, and largely eliminated the geometric gaps that existed between adjacent ACTPol detector wafer stacks to provide clearance for nominal edge geometry features (e.g. epoxy trenches and alignment features). The alignment feature and and epoxy trench geometries which were proven successful for the ACTPol detector stacks were imported to the Advanced ACTPol polarimeter wafer stack design, with each monolithic wafer stack again consisting of four components with pixel feature geometries corresponding to the targeted central frequency of each array, namely monolithic waveguide-interface-plates, or WIPs, (again with “WIP wing” features included to enable mounting for readout flexible circuitry flanges), detector wafers, backshort cavity wafers (again with moat, corral, and standoff features), and backshort cap wafers. The initial design variant of the Advanced ACTPol project has focused on the design of the ACTPol HF polarimeter array package, again featuring gold-plated OFHC mounting components and a coupled bandpass filter cell, which features many of the successful subsystem and component-level array package technologies developed for the ACTPol polarimeter array packages. Mechanically, this includes a similar variant of the ACTPol BeCu l-bracket and spoke interface mounting mechanism, as well as the introduction of an array of BeCu tripod springs on a single mounting component (replacing the ACTPol polarimeter array package “snaketongue” component coupling designs) to provide coupling between the now monolithic polarimeter array stacks and their corresponding feedhorn arrays. The principal design evolution from the ACTPol polarimeter arrays to those on Advanced ACTPol has to do with the reconfiguration of the ACTPol 1K optomechanical subsystem region. To allow for greater clearance and improved coupling geometry for cryogenic conduits reaching between the dilution refrigeration cold stage and the array.
packages, in which conduit runs directly to each array package, eliminating the challenges associated with the ACTPol central cryogenic conduit distribution tower, the Advanced ACTPol arrays will feature a large-scale monolithic detector stack readout interface PCBs, with series array PCBs mounted plane parallel to the detector plane. Aside from PCB size and mounting geometry, for readout, flexible circuitry and readout chips will remain the same for the Advanced ACTPol design, again reusing successful technology subsystem variants developed during the ACTPol era. Figure 7.6 provides projected TES numerology, frequency center, frequency width, projected array sensitivity, and beam size for the five Advanced ACTPol multichroic polarimeter array packages (Henderson et al. 2016). Figures 7.7, 7.8, and 7.9 provide early design work that has been completed for the Advanced ACTPol HF polarimeter array package, including an overview of monolithic polarimeter array stacks, monolithic corrugated silicon-platelet feedhorn array, and integrated polarimeter array package in the modified 1K region of the ACTPol receiver. The Advanced ACTPol project will commence operations in 2016, and will cycle LF, MF, and HF array packages into service (again demonstrating the modular optimization of the ACTPol receiver) for three CMB science observing seasons in 2016, 2017, and 2018. With the Advanced ACTPol project utilizing the principal optomechanical, cryogenic, and readout components of the ACTPol receiver, the in-field operational lifespan of the ACTPol receiver has thus been extended from three to six years, and perhaps beyond.

7.2 Next Generation CMB Polarization Experiments, The CMB Stage IV Program, and CMBPol - A Seminal Inflationary Probe Mission

The development and operation of Advanced ACTPol does not represent the only next-generation activity in the development of experimental cosmology facilities probing the inflationary epoch of the Universe and extending our understanding of the initial state
Figure 7.6: Overview of the TES numerology, frequency center, frequency width, projected array sensitivity, and beam size for the five Advanced ACTPol multichroic polarimeter array packages. (Henderson et al. 2016)

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Figure 7.7: Advanced ACTPol HF polarimeter detector array stack isometric view, and illustration of two initial design splits for the interface of the rhomboidal detector wafer pixel design with flexible circuitry for interface readout.
Figure 7.8: Advanced ACTPol HF monolithic silicon-platelet feedhorn array assembly isometric and sectional views.
Figure 7.9: Detail views of the Advanced ACTPol HF polarimeter array package assembly (with monolithic, planar interface electronics), and illustration of this design variant in a modified 1K region in the ACTPol receiver.
and evolutionary history of the Universe. Here we briefly describe three such proposed platforms: the development of a next-generation BICEP project and the Cosmology Large Angular Scale Surveyor, CLASS. We then briefly describe future-generation CMB science programs, including the CMB Stage IV Program and CMBPol, a seminal inflationary probe satellite mission.

7.2.1 Next-Generation BICEP Project Development

Planning is already underway within the BICEP/Keck team to extend the reach of BICEP operations to both mid- and northern-latitude sites, which will extend sky coverage and corresponding scientific reach compared to the current BICEP operations at the Antarctic South Pole station. For this project, operations would begin with the deployment of initial site-testing equipment to characterize the observational environment of a mid-latitude site specifically for BICEP operations, located in the Chajnantor region of the Atacama (home to a robust program of CMB polarization facilities including ACT, CLASS, and PolarBear), as well as proposed northern-latitude sites at the Greenland Summit station and in Tibet. Following this initial effort, early CMB instrumentation would be deployed to selected sites for on-sky measurements, including two fully-operational receivers identical to the fielded Keck Array versions at the South Pole, including K7, a deployment-grade receiver currently used as a focal plane and beam mapping test-bed at Harvard. A repurposing and optimization of these receivers for operation with spare BICEP/Keck Array TES polarimeter arrays would allow for work to begin in earnest to develop methods and logistics for CMB-polarization-grade measurements on-sky at both Chile and Greenland Summit station sites. From a scientific standpoint, creation of such mid- and northern-latitude sites will greatly enhance the reach of BICEP science as these platforms will gain access to patches of sky that have potentially lower foreground levels than the South Pole station (to be better informed by the next Planck data release), allow for overlap with a large number of multi-wavelength surveys that can offer improved constraints on systematics including channels
above and below CMB frequencies to clean potential dust and synchrotron contamination from inflationary measurements, and offer multiple complete data sets on separate areas of the sky for independent confirmation of results. In addition to the rich science that will be enabled by data overlap and partnership with the neighborhood of Atacama CMB polarization facilities, development of BICEP sites in Greenland and Tibet will also allow for the opening of previously inaccessible locations for future observatories developed by the astronomical and cosmological community.

7.2.2 CLASS: The Cosmology Large Angular Scale Surveyor

CLASS is a novel, ground-based experimental cosmology platform to feature an array of four telescopes observing at high-altitude in the Atacama Desert of northern Chile, located a few tens of kilometers from the ACT site, in four frequency bands centered at 38, 93, 148, and 217 GHz, which will make survey measurements of the polarized CMB across 70 percent of the sky to detect the signature of the gravitational-wave background from inflation. Telescope operation and deployment will be staged and partitioned with one receiver deployed to each telescope, first with a Q-band receiver operating at 38 GHz in the first season, to be joined by dual 93 GHz W-band receivers on the second two telescopes in the second season, with completion of the fully-deployed CLASS instrument with a final receiver, with multichroic sensitivity at 148 and 217 GHz by the start of the third season of operation. In late-October 2014, the CLASS experiment broke ground for the construction of its high-altitude site in northern Chile, and work began to work toward the deployment of its first receiver, to operate at 40 GHz (Q-band) utilizing polarimeters developed and fabricated at Goddard Space Flight Center’s Observational Cosmology Laboratory. Current work will result in the finalization of the design and fabrication of the full-complement of 90 GHz polarimeter arrays (prototype array wafers have already been designed and completed) to populate the dual W-band receivers for CLASS.
Like ACTPol and Advanced ACTPol, not only will space technology development for CLASS support potentially revolutionary breakthroughs in CMB polarization measurements with standalone science impact, but will also allow CLASS to serve as a fully-integrated, ground-based pathfinder experiment to move forward the state-of-the-art in polarimeter development, which will be required for a NASA-led future-generation Inflationary Probe mission, CMBPol, which was recommended as a high-priority of the most recent National Research Council (NRC) Astro2010 decadal survey. Such advanced polarization-sensitive focal plane development has been identified specifically by NASAs Physics of the Cosmos (PCOS) program, Science Mission Directorate (SMD), and Space Technology Mission Directorate (STMD), via its Technology Area Breakdown Structure 08 (TABS-08) supporting detector and focal plane development within the Science Instruments, Observatories and Sensor Systems framework, as a critical priority to realize a future CMBPol mission. Furthermore at the top-level, this research will powerfully support the development of New Tools for Discovery under the NASA Space Technology Grand Challenge initiative, since these CMBPol enabling technologies will directly allow our nation to continue to be at the forefront of global cosmology initiatives that endeavor to answer some of the most fundamental questions of our universe via game-changing technologies (as well as those able to foster economic growth through transfer to the private sector), including those which investigate the origin, phenomena, structures, and processes of all elements of the solar system and of the universe.

### 7.2.3 CMB Stage IV and CMBPol

In order to fully realize the potential of high-sensitivity, polarization-sensitive observations of the CMB as a probe of early-universe inflationary models, ultra-high energy physics regimes, and to provide insight toward identifying the fundamental driver of the current accelerated epoch of expansion in the universe (e.g. determining if dark energy or a modified gravitational model is the primary cause), three large-scale federal research programs have
recently been formed. First, the U.S. Department of Energy (DoE) has endorsed recommendations of the Particle Physics Project Prioritization Panel toward the creation of broad framework to address these critical science goals, referred to as CMB Stage 4 (CMB-S4). CMB-S4 is a transformational initiative that will ensure continued American leadership in these high-impact fields of CMB science, by leveraging existing large-scale federal investment in national laboratory technology development and fabrication capabilities, as well as leading facilities in observational cosmology administered by University-based CMB research groups. Specifically, CMB-S4 will create a new paradigm within the field, by creating a unified organizational framework to achieve high-priority national CMB science goals, through the creation of interagency and multi-institutional partnerships among observatories and federal fabrication facilities that have been traditionally competitive and insular over the past few decades. The scale of technology required to achieve CMB-S4 science objectives, which includes the development of large-throughput cryogenic optics and ambitious focal plane designs featuring megapixel-level transition edge sensor (TES) polarimeter arrays with multichroic sensitivity, read out with efficient multiplexing techniques, is simply not commensurate with the resources of any single university-based CMB collaboration or federal laboratory, making unprecedented supra-collaboration partnerships essential. Ultimately, CMB-S4 will allow for the full-population of current-generation ground-based observational cosmology platforms from the Antarctic, including the South Pole Telescope (SPT) and BICEP/Keck Array, Atacama, including the Atacama Cosmology Telescope (ACT) and POLARBEAR, which have recently merged for the development of a next-generation array experiment following the completion of Advanced ACTPol operations, called the Simons Observatory (primarily funded by the Simons Foundation), and future northern hemisphere facilities (including proposed BICEP sites in Greenland and Tibet), with next-generation polarimeter arrays produced through coordinated large-scale fabrication efforts at federal laboratories. Not only will CMB-S4 enable these observational cosmology facilities to yield revolutionary breakthroughs in CMB polarization measurements with standalone science
impact (made possible through shared CMB data products at a variety of wavelengths using novel analysis methods developed by once rival teams), but will also allow each of these facilities to serve as fully-integrated, ground-based pathfinder experiments to significantly enhance the state-of-the-art in CMB polarimeter development—a central enabling technology for the second of these major inflationary science recommendations; namely, a seminal, future-generation Inflationary Probe mission (CMBPol), which NASA’s Science Mission Directorate, supported by recommendations from the National Research Council (NRC) Astro2010 decadal survey, has placed at the forefront of space technology research for the next-decade. Following or perhaps operating simultaneous to the ground-based CMB-S4 facilities, CMBPol will allow for an integration of the collected development of roughly two decades of space technology development for CMB science from the global experimental cosmology community and will be able to, among this collection of ground- and satellite-based experiments, definitively verify if inflationary models of the primordial Universe allow for formal inclusion as an extension of our standard cosmological model, $\Lambda$CDM cosmology.

7.3 Summary

Throughout this Chapter, we have demonstrated the manner by which the development of ACTPol has been not only beneficial to the current-generation technology development and CMB science yield for the experimental cosmology community, but also serves as a pathfinder experiment for next-generation operations on the ACT site, including Advanced ACTPol, the preliminary design and operational characteristics of which were described. Ultimately, these experiments exist within a larger continuum of instrumentation development efforts that will culminate in the next decade with horizional CMB science and technology development efforts, such as the CMB Stage-IV program and a future inflationary probe mission, CMBPol. In the chapter, which follows, we will contextualize this
continuum of science and technology development and provide a brief outlook for the future of experimental cosmology.
Chapter 8

Conclusion

So, girt with tempest and winged with thunder,
and clad with lightning and shod with sleet,
and strong winds treading the swift waves under
the flying rollers with frothy feet.
One gleam like a bloodshot sword-blade swims on
the skyline, staining the green gulf crimson,
a death stroke fiercely dealt by a dim sun,
that strikes through his stormy winding-sheet.

Oh! Brave white horses! You gather and gallop,
the storm sprite loosens the gusty reins;
Oh! Brave white horses! You gather and gallop,
the storm sprite loosens the gusty reins;

Now the stoutest ship were the frailest shallop
in your hollow backs, on your high arched manes.
I would ride as never man has ridden
in your sleepy, swirling surges hidden.
I would ride as never man has ridden.

To guls foreshadowed through strifes forbidden,
where no light wearies and no love wanes,
no love, where no love,
no love wanes.

from Edward Elgar’s “Sea Pictures: The Swimmer”

8.1 Conclusion

Over the course of this dissertation, a broad scope of science and technology development has been discussed, wherein each developmental element has been vital to the realization of ACTPol: a millimeter-wavelength, polarization-sensitive receiver upgrade for the Atacama Cosmology Telescope. In its own right, the successful design, integration, deployment, and operation under a CMB-science observing regime of ACTPol has exemplified a unique era of cosmology, viewed as an experimental scientific discipline. The first section of this manuscript provided context regarding the state-of-play of scientific understanding of the Cosmic Microwave Background (CMB) at the end of the first decade of the 2000’s - namely the era, directly preceding ACTPol, in which the CMB had been characterized strictly in terms of temperature anisotropies by both ground- and satellite-based experimental cosmology observatory platforms. These experimental platforms, which included the ground-based first-generation receiver, MBAC, of the Atacama Cosmology Telescope and the satellite-based Wilkinson Microwave Anisotropy Probe (WMAP), among many others, were revolutionary observing platforms in their own right, and marked a significant advancement of a wide-range of key CMB science objectives, notably showing good
agreement with the predicted $\Lambda$CDM model of the Universe.

The advancement of detector, readout, cryogenics, and optical technologies associated with period spanning the first half of the decade beginning in 2010 has been successful at pushing the forward the state-of-the-art to enable a next step in the so-called “era of precision cosmology.” Namely, the development of the Atacama Cosmology Telescope optimized for operation in tandem with the ACTPol receiver, along with its ground-based observatory contemporaries, were able to open mapping of the CMB in both temperature and polarization at unprecedented sensitivities. These experimental cosmology platforms, operating at a wide-range of angular scales, provided in this era vital complementary data sets to the CMB temperature and polarization mapping results that were released from the European Space Agency’s Planck satellite-platform, which operated over the same period. (In particular, the Planck satellite was launched on 14 May 2009, and operated until its decommissioning on 23 October 2013, a period entirely contained within the space technology development period of the ACTPol experiment). ACTPol in particular was able to successfully be designed, deployed, and operated between 2009 and 2015, providing precision small-angular-scale mapping of CMB in temperature and polarization, unlocking a wide array of CMB mapping and science results, as well as Sunyaev-Zel’dovich effect detected galaxy clusters, which, combined with analogous Planck (and other ground-based experimental) results in overlapping regions of the sky, provided increased data and science richness compared to what would be achievable by a single-standalone instrument.

The second section of this manuscript described the key technology development requirements associated with the successful upgrade and optimization of the Atacama Cosmology Telescope optomechanical superstructure and associated site logistics installations and systems, which would allow for the efficient deployment and operation of the ACTPol receiver with the ACT telescope. Key attention was given to the manner by which the development of the principal constituent subsystems-level technologies necessary to meet the science observing requirements of the ACTPol receiver fed into broader programs and policies of U.S.
federal space technology research. In particular, the manner by which the development of subsystem-level technologies were able to contribute to the advancement of the technical readiness levels (TRLs) of specific NASA technology area breakdown structures is notable. Among others, key space technology advancements were demonstrated through the design, integration, characterization, and science operation of the ACTPol receiver fully-loaded with unique subsystem technologies, including, e.g. high-purity silicon reimaging optics with novel metamaterial anti-reflective coatings, a pulse-tube-backed $^3\text{He} - ^4\text{He}$ dilution refrigerator optimized for field-deployable and in situ operation, and monochromatic and dichroic polarimeter array assemblies comprised of a monolithic, corrugated silicon feedhorn subassemblies and coupled silicon polarimeter wafer stacks featuring transition edge sensor (TES) bolometers, and readout systems featuring time-domain SQUID multiplexing. While the introduction of a near-continuous-base-temperature cryogenic regime through the integration of ACTPol with a dilution refrigerator allowed for the ACT experiment to (theoretically) operate for 24-hours in an observing day (compared to a maximum continuous-observing duration of roughly 12 hours for the previous-generation ACT receiver, MBAC), the development of novel operational protocols, supply-chain-logistics, and a new remote observing regime was able to increase the operational efficiency of ACT+ACTPol not only within a given observing day, but also on a per-season level compared to earlier-generation experiments. ACTPol was thus able to generate a larger, and deeper, observational dataset than would have been possible if these protocols for increased operational efficiency were overlooked. Furthermore, these protocols will provide important lessons-learned to boost the observing efficiency of future ground-based CMB experiments. These technologies, operating together in the fully-integrated ACTPol receiver on the ACT telescope superstructure were able to allow ACTPol to contribute to key early Universe science objectives of the U.S. National Science Foundation, as well as NASA Grand Challenges.

Moreover, in addition to demonstrating the ability to be a successful-standalone experimental cosmology facility, the operation of ACTPol in the Atacama Desert of Northern
Chile was able to provide key science, technology, and operational logistics’ lessons-learned for next- and future-generation observing platforms, thus allowing ACTPol to be viewed simultaneously as a key pathfinder experiment. The early science results presented in this dissertation include both temperature and polarization (I, Q, and U) mapping results within ACTPol’s deepest observing sets within its first season, providing precision measurements of the CMB E-mode power spectrum at small-angular scales ($\ell \geq 200$), as well as preliminary I, Q, and U mapping results for a region of the galactic field observed by ACT+ACTPol at 150 GHz, which was reported for the first time in this manuscript. Comparison performed in this work of these ACTPol galactic field temperature and polarization mapping results with analogous observing regions in the Planck satellite data set the stage for future polarization calibration of ACTPol data with Planck data, as well as joint analysis and constraint of ACTPol+Planck galactic foreground emission, which will set a critical framework for next-generation foreground analysis that will be necessary to enable future probes of cosmological inflation. Given that the Advanced ACTPol receiver upgrade will be able to operate over a wider array of relevant frequency channels (e.g. low-frequency regimes that will enable constraint of synchrotron radiation, mid-range primary CMB channels, and high-frequency regimes for dust constraint), this early, single-channel ACTPol galactic analysis will provide a useful basis from which to analytically proceed once these additional next-generation frequency channels are deployed and operated. Additionally, in their own right, these galactic field maps will provide a useful set of millimeter-wavelength temperature and polarization maps for use in the broader galactic astronomy community worldwide.

The final section of this dissertation manuscript described early design and development work performed to directly apply lessons-learned from the development of the ACTPol focal plane to a set of higher-pixel-density, fully-multichroic polarimeter array packages over three distinct frequency ranges, which would be fielded to upgrade the ACTPol receiver, to the next-generation of operation, referred to as Advanced ACTPol. The development and integration with ACTPol of a novel polarization modulator, namely a rapidly-spinning (2.5
Hz), broad bandwidth warm half-wave-plate system would increase ACTPol’s science range to include high-sensitivity CMB temperature and polarization results at larger-angular-scale regimes. Early development of Advanced ACTPol technologies focused on the development of high-pixel-density multichroic focal planes that would enable operation of the resultant upgraded ACTPol receiver across five frequency bands, with channels concentrated at five locations in the range of 30 to 230 GHz. These arrays would allow for monolithic six-inch diameter silicon feedhorn and polarimeter array wafer designs, which would also support future generation technology needs for, both ground-based platforms, including the Simons Observatory, CMB Stage-IV instruments, and a future-generation inflationary probe satellite platform. At the time of the writing of this dissertation, Advanced ACTPol arrays have already begun seasonal deployment, demonstrating the strategic advantage of the modular ACTPol receiver design, which would not require a full-receiver replacement for this next generation of the experiment, while opening a wide range of new CMB science regimes unaccessible to the ACTPol receiver. Additionally, development and planning for future-generation CMB observing platforms continues apace, including early principal design work for next-generation South Pole-based platforms (e.g. next-generation BICEP experiments), the Atacama-based platforms (e.g. the Simons Observatory), and policy, technology, and organizational planning for CMB Stage-IV and a possible future-generation NASA inflationary probe satellite.

It is with these future-generation instruments and missions in mind that one can structurally contextualize the role and relative-importance of the science and technology demonstrated through the design, integration, deployment, and science operation of the ACT plus ACTPol experimental cosmology platform. Namely, the ACTPol experiment can be accurately characterized as residing within not only a unique period within the “era of precision cosmology,” but also in a broader continuum of astronomical and experimental cosmology platforms, both within the historiographic contextualization of the development and proliferation of world-class astronomy, astrophysics, and cosmology observatories within the
Atacama region of Northern Chile (as was described in Chapter 2), as well as within the global advancement of experimental cosmology science and technology development. In his 2005 article, *Environmental History without Historians. What’s next for Environmental History?*, Steven Pyne argues that “...the environmental sciences need environmental historians, [...] They need our thick description of how things came to be as they are, and our capacity to evoke context and contingency. [...] we need their vigor, their ability to focus, their methodological skepticism.” (Pyne 2005) Indeed, all of the natural science, (experimental) cosmology included benefit from a significant understanding not only of the core scientific, engineering, and technology principles and associated development techniques, but also the lessons learned during earlier generation experiments - the operational principles developed in the aforementioned astronomy expeditions mounted in the nineteenth-century Atacama region undoubtedly provided not only the context, but laid the groundwork for techniques employed by contemporary instruments residing in the very same region.

In this sense, it is imperative that contemporary cosmologists have both a respect and understanding for the stories and thematic elements that allowed for the success of prior generation experiments and scientists, while also recognizing those that are intrinsic to the current-generation, in order to press on toward future field-advancing science and technology development. Ultimately, the presentation of the development of the ACTPol experiment represented in this dissertation illustrates several critical themes that can guide the success of future experiments and experimentalists. With respect to the advancement of scientific research, Joana Gaspar de Freitas and Joao Alveirinho Dias explain that, "...Reality, however, constitutes a multifaceted continuum that can only be adequately grasped through a conjunction of differentiated but integrated observations (that is interdisciplinarity), and can only be completely understood through the fusion of the maximum possible points of view (that is, transdisciplinarity).” (Jonana Gaspar de Freitas 2005) Clearly, the theme of interdisciplinarity and multidisciplinarity is evident not only throughout the example of ACTPol presented in this work, but applies to the broader field of experimental cosmology.
In fact, experimental cosmology, given its broad scope and reliance on a wide-range of fundamental physical principals in its scientific motivation, in addition to the broad-spectrum of seemingly disparate technological elements needed to integrate a given observational platform into an effective platform for next-generation CMB science results, may rely even more heavily on the necessity of a multidisciplinary approach than other natural sciences. Of course, the disciplines that were utilized to successfully field an instrument such as ACTPol expand even wider than the core spectrum of science and technology development fields that constitute the receiver and telescope itself. Understanding and consideration of international supply chain logistics, private-sector interfacing and subcontracting, organizational management and dynamics, project management, and economic analysis were also vital to the successful deployment of ACTPol. Since ACTPol is fully supported by federal funding, and relies on strategic partnerships with multiple federally funded research and development facilities (in multiple countries), a deep understanding and consideration of science policy and national science development goals and overarching challenges is required. Moreover, given the global nature of the ACTPol collaboration, and the necessity to operate the physical experiment itself in a country foreign to its primary source of funding, require the development of an understanding and operationalization of foreign policy and diplomatic skills to effectively interface with, e.g. the Chilean federal government, customs officials, Chilean federal scientific agencies (CONICYT), and regional law enforcement and public works officials, among others. Overlooking any of these disciplines would likely lead to strategic consequences for an experiment like ACTPol, and this consideration of course would extend (perhaps to an even greater extent) to future-generation experimental cosmology endeavors (i.e. the Simons Observatory and CMB Stage-IV initiatives), which look to integrate larger and more diverse global astronomy and cosmology research institutions and organizations.

Finally, perhaps the most fundamental themes that have been made evident through this presentation of the development of the ACTPol experiment and its early CMB and galactic
science results, are those of curiosity, creativity, adventure, and risk-taking. The latter two of these themes have been intrinsic to the entire history of Atacama-based astronomy and cosmology research, and are central to the advancement of future successful experimental cosmology installations in the region. In addition to the necessity to take-risks to press forward the boundaries of observational cosmology performance through novel and disruptive technology development, a spirit of adventurism will always have a place in Atacama-based cosmology given the remote, rugged, arid, and geomorphologically demanding environment unique especially to the Chajnantor Region of the Atacama Desert of Chile. The former two themes - curiosity and creativity - are central to driving the innovations in theoretical cosmology and the advancement of observational technologies needed to advance CMB science, and must be in great abundance to ensure that the forward arc of scientific progress is indeed a positive one. As Daniel Yergin aptly describes, “There is no assurance on timing for the innovations that will make a difference. There is no guarantee that the investment at the scale needed will be made in a timely way [...]...the risks of conflict, crisis, and disruption are inherent. Things can go seriously wrong, with dire consequences. Thus, it is essential that the conditions are nurtured so that creativity can flourish. For that resource - creativity - will be critical for meeting the challenges...for a...growing world.” (Yergin 2011, 2012) Indeed, advancement of our understanding of cosmology, the oldest of the natural sciences, has been driven over the course of time by human curiosity and creativity, and requires continued nurturing of this most precious resource to foster continued progress. It is up to us to ensure that this spirit of discovery is passed to future generations so that the story of cosmological understanding is one without end. There is no more fundamental aspect of the human condition than the drive to gaze skyward and question the very nature of our own existence and the origins, structure, and nature of the Universe in which we live. The very human pursuit of these questions ensure that cosmology will remain at the forefront of scientific endeavors through the end of human society.
Appendices
Appendix A

The ARTacama Project

In this Appendix, we highlight considerations leading to the completion of The ARTacama Project, a unique partnership between federally-funded research organizations in both the United States and Chile. The ARTacama Project is fundamentally centered on the goal of fostering broadly strategic stakeholder engagement via the deliberate and critical intersection of programs in fundamental science and applied technology development, visual fine art, as well as the support of overarching initiatives toward basic STEM and arts education. Continuing to the present since its inception in early 2012, the principal objective of The ARTacama Project has been the creation of a distinct vehicle in which to promote public awareness of ongoing world-class research programs in experimental cosmology and the visual fine arts, as well as to inspire the next generation of scientists, technologists, and artists through direct engagement within communities in the United States and Chile.

Specifically, The ARTacama Project is a partnership between the Atacama Cosmology Telescope (ACT) collaboration, which receives public support from federal agencies in the United States and Chile, the University of Pennsylvania Department of Fine Arts, and the Pentimenti Gallery in Philadelphia. Central to the project has been the creation of a large-scale, mixed media painting used to cover the surface of ACTPol, a next-generation,
millimeter-wavelength, polarization-sensitive receiver, now in operation at the ACT field site, located at over 17,000 feet (5190 meters) in elevation on Cerro Toco, an extinct stratovolcano situated near the village of San Pedro de Atacama, in the Chilean Andes of the Atacama Desert region of Northern Chile. As such, since its installation to the ACT site in early 2013, The ARTacama Project has simultaneously taken its place among the highest-altitude, ground-based telescopes and contemporary art installations worldwide. The aim of the Appendix, which follows, is to highlight the evolution of this deliberate intersection between the scientific and artistic assets involved, and provide an overview of the manner by which The ARTacama Project has enabled a unique multidisciplinary bilateral dialogue between scientists, technologists, artists, and political and cultural officials from both the local and national levels in both countries. We highlight the high-level support received for the project from both of the involved hemispheres, as well as interaction with the general public and students across this broad expanse.

**A.1 Context of The ARTacama Project to The Atacama Cosmology Telescope**

The Atacama Cosmology Telescope (ACT) is a six-meter telescope located in northern Chile, dedicated to enhancing our understanding of the structure and evolution of the early Universe via direct measurement of the Cosmic Microwave Background (CMB). Figure A.1 illustrates views of the ACT facility and site in Chile during daytime and nighttime operations.

The CMB is the earliest relic light in the Universe, and mapping of the temperature and polarization characteristics of the CMB can yield constraints on fundamental cosmological parameters that can be utilized to describe the nature of the evolution of the large-scale structures that are present in the contemporary Universe, as well as the nature of the so-called dark matter. Principal funding in support of the creation of the ACT site was
Figure A.1: Views from Cerro Toco of the Atacama Cosmology Telescope (ACT) facility and site during daytime (left) and nighttime (right) operations during December 2013, the inaugural season of ACTPol operations with installation of The ARTacama Project.
received from the United States National Science Foundation (NSF) in 2005, after which, in partnership with the Chilean Comisión Nacional de Investigación Científica y Tecnológica (CONICYT), the Chilean analog of the NSF, work began on the construction of the ACT telescope site in the Andes Mountains of Northern Chile. Specifically, the ACT field site is located at over 17,000 feet (5190 meters) in elevation on Cerro Toco, an extinct stratovolcano situated near the village of San Pedro de Atacama, in Chile’s expansive Atacama Desert.

The ACT site was selected due to its relatively accessible elevation, accessed by leveraging pre-existing roads, infrastructure, and logistics from the Chilean mining industry in the area, as well as the Atacama providing one of the driest and most stable airmasses on Earth, which allows for excellent observing conditions for millimeter-wavelength astronomy and cosmology. Additionally, as a mid-latitude ground-based observational platform located near the summit of Cerro Toco at latitude 22° 57′ 0″ South and longitude 67° 47′ 0″ West, ACT is also able to overlap with a myriad of observational results from associated telescope facilities, allowing for improved data richness and precision of scientific results via multi-wavelength follow-up observations. First light was achieved on ACT with its first-generation imager, the Millimeter Bolometer Array Camera (MBAC), in 2007, and observing operations continued with MBAC integrated and operational on ACT through 2010. Figures A.2 and A.3 illustrate the physical location of the ACT site on Cerro Toco, which is positioned on the confluence of the Chilean, Bolivian, and Argentinian borders in Northern Chile.

In mid-2010, the NSF reinvested in the ACT project, providing funding for the development of a next-generation imager, called ACTPol, which would extend the lifetime of the ACT telescope and site through 2015. The ACTPol project would combine a number of novel technologies to extend the scientific scope that MBAC began in probing the CMB, including advanced cryogenics (with operating temperatures below 100mK, offering unprecedented sensitivity), large-bandwidth silicon optics, transition-edge-sensor bolometers, and high-pixel-density multichroic focal planes. Although developed primarily in the
Figure A.2: Location of Cerro Toco and the ACT site as a mid-latitude (22° 57' 0'' South and longitude 67° 47' 0'' West) telescope facility in the Chilean Andes of South America.
Figure A.3: Detail location of the ACT site on the west slope of Cerro Toco, with situation to nearby village of San Pedro de Atacama, the volcano Licancabur, the Chajnantor Plateau, and the Bolivian border indicated.
United States between 2010 and 2013, ACTPol technology development has been a truly global effort with input from collaborators on five continents led by researchers at the University of Pennsylvania, Princeton University, and the National Institute of Standards and Technology (NIST-Boulder), as well as a team at the Pontificia Universidad Católica de Chile. Figure A.4 illustrates a number of the component advanced millimeter-wavelength imaging systems which, taken together, comprise ACTPol.

Integration of ACTPol was completed and the instrument and support equipment were shipped to Chile in January 2013. After a six-week sea shipment and landfall in the port of Iquique, the ACTPol camera and support equipment were transported to the ACT site on Cerro Toco in late-February 2013. Led by a team of researchers from the University of Pennsylvania, Princeton University, and the Pontificia Universidad Católica de Chile, ACTPol on-site integration and installation operations proceeded from February 2013 through first light, achieved on 17 July 2013. Given the staged deployment strategy of the ACTPol collaboration, the first season included installation of a single 150GHz polarimeter array package within the ACTPol receiver, which would operate for roughly six-months while the remaining two planned polarimeter array packages were readied and moved to the site for eventual integration in the ACTPol receiver. ACTPol, installed on the ACT telescope superstructure operated in its inaugural season until 04 January 2014, at which point upgrades were again led by the previously-mentioned field operations teams, including the installation of the second of three polarimeter array packages. The receiver operated throughout the 2014 season with two polarimeter array packages, until January 2015, when final upgrade operations were completed to result in the full-deployment of the ACTPol receiver with two 150 GHz polarimeter array packages, and an additional multichroic polarimeter array package, with simultaneous 150 GHz and 90 GHz sensitivity. ACTPol is currently taking critical CMB data from its perch in Chile, and will continue to operate through its final season, with operations concluding in early 2016. Figure A.5 illustrates the integration and deployment of the ACTPol camera to the ACT telescope on Cerro Toco.
Figure A.4: (Top, Left) Installation of principal ACTPol cryogenic Dilution Refrigeration subsystem. (Top, Right) An ACTPol large-aperture, wide-bandwidth silicon reimaging optic with diced antireflective coating surface. (Bottom, Left) ACTPol 150 GHz polarimeter array package assembly. (Bottom, Right) An ACTPol semi-hex high-pixel density polarimeter wafer.
Figure A.5: Flow chart indicating the staged-deployment strategy employed by the ACT collaboration for the on-site integration and operation of ACTPol in its first two seasons of operation on Cerro Toco.
First science results including temperature and polarization maps of the CMB acquired by ACTPol during its inaugural season were published in May 2014. A recent decision by the NSF has again extended the lifetime of the ACT project through funding of Advanced ACTPol, a project that will continue to upgrade the number and frequency ranges of detectors in the ACTPol receiver, with operations scheduled to continue through 2020. It should be noted that the continued partnership between the ACT collaboration and NSF with CONICYT has been essential for the continued success of ongoing efforts to support a robust program of field observing operations, most notably through the creation of the Parque Astronómico Atacama, a protected region in the Atacama Desert encompassing Cerro Toco, Cerro Chajnantor, and the entire Chajnantor Plateau, covering over 36,000 hectares, specifically reserved for the installation and support of a myriad of ecologically sustainable sites of astronomical research, including ACT.

A.2 Development of The ARTacama Project

To foster critical outreach and stakeholder engagement among the general public and, especially, to inspire the next generation of researchers in STEM fields, The ARTacama Project was conceived to bridge the traditional void between science and technology fields, and the visual fine arts. The project, which was initially conceived to call on University of Pennsylvania undergraduate and graduate fine arts students to show their art aptitude at high altitude, included a competition first presented to the campus community as a competition in which students were asked to submit proposals to cover the outer shell of the ACTPol receiver cryostat with a fine-art design, with the underlying theme to be a ‘reflection of the spirit of collaboration in cosmology research in the Atacama setting.

Unfortunately, given the timing of the competition call before the beginning of the Autumn 2012 semester, very few entries were received for the competition call from the Penn student body. In speaking with the Penn Design and Fine Arts departments, there remained interest generated by the faculty of those departments in taking on the project,
and it was ultimately decided to enter into a partnership with the studio of Penn Fine Arts Professor, Jackie Tileston.

After several initial planning meetings, ultimately a large-scale, abstract mixed-media diptych painting was commissioned by Benjamin Schmitt with input from Professor Mark Devlin of the ACTPol team at Penn, and completed by Professor Jackie Tileston, assisted by her husband, sculptor, Kirk McCarthy. Rather than depict any one area of the science or technology development associated with the ACTPol project directly, Schmitt and Devlin worked with Tileston and McCarthy to develop an overarching theme of depicting the evolution of the universe from homogeneity after the Big Bang through the development of structure in the present day Universe, while leveraging Tileston’s interpretation of abstract ethereal spaces and discordant systems, of which the structural evolutionary development of the Universe lends itself naturally. In particular, the work was structured such that the areas covering the front end of the ACTPol receiver (the receiver input aperture surface) would reflect the tendency of the early Universe toward homogeneity, while the rear of the receiver represented the evolution of the universe toward the formation of large-scale structure. In order to accommodate the usual style of flat canvas work by Professor Tileston, and to mitigate any interruptions to the deployment schedule of the receiver to Chile itself, the Penn Fine Arts department allocated a subgrant to allow for the flat canvas paintings that were commissioned of Professor Tileston for The ARTacama Project to be completed physically separate from the receiver. These paintings would then be photographed in high-resolution, and printed as a high-resolution vinyl auto-body wrap cover, to be applied to the receiver in a single session by a professional team of auto-body wrap engineers. The original work, entitled Radical Measure (Not Entirely Random), was exhibited in a solo exhibition entitled This is Elsewhere from 02 November until 15 December 2012 at Pentimenti Gallery in Philadelphia. In the work, Tileston completed an oil and mixed media painting on linen, which conjures simultaneously the silence of an interstellar atmosphere to a fleeting spectral apparition. In this piece, Tileston succeeds in bringing multiple phenomena together to
create an environment that exists on its own terms. (Pfister 2015) Figure A.6 illustrates the Pentimenti Gallery unveiling of the original work, which included a brief lecture by the artist, concluding with a formal reception, as a participating event in the Philadelphia “Old City” First Friday Festival fine arts series. (Philadelphia 2016)

During the exhibition at Pentimenti Gallery, the painting was then digitally photographed, and printed in high-resolution on a full-scale vinyl canvas, which was then professionally wrapped onto the ACTPol camera surface, with full installation completed by a local Philadelphia auto-body wrap company, Apple Graphics. (Graphics 2016) Following this installation, Tileston, assisted by McCarthy completed several sessions of painting on the ACTPol receiver, in order to bring a coherent, and visually appealing unification of the wrap with the existing experimental instrumentation. Figure A.7 illustrates the ACTPol receiver coupled to the ACTPol Receiver Alignment Mechanism (ACTPol RAM) outside the Penn Experimental Cosmology High-Bay facility before ARTacama installation in Autumn 2012. Moreover, Figure A.8 illustrates the final wrap installation and painting effort by Tileston and McCarthy, while Figure A.9 illustrates the entire ARTacama Project team following completion of the project installation at Penn, with official project press release shown in the inset.

Thus, after installation to the ACT telescope in Chile in 2013, The ARTacama Project has been able to create the highest-altitude permanent contemporary art installation on Earth, while simultaneously creating an object representative of the interdependence of art and science, used to better convey the subject matter of both areas more directly than might be enabled through a traditional standalone project. Thus far, over 50 visitors to the ACT site have witnessed the installation in its operational location on Cerro Toco, including director of CONICYT astronomy programs, Monica Rubio, and her team. The long-term intent will be to increase local programming over future observing seasons, to enable especially local students from the San Pedro de Atacama and Calama communities to interface with the work through programming meant to enable these local populations
Figure A.6: Illustrated overview of The ARTacama Project. (Top) High-resolution digital image of the originally-commissioned diptych painting serving the basis of the high-resolution vinyl wrap for the cryostat, entitled Radical Element (Not Entirely Random), from Penn Fine Arts Professor Jackie Tileston. (Lower) Benjamin Schmitt, Jackie Tileston, and Kirk McCarthy (artist of the front and rear canvas panels of The ARTacama Project) at the Pentimenti Gallery, This is Elsewhere Graphic work of Jackie Tileston, First Friday Festival Opening in Philadelphia, Pennsylvania.
Figure A.7: Views of the ACTPol receiver coupled to the ACTPol Receiver Alignment Mechanism (ACTPol RAM) outside the Penn Experimental Cosmology High-Bay facility before installation of The ARTacama Project in Autumn 2012.
Figure A.8: (Above) Final high-resolution vinyl wrap installation by Philadelphia-area auto-body wrap company, Apple Graphics. (Graphics 2016) (Below) Final painting session following the ARTacama wrap installation to the ACTPol receiver at Penn.
Figure A.9: The entire ARTacama Project team following completion of the project installation at Penn, with official project press release shown in the inset. (From left-to-right: Benjamin Schmitt, Robert Thornton, Jackie Tileston, Kirk McCarthy, Mark Devlin.)
to be inspired to take part in the rich cultural heritage of astronomical observations and art that have taken place in the region for thousands of years, and in particular, take an intrinsic ownership of the current project investments literally residing in their own backyard. Figure A.10 illustrates the finished project prior to shipment of the ACTPol receiver and support equipment to Chile, as well as The ARTacama Project and on-site visitors following deployment to the ACT site in mid-2013.

A.3 Stakeholder Engagement with The ARTacama Project

Concurrent to the core science, technology, and fine art deployment operations and foreign stakeholder engagement on-site in Chile, as discussed in the previous Section, The ARTacama Project also was developed into an effective tool for United States domestic federal and diplomatic stakeholder engagement between deployment of ACTPol and The ARTacama Project between 2013 and 2015. This section illustrates several of these domestic stakeholder engagement highlights, including astrophysics advocacy events across the United States. Through the NASA Space Technology Research Fellowship program, the primary funding source for the work described in the dissertation herein, program administrators at NASA Headquarters organized involvement of ACTPol and The ARTacama Project representation at the 2013 NASA Space Technology Day on the Hill event, which took place in July 2013 at the Rayburn U.S. House of Representatives Office Building, on Capitol Hill, in Washington, D.C. The aim of this event allowed for direct description of both core ACTPol research, as well as the unique value-added aspects of The ARTacama Project to be presented to both U.S. executive and legislative branch officials, while advocating for continued and robust American investment in space technology and basic science research. Figure A.11 illustrates the various critical engagement opportunities provided during this event, in which ACTPol basic science research narratives were enhanced by the broader impacts scope of The ARTacama Project. This event included ACTPol and ARTacama Project discussion with NASA officials, including NASA Administrator (and former
Figure A.10: (Top: Left, Right) Final views of the finished ARTacama Project installation prior to shipment to Chile in January 2013. (Lower, Left) First off-telescope operation of the fully-integrated ACTPol receiver with The ARTacama Project on the ACT site in mid-2013. (Lower, Right) Visit of Monica Rubio (center), director of Astronomy programming for CONICYT and colleagues at the ACT site in mid-2014.
Astronaut) Charles Bolden, NASA Chief Technologist Mason Peck, and NASA Space Technology Mission Directorate Associate Administrator Michael Gazarik, as well as legislative policymakers, including Ranking Member of the House Committee on (science) Appropriations, Representative Chaka Fattah (D-PA), and House Science, Space, and Technology Committee Member, Representative Chris Collins (R-NY).

Following the NASA Space Technology Day on the Hill event, hybrid ACTPol and ARTacama Project engagement proceeded on Capitol Hill again in 2014, through participation in the American Astronomical Societys Congressional Visit Day. This event allowed for two days of intensive training in the structure and execution of the federal science policy, advocacy, and appropriations process, followed by a full day of engagement with policymakers and their staffs on the Hill. During this event, ACTPol basic science and technology objectives were presented through the vehicle of The ARTacama Project during meetings with the offices of eight House and Senate Members, including advocating for science appropriations, again with ACTPol as a central example, which included a 45-minute briefing of House Science, Space, and Technology Committee Member Representative Chris Collins (R-NY), and was followed by a briefing on the state of the Presidential Budget Request at the Executive Office of the President, Office of Science and Technology Policy, at The White House. Figure A.12 illustrates again the broad areas of science and technology advocacy enabled by a hybrid presentation of both ACTPol and The ARTacama Project. Additionally, in between these events, while abroad in the remote Atacama Desert for site deployments, this drive continued. During site deployments until the final ACTPol PA3 deployment in 2015, not only was ACTPol with The ARTacama Project and effective engagement tool during events leading multiple official visits of the CONICYT astronomical delegation on the high-altitude telescope site, but was also fundamental in raising the profile of both ACT and the Chajnantor region at large, resulting in leading a group of consultants dispatched by CONICYT to assess and advocate for improvements to be made by the Chilean government to improve site logistics and access to the myriad of foreign telescope investments in
the region. Adding to these engagement experiences was the use of *The ARTacama Project* to highlight the broader impacts of the core science and technology development objectives of the ACTPol collaboration to celebrity astrophysicist and Frederick P. Rose Director of the Hayden Planetarium at the American Museum of Natural History in New York, Neil deGrasse Tyson. Figure A.13 highlights this meeting, which took place at the Los Angeles International Airport United Lounge, while in transit to the ACT site for final PA3 deployment operations in January 2015. (of Natural History 2015) Finally, during preparation of this dissertation manuscript in Washington, D.C. during late-2015 and early-2016, ACTPol and *The ARTacama Project* were again used as a distinct vehicle to enable broader impact highlights of the ACTPol collaboration, both in meetings with NASA Astronaut, Sandra Magnus, as well as U.S. Ambassador to Chile, Michael Hammer, and Massachusetts Senator Edward Markey, meetings of which are highlighted in Figure A.14.

### A.4 U.S.-Chilean Bilateral Diplomacy with *The ARTacama Project*

Building on the momentum of the installation of ACTPol to the ACT site, in which ACTPol has become simultaneously one of the highest-altitude ground-based telescopes on the planet, as well as the highest-altitude contemporary art installation on earth, targeted programming events were also initiated to foster robust U.S.-Chilean diplomatic relations through this unique platform of science and technology diplomacy, the context and critical nature of which was described in detail in Chapter 2. In order to use *The ARTacama Project* to highlight ACTPol and over a decade of U.S. critical investments in Atacama-based astronomy, an effort was developed and initiated beginning in June 2014 to host a formal symposium on the project, which was initially devised to coincide with the Spring-2015 state visit of Chilean President Michelle Bachelet to the Philadelphia area. This event, allowed for ACTPol engagement directly with the Honorary Counsul of Chile in Philadelphia,
Figure A.12: Highlights of Congressional and White House briefings during the American Astronomical Society 2014 Congressional Visit Day event in Washington, D.C. during late-March 2014.
Figure A.13: Meeting with Neil deGrasse Tyson to discuss ACTPol science and technology development, as well as continued critical outreach efforts of the ACTPol collaboration including *The ARTacama Project* at the Los Angeles International Airport en route to lead the third ACTPol focal plane deployment at the ACT site in the Atacama Desert of Northern Chile, which included getting an autograph on an upgraded ACTPol multi-channel electronics synchronizer computer box that was being transited for on-site deployment.
Figure A.14: Additional meetings in Washington, D.C. during late-2015 and early-2016, in which ACTPol and The ARTacama Project were again used as a distinct vehicle to enable broader impact highlights of the ACTPol collaboration, both in meetings with NASA Astronaut, Sandra Magnus, as well as U.S. Ambassador to Chile, Michael Hammer, and Massachusetts Senator Edward Markey.
depicted in part in Figure A.15, would include a unique formal reception on the University of Pennsylvania campus. The original timing of the event was designed to coincide with the aforementioned state visit of President Michelle Bachelet of Chile, with the aim of receiving President Bachelet and other visiting dignitaries, as well as local, state, and national officials from the United States, including Philadelphia district U.S. House of Representatives Representative Chaka Fattah, to recognize and celebrate the ongoing partnership in world-class scientific research between federal agencies of both the United States and Chile as is represented uniquely in *The ARTacama Project*. For the event, the Pentimenti Gallery, which supported the original commissioning effort of *The ARTacama Project* agreed to supply the original diptych canvas of *Radical Element (Not Entirely Random)* on loan for display and interaction with both federal officials, academics, students, and the general public that would be invited to the event. Additionally, a series of lectures proposed for the duration of the event, including a scientific overview of overarching scientific topics in cosmology, a description of the technologies and operations represented through the Atacama Cosmology Telescope in operation with ACTPol, an overview of the nature of mixed-media abstract painting relevant to the project, and an overview of *The ARTacama Project* and mission itself. Following these brief lectures, remarks would be welcomed by politicians and dignitaries in attendance, followed by a question-and-answer panel discussion between all in attendance. It was proposed to have full media coverage of the event, which will foster not only to connect a broader audience to *The ARTacama Project* directly, but also increase the profile of the areas of cosmology and fine arts represented through engagement of a wider population than would normally interact with these fields. In support of this event, contributions would be made by all members of *The ARTacama Project* team, in the Penn departments of Physics and Astronomy and Fine Arts, the Pentimenti Gallery, as well as the Chilean Consulate in Philadelphia.

The resultant proposal process allowed for leadership through *The ARTacama Project* team in diplomatic efforts to secure a visit to this symposium at Penn by President Bachelet,
Figure A.15: Overview of ACTPol and The ARTacama Project policy stakeholder engagement planning with the Honorary Consul of Chile in Philadelphia, including a reception on the Penn Campus commemorating over a decade of ACT operations and two-years of ACTPol operations with installation of The ARTacama Project.
which began with a series of meetings to develop strong ties and backing of the project from
the Honorary Consul of Chile in Philadelphia, Benjamin Leavenworth, illustrated, as afore-
mentioned, in Figure A.15, and proceeded through the drafting of an official white paper
that was carried by the Consul of Chile during his August 2014 visit to meet with members
of the Chilean Senate in Santiago. As a result of that visit, the Consul was able to organize
a private meeting in Philadelphia between representatives of The ARTacama Project team
and Ambassador of Chile to the U.S. Juan Gabriel Valdés. This meeting, which took place
in October 2014, is illustrated in Figure A.16. During the meeting, presentation highlighted
the science and technology results of ACTPol with a focus on small business development
associated with the project in Chile and the U.S., and the manner by which universally en-
gaging cosmology projects like ACTPol contribute to bilateral diplomacy between the two
nations. The description also included ongoing programs from the ACTPol collaboration
to help to continue to inspire Chilean students to take an active role in their heritage of
astronomical research, while also commenting on the great pride that is regularly expressed
by Chileans in their burgeoning role as international hosts to multinational observatory
facilities, which has directly resulted in their own investment in home-grown basic science
and technology development programs over the past few decades. While, ultimately, the
visit of President Bachelet was not able to coincide with the resultant Spring-2015 ARTa-
cama Project exhibition at the University of Pennsylvania, due to the President’s schedule
resulting in her visit to Philadelphia during principal ACTPol PA3 deployment operations
in Winter 2015, this effort was nonetheless fundamental in increasing the diplomatic profile
that large-scale experimental cosmology projects like ACTPol represent to support bilat-
eral relations between key allies, and also laid the groundwork for such an exhibition of any
future visit to the Philadelphia area by President Bachelet, or other Chilean dignitaries.

Also resulting from the ARTacama Project diplomatic reception development process
was the ultimate hosting of a capstone interdisciplinary installation, panel discussion, and
laboratory tour, which was held in recognition of The ARTacama Project at the University
Figure A.16: Illustration of *ARTacama Project* team participation in private a diplomatic meeting with Chilean Ambassador to the U.S. Juan Gabriel Valdés to both highlight bilateral diplomacy between the two nations resulting from fundamental science and technology development, as well as planning of both the state visit of Chilean President Michelle Bachelet and an eventual event to highlight U.S.-Chilean investments in critical telescope technologies enabling projects such as ACTPol in Northern Chile.
of Pennsylvania in May 2015. This professional art, science, and technology installation is illustrated in Figure A.17. Ultimately, this commemorative event included a formal gallery opening at the Charles Addams Fine Arts Gallery on the Penn Campus that attracted over 60 attendees from a wide range of backgrounds, and featured the main painting on loan from the Pentimenti Gallery, along with a collection of ‘modern art’ based on components designed and fabricated during the development of the ACTPol project that were gathered from around the ACTPol collaboration, including contributions from NIST-Boulder, Penn, and Princeton. The highlight of the event was what was ultimately a very interesting, and trimodal multidisciplinary panel discussion and public question and answer session, featuring the Honorary Consul of Chile in Philadelphia, and greetings he carried from the Chilean Ambassador to the U.S., Benjamin L. Schmitt, Professor Mark Devlin, and the ARTacama artist Professor Jackie Tileston, as well as the director of the Pentimenti Gallery of Philadelphia, which officially represents the work of Professor Tileston, where the panel was were confronted with an array of technical questions concerning diplomacy, fine arts, and the sciences - all within a single discussion dialogue. Media outcomes from the official event include a permanent event and installation website highlighting the main work of The ARTacama Project and the broader exhibition collection, along with a Flickr page from Penn featuring professional photography of the event, and two reviews written by professional art critics who were in attendance. (Pfister 2015) Resulting from The ARTacama Project installation was an agreement to allow the the original ARTacama Project diptych canvas Radical Measure (Not Entirely Random) to remain in residence at the Penn Department of Physics and Astronomy, which and is open to the members of the Penn community and public for continued interaction and engagement, in direct dialogue with the science and technology development work undertaken by faculty and students in the Department. The canvas residence installation in the Penn Department of Physics and Astronomy is illustrated in Figure A.18.
Figure A.17: Overview of *The ARTacama Project* installation opening, panel discussion, and laboratory tour, held at the Charles Addams Fine Arts Gallery of the University of Pennsylvania on 14 May 2015, which resulted in a multidisciplinary discussion focusing on the critical intersection of science, technology, diplomacy, and the fine arts and included over 60 attendees from the campus, Philadelphia, and broader communities.
Figure A.18: The original ARTacama Project diptych canvas Radical Measure (Not Entirely Random) in residence at the Penn Department of Physics and Astronomy, which and is open to the members of the Penn community and public for continued interaction and engagement.
A.5  Outlook for Future Programming Including The ARTacama Project

The extension of the ACTPol receiver operational lifespan through 2020, upgraded as Advanced ACTPol, which was highlighted in Chapter 7 ensures that The ARTacama Project will also continue in permanent installation at the high-altitude ACT site on Cerro Toco in the Atacama Desert of Northern Chile through at least the end of the decade. To bolster associated engagement effort further during this operational deployment period, a Spring-2015 meeting of project stakeholders was held at the Teatro del Lago, a modern opera house facility constructed within the past decade on the shoreline of Frutillar, Chile, situated in northern Patagonia. (del Lago 2015) This meeting, which took place directly following final ACTPol PA3 deployment completion, involved a direct dialogue with the Artistic and Executive directorate of the Teatro del Lago for initial planning of a white paper proposal for a multidisciplinary music and technical program to both highlight the central work and thematic reach of The ARTacama Project, as well as continued bilateral diplomacy that is represented by the continued investment and exchange of scientific and technical know-how and facilities development in experimental cosmology between the United States and Chile. The highlight of this program would be a multinational initiative to join astronomers, policy makers, and performing artists in an interdisciplinary master class series event at the Teatro del Lago itself, to take place during the deployment and tenure of Advanced ACTPol. Figure A.19 provides an illustration of the Teatro del Lago facility in Frutillar, Chile, as well as the meeting by project stakeholders which took place at the facility in February 2015. In addition to this programming during the ACTPol deployment extension via Advanced ACTPol, early feasibility discussions have been held for a future display of the ACTPol receiver with ARTacama Project installation across Chile, including in San Pedro de Atacama, Santiago, and Frutillar, among other locations. Ultimately, when the ACTPol receiver is returned to North America following the conclusion of Advanced ACTPol operations (and Chilean
ARTacama Project exhibitions), the project will be displayed across venues in the United States, including in Manhattan as a part of the SciArt Center of New York (of New York 2015) and in Washington, D.C. as a part of the D.C. Art Science Evening Rendezvous (DASER) installation series at the National Academy of Sciences, on the National Mall. (of Sciences 2015) The final permanent installation plan for the ACTPol receiver and The ARTacama Project is at the Franklin Institute in Philadelphia, where exhibition proposals include the original diptych canvas displayed near the receiver 300K vacuum jacket covered by the ARTacama Project wrap, though cut in half to allow visitors to interact with both the fine art installation, as well as the technical systems that ensure proper operation of both the ACTPol and Advanced ACTPol receiver systems. (Institute 2015b)

A.6 Summary

As we have seen throughout this Appendix, the unique scope and multidisciplinary focus of The ARTacama Project has provided a novel vehicle to allow for effective stakeholder engagement and educational broader impact opportunities, which has served to augment the strong history of creative education and public outreach programming associated with the ACTPol collaboration. This initiative has both benefited from and offered robust support for increased bilateral diplomatic relationships between the United States and Chile through science, technology, and fine arts partnerships, and also supported basic science and technology advocacy within domestic science policy fora, including through engagement with domestic federal policymaking spheres. More notable, throughout this Appendix, it has been made clear that The ARTacama Project was made possible with generous support, both monetary and effort-based, from individuals and organizations across both the United States and Chile with a distinct passion for supporting the arts, sciences, and the U.S.-Chile bilateral relationship, since The ARTacama Project was supported entirely independent from core ACTPol or Advanced ACTPol funding frameworks. To this end, the ultimate success of a program like The ARTacama Project is made paramount by its ability
Figure A.19: Meeting in Chile following the completion of ACTPol PA3 deployment operations with the Artistic and Executive directorate of the Teatro del Lago for initial planning of a white paper proposal for a multidisciplinary music and technical program to highlight The ARTacama Project and continued bilateral diplomacy that is represented by the continued investment and exchange of scientific and technical know-how and facilities development in experimental cosmology between the United States and Chile.
to organically connect and find support from individuals and groups from disparate cultural, academic, and strategic backgrounds, united in basic human experience to express and understand the Universe in which we live.
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Biographical Sketch

Benjamin L. Schmitt: Benjamin L. Schmitt is currently a European energy security and science and technology policy advisor for the U.S. Department of States Bureau of Energy Resources (ENR), where he has also served as a IEEE Department of State Science and Technology Policy Fellow. In his role at the State Department, Schmitt serves as a European energy security advisor leading novel policy development across the Eurasian region, drawing on his hard science and technology background to develop and implement policy strategies for the advancement of joint U.S. and EU shared priorities at the intersection of energy and security geopolitics. Schmitt regularly advises senior U.S. officials on matters of European energy security from the U.S. Department of State, U.S. Department of Energy, and the White House National Security Council, as well as regularly engaging on these topics at the Ministerial level across Europe.

Immediately prior his service as the IEEE Department of State Fellow, Benjamin served as a NASA Space Technology Research Fellow, while completing the core research objectives associated with the doctoral program described in this dissertation manuscript, as a Ph.D. Candidate in Physics and Astronomy at the University of Pennsylvania focusing on experimental cosmology research with the group of Professor Mark J. Devlin.

Central to this degree program has been a primary concentration on the development of novel millimeter-wavelength imaging technologies framed through the design and integration of ACTPol, a polarization-sensitive receiver upgrade for the Atacama Cosmology Telescope. Benjamin’s research connected to ACTPol was supported by a NASA Space Technology Research Fellowship (NSTRF), as well as an National Science Foundation Graduate Research Fellowship Program (NSF-GRFP) grant, which supported his active collaborative
work with teams at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, NASAs Goddard Space Flight Center in Greenbelt, Maryland, as well as field operations at the ACT site in the Atacama Desert region of northern Chile.

Benjamin previously served as a U.S. Department of State Fulbright Research Fellow at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany, where he engaged in plasma diagnostics research via precision measurement of the photoionization of highly charged ions propagated in an electron beam ion trap with modern synchrotron radiation light sources. He also supported the development of x-ray diagnostics systems for the OMEGA laser system at the University of Rochesters Laboratory for Laser Energetics, a Department of Energy inertial confinement fusion research center, and has been a visiting researcher at both Cornell and Columbia Universities. Benjamin is a professional member of the American Astronomical Society (AAS), the Institute for Electronics and Electrical Engineering (IEEE), the American Physical Society (APS), the Optical Society of America (OSA), and SPIE (the international society for optics and photonics), and has participated in federal science and technology policy engagement events with members of Congress, the Office of Science and Technology Policy of the Executive Office of the President, and the Fulbright Academy of Science and Technology at the United Nations in the United States, as well as CONICYT in Chile. An accomplished classical vocalist with numerous principal roles with the Eastman Opera Theatre company at the Eastman School of Music in Rochester, New York, prior to this Doctoral degree, Benjamin earned a Master of Science degree in Physics and Astronomy from the University of Pennsylvania (Philadelphia, Pennsylvania), and earned a Bachelor of Science degree in Physics and Astronomy, as well as a dual Bachelor of Arts degree in Mathematics and Modern German Languages and Cultures from the University of Rochester (Rochester, New York). He resides in Georgetown, Washington, D.C.