Chapter 1

Introduction

1.1 Overview

Cosmology has blossomed into a mature and precise scientific field over the past few decades. During this time, measurements of phenomena as diverse as Cosmic Microwave Background (CMB) anisotropies, large-scale galactic structure, high redshift Type Ia supernovae, and primordial nucleosynthesis abundances have produced a surprisingly consistent picture of our universe's dynamics and composition. We live in a universe that is composed of only 4% baryonic matter, with the remainder split between cold (non-relativistic) dark-matter (20%) and a poorly understood dark energy (76%) that is causing the expansion of our universe to accelerate. The geometry of space in our universe is flat on the largest observable scales and we hypothesize that this was fine-tuned by a period of rapid expansion in the first fraction of a second after the Big Bang. We also suspect that this rapid expansion amplified gravitational wells to cosmic scales and that matter later fell into them to form stars and galaxies. This model of our universe's structure and evolution is known as the inflationary Lambda-CDM (Cold Dark Matter) cosmology.

While this model enjoys consistent support from a wide variety of measurements, none of these observations have matched the CMB data set in terms of variety and precision of constrained cosmological parameters. The CMB is our most ancient optical image of the universe, created a scant 300,000 years after the Big Bang when atoms first formed from the hot primordial plasma. Because it was created so early in our universe's history and has only been slightly perturbed since, the microwave background bears the signature of our universe's structure long before matter gravitationally collapsed into starts and galaxies. As a result, the features of the CMB can be compared against models where matter and energy have a sufficiently low density that their dynamics are described by linear equations. Such linear equations are significantly simpler than the full non-linear models relevant later in the universe's history. This relative simplicity has allowed cosmologists to make a deep comparison between theory and CMB observations and to constrain numerous cosmological parameters to unprecedented accuracy. Because of these successes, the cosmic microwave background has been referred to by some as a "Cosmic Rosetta Stone."

1.2 History

Despite the linear theory underlying the CMB's structure making it easy to interpret, its weak signal has made it one of the most technologically challenging astrophysical sources to measure. Historically, most experimental advances in this field have been linked to technological advances in the receivers. In fact, the sensitivities of bolometric receivers have followed a Moore's-Law-like growth, where the Noise Equivalent Powers (NEPs) have dropped in half roughly every 2 years for the past half-century (see Figure 1.1).

The CMB was first detected serendipitously by Bell Labs scientists Penzias and Wilson in 1964 as a 3.5K signal that was uniform across the sky. While they initially thought this to be simply "excess noise" generated within their microwave telescope, it was soon realized to be relic radiation from the Big Bang. Numerous follow-up experiments used similar heterodyne receivers to measure the CMB's spectrum in the Rayleigh Jean's limit, but they all suffered from limited sensitivity at higher frequencies (*Partridge* [1995]). This limitation was finally overcome with the Woody-Richards balloon-borne experiment that used a far more sensitive bolometer behind a Fourier-Transform Spectrometer (FTS) to provide spectral discrimination over nearly a decade of bandwidth (*Woody and Richards*

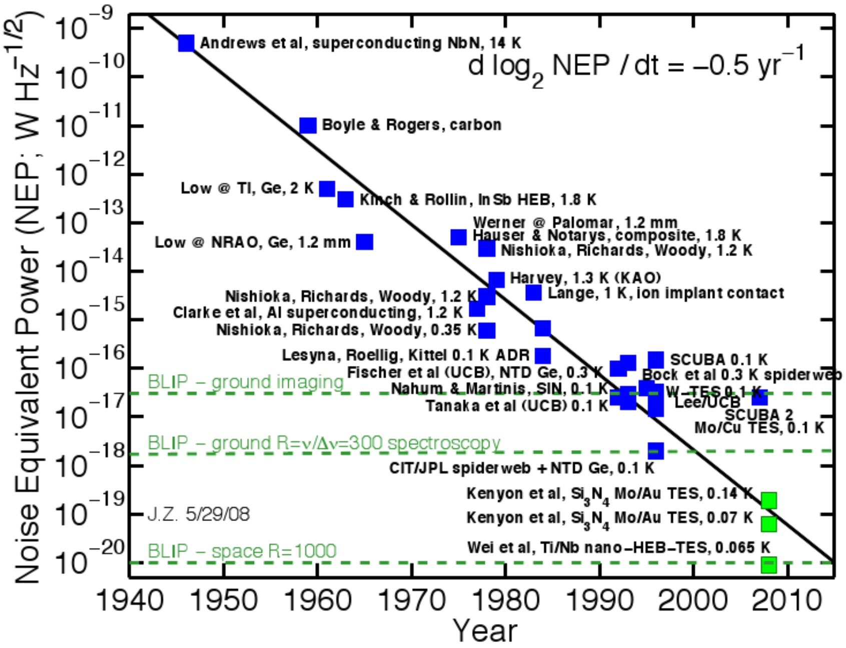

Figure 1.1. NEP of Bolometeric detectors vs publication date. NEP is defined as the source power that a detector would have to look at to attain a signal to noise ratio of unity for a half second of integration time. Figure courtesy *Zmuidzinas* [2010].

[1979]). This was the first experiment that measured the CMB's spectrum out into the Wein-tail and demonstrated it to be a true blackbody. These spectral measurements culminated in the late 1980s FIRAS (Far Infrared Absolute Spectrometer) experiment on the COBE (Cosmic Background Explorer) satellite which characterized the spectrum from 60 to 600 GHz and constrained it's temperature to 2.728 ± 0.004 K (*Fixsen et al.* [1996]).

Despite the CMB's remarkable uniformity across the sky, scientists made considerable efforts to detect anisotropies in temperature. George Smoot's team at LBNL first detected a $3.5mK$ dipole anisotropy in 1977 with a differential radiometer aboard a U-2 aircraft. They attributed this to a Doppler shift caused by the Earth's motion relative to the CMB (*Smoot et al.* [1977]). Anisotropies with cosmological origins were finally seen in 1992 with COBE's Differential Microwave Radiometer (DMR), detecting $16 \pm 4 \mu K$ variations on scales larger than 7^o (*Smoot et al.* [1992]). This detection, as well as dramatic improvements in bolometric and HEMT receivers, triggered a race to see degree scale anisotropies generated by acoustic oscillations in the early primordial plasma. These anisotropies were finally seen in the late 1990s by two balloon-borne bolometric experiments (BOOMERANG and MAXIMA, *de Bernardis et al.* [2000] and *Hanany et al.* [2000]), and terrestrial HEMT-based receivers (TOCO and DASI, *Miller et al.* [1999] and *Halverson et al.* [2002]), detecting a primary peak in the anisotropies at $l \sim 200$. Two other terrestrial bolometric receivers (CBI and ACBAR, *Pearson et al.* [2003] and *Reichardt et al.* [2009]) measured anisotropies during this time at even higher scales out to $l \sim 2000$. These efforts culminated in the well known WMAP satellite experiment that mapped the full sky (2003-present) out to $l \sim 1000$ with HEMT-based detectors (*Larson et al.* [2010b]). The Plank Satellite, with a mixed HEMT/ bolometer focal plane, will provide an even higher precision full sky map in the years to come.

Through the past decade, several teams, most-notably South Pole Telescope (SPT) Collaboration, have detected the Sunyaev-Zeldovich (SZ) Effect, a spectral distortion of the CMB on angular scales above $l = 2000$ that arises when when photons pass through hot ionized gas in galaxy clusters. They have successfully used this effect to discover numerous high-redshift galaxy clusters and are using them to constrain cosmology late in the universe (*Vieira et al.* [2009] and *Staniszewski et al.* [2009]). However, these measurements required much higher sensitivity than the previous-generation of CMB experiments. This was attained by switching to TES-bolometers that can be monolithically integrated into focal planes with hundreds to thousands of detectors. By contrast, the old-generation cameras had less than 100 detectors each.

Finally, the cosmic microwave background's E-mode partial polarization was first detected at the μK level by DASI in 2002 (*Kovac et al.* [2002]). Since then, the terrestrial experiments QUAD and BICEP-1 have both used focal planes with tens of detectors to map E-mode polarization and construct angular power spectra with features consistent with the temperature power spectrum (*Ade et al.* [2008] and *Chiang et al.* [2010]). Over the years following the writing of this thesis, several experiments, including Polarbear, SPT-pol, BICEP-2, SPIDER, and the Keck Array will deploy with TES-bolometer focal planes. These experiments will bring the level of sensitivity used for SZ measurements to polarization measurements in an attempt to detect B-mode polarization. These experiments' detectors have lithographed transmission lines between the antennas and bolometers to integrate optical filtering into the chip. This design obviates some of the filters that can complicate beam systematics. All of these experiments will have focal planes with thousands of dual-polarized antenna-coupled bolometers.

Antenna-coupled bolometers can potentially integrate other high-frequency optics into the lines between bolometers and antenna. For example, researchers at NASA's Goddard Flight Center have investigating placing a MEMS switch in the lines to rapidly chop on-chip (*Kogut et al.* [2006]). Another new possibility is to place multiple filters behind a single antenna to partition its bandwidth between multiple bolometers. A detector with this design could be very advantagous for CMB measurements.

1.3 Motivation for Multi-color detectors

As is clear from the history of CMB measurements, the required increases in sensitivity have often come from gains in sensitivity of the focal plane. In fact, our field has witnessed more than seven orders of magnitude improvement over the past half century *Zmuidzinas* [2010]. These advancements have been achieved through either decreasing the internal noise of the detectors or increasing the optical throughput by expanding to ever larger arrays of pixels. A third way to increase sensitivity that has not been explored until recently is to increase the optical throughput of each pixel by expanding their bandwidth.

Most recent CMB experiments have used detectors that receive a relatively narrow spectral range(20%-40%) because it was not practical to receive a larger continuous bandwidth. However, the advent of lithographed antenna-coupled bolometers that integrate filtering onto the chip provides the possibility of coupling a very broadband planar antenna to a channelizer circuit. Such a circuit can partition that bandwidth into narrow frequency channels before terminating each at different bolometers. This architecture would provide a significant increase in throughput, but still allow for beams with narrow frequency channels and well controlled properties. Submillimeter astronomers are already exploring this possibility and it is not a huge leap to use these techniques in CMB measurements as well.

Future CMB-polarization measurements will likely need to remove polarized galactic foregrounds from their maps. In principle, this can be done by mapping the sky at multiple frequency channels. Most experiments plan to receive the different channels in different pixels or in separate receivers. In both cases, all but a narrow spectral range is reflected away or absorbed before the bolometer. Multi-color pixels naturally facilitate these systematic controls while maintaining a higher optical throughput.

Finally, terrestrial experiments must often contend with an unstable atmosphere that itself anisotropically absorbs and re-emits in the millimeter spectral range. To control for atmospheric fluctuations, some experiments have designed observing channels centered at 90GHz or 150GHz and then an additional channel at 200-300GHz that receives stronger loading from water than the others. While such instruments have also used different pixels in their focal planes for different channels, multi-color pixels would once again naturally help address this challenge. In fact, SuZie-II has already demonstrated Background limited millimeter observations with a small focal-plane array of four multi-color pixels (*Benson et al.* [2003]). The highest channel was used to remove atmospheric fluctuations.

1.4 Outline

Chapters 2, 3, and the first half of 4 are background material that provide context for the original work described in later chapters. The second chapter summarizes the physics behind Cosmic Microwave Background Anisotropies and quantifies the foreground challenges with which future experiments will have to contend. The third Chapter contrasts TES-bolometers to competing technologies, summarizes the theory of their operation, and describes how the bolometers used in this thesis were fabricated and read-out. The fourth chapter describes the detectors to be used in the imminent Polarbear deployment. This design was the inspiration for the sinuous-based detectors. The chapter also discusses a raytracing script we wrote to account for the curved surface of our contacting lenses over the antennas in simulations.

The centerpiece of this thesis is the sinuous antenna, which is described at great length in chapters 5 and 6. The sinuous is a dual-polarized antenna with a bandwidth of nearly two octaves. Chapter 5 describes the theory of it's operation and scale model measurements that demonstrate its valuable properties. Chapter 6 shows data from sinuous antennas coupled to TES bolometers through single band-defining filters.

Chapters 7 and 8 discuss microstrip circuits that we use to partition the antenna's bandwidth into narrow channels. Chapter 7 describes diplexer and triplexer circuits that would naturally avoid atmospheric lines in a terrestrial experiment. Measurements are presented demonstrating that the circuits work as designed when coupled to a sinuous antenna and bolometers. We also show measurements of a broad-band anti-reflection coating for the lenses above these devices. Chapter 8 describes a log-periodic channelizer design that can partition a continuous bandwidth into contiguous channels. We envision this design being used in satellite missions where our atmosphere is not a concern or in future spectroscopic experiments such SZ surveys and sub-millimeter observations of distant galaxy clusters. Both the channelizer and the antenna are log-periodic structures, which means they attain their large bandwidth from their self-similar design. We show measurements of the channelizer coupled to the sinuous and bolometers to demonstrate that it works roughly as expected.

This thesis concludes with chapter 9 that quantifies the advantages this design might hold over more traditional technology and discusses how it will be implemented into a focal plane for future experiments. Focal plane design is a common engineering challenge at all wavelengths, but most have monochromatic pixels above the sub-millimeter. However, both the radio-astronomy and sub-millimeter have experimented with multichroic arrays, and this chapter explains the considerations associated with this design. This chapter also discusses the primary unresolved issue with this technology: forming symmetric beams in pixels with more than a single filter. We mention a candidate balun design that should help balance the arms and produce the desired circular beams at all wavelengths.