Point Source Analysis, Hardware Development, and Focal Plane Characterization for the South Pole Telescope

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Point source analysis, hardware development, and focal plane characterization for the South Pole Telescope

by

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written by Wendeline Bray Everett
has been approved for the Department of Astrophysics and Planetary Science

Prof. Nils Halverson

Prof.

Prof.

Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Everett, Wendeline Bray (Ph.D., Astrophysics and Planetary Science)

Point source analysis, hardware development, and focal plane characterization for the South Pole Telescope

Thesis directed by Prof. Nils Halverson

The South Pole Telescope is a millimeter-wavelength telescope with a 10-m primary aperture, located at the geographic South Pole, Antarctica, designed to measure faint anisotropies in the Cosmic Microwave Background (CMB) with high sensitivity. Since the telescope’s deployment in 2007, three different multichroic cameras have been installed and undertaken observations: SPT-SZ (2008–2011), SPTpol (2012–2016), and SPT-3G (2017–current). In this thesis, we present a catalog and number statistics of 4841 compact, emissive sources detected in the 2500-square-degree SPT-SZ sky survey, representing the third and final compact source catalog release from SPT-SZ. Point sources bright at millimeter wavelengths fall generally into two types of physical objects, which can be separated in the SPT-SZ data using their measured spectral behavior in the SPT-SZ bands: AGN, observable via synchrotron radiation, and dusty star-forming galaxies, often undetectable in optical wavelengths but bright in millimeter wavelengths due to thermal emission from dust. Millimeter wavelengths are particularly powerful for detecting high redshift dusty galaxies, as their flux benefits from negative K-correction with increasing redshift. For large-area surveys probing the brightest and rarest objects, many of these sources are known to be gravitationally lensed, providing a powerful probe of these high redshift objects. We also present work undertaken to aid in deployment of a new, polarization-sensitive camera for the SPT, SPT-3G, with the goal of increasing the number of detectors in the focal plane to of order 15,000, an order of magnitude increase relative to the previous camera, SPTpol. We detail methods employed prior to deployment to characterize bolometer performance at CU Boulder both to inform the development of detector fabrication and predict the performance of the deployed focal plane for SPT-3G. We also overview bolometer parameters, as well as expected and achieved performance of the focal planes deployed.
in the first and second years of SPT-3G operation. Currently in its third year of operation, SPT-3G
is in the midst of undertaking a five year survey of 1500 square degrees of sky area, expected to
map to a depth of 3, 2, 9 $\mu$K-arcmin in temperature at 95, 150, 220 GHz, respectively, and a factor
of $\sqrt{2}$ higher in polarization.
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Working on SPT began as a lucky chance for me, I was selected for an REU program at the University of Chicago in the summer after my sophomore year of undergraduate, with Dr. John Carlstrom as my advisor. After graduating from undergrad, I returned to Chicago to work on SPT for another year, which in turn made my decision to pursue working on SPT in graduate school an easy one. Through eight years of graduate school, including three trips to the South Pole, it has been an enormous honor to work beside and learn from all the members of the SPT collaboration, who have shaped me into the scientist that I am, and have provided me constant motivation and example for the scientist I strive to be. Especially large thanks to my advisor, Dr. Nils Halverson for so many years of support, guidance, and encouragement.

Finally, huge thanks to my family, and particularly my parents, who instilled in me from a young age a drive to pursue my passions without hesitation.

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Three SPT sources appear to be cross-matched with IRAS objects with comparable 12 \( \mu \text{m} \) flux as the stars but are not identified as stars. In the case of two of these objects, they appear to be false associations due to blends of unrelated objects along the line of sight. In the case of the third, it appears to be a repeat cross-match with the IRAS detection associated with V* RZ Sgr, which may be due to superposition of unrelated objects or repeat detections of V* RZ Sgr, measured to have an extended circumstellar shell in IRAS at 60 \( \mu \text{m} \). (Young et al., 1993).

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5.4 Left: Stacked histograms of measured $T_c$ for optically-coupled bolometers in the first-year focal plane, separated by wafer. Plot from Everett et al. (2018). Right: Same as left but shown for dark-only bolometers.

5.5 Top left: Stacked histograms separating by wafer of measured normal resistance measured from $R(T)$ in-situ on the SPT-3G receiver during characterization of the first-year focal plane. Top right: Same as left but showing measured parasitic resistance. Bottom: Same as upper right but coloring by frequency band. All three plots are from Everett et al. (2018).

5.6 Top panels: Stacked histograms of measured $P_{sat}$ for optically-coupled bolometers for wafers deployed in the first year of SPT-3G, separated by wafer and band. Vertical lines show median dark $P_{sat}$ per wafer and band. From Everett et al. (2018).

5.7 Histograms of measured $P_{sat}$ per band and per wafer for wafers W172, W174, W176, W177, and W180 deployed in the second year of SPT-3G. Separate histograms are plotted for optically-coupled bolometers compared with dark bolometers, where the difference in $P_{sat}$ provides a measurement of the optical power present on the focal plane. $P_{sats}$ are calculated in this plot with no correction for $R_p$.

5.8 Histograms of measured $P_{sat}$ per band and per wafer for wafers W181, W187, W188, W201, and W203 deployed in the second year of SPT-3G, separating by optically-coupled compared with dark bolometers. $P_{sats}$ are calculated in this plot with no correction for $R_p$. 

5.9 Histograms of measured $R_n$ per band and per wafer for wafers W172, W174, W176, W177, and W180 deployed in the second year of SPT-3G. Separate histograms for optically-coupled bolometers are compared with dark bolometers as a cross-check, as we expect the two groups to show no significant difference in $R_n$. $R_n$s are shown in this plot with no correction for $R_p$ and no correction for the cold hardware transfer function, which has been shown to cause the bimodality in measured $R_n$ for 220 GHz bolometers due to differences in LCR compared with CLR ordering in the DfMUX circuit (Dutcher et al., 2018).

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5.11 Optical loading measurements for a single wafer deployed in the first year of SPT-3G, from per-bolometers comparisons of optically-loaded $P_{sat}$ values measured in the SPT-3G receiver at Pole with dark $P_{sat}$ measurements taken in a dark configuration in a northern cryostat prior to deployment. Top left: plotting per-bolometer dark and optical measured $P_{sat}$ as well as $\Delta P_{sat} = P_{sat,dark} - P_{sat,opt}$ as a function of bias frequency in the LC comb. The other three panels show histograms for 95, 150, and 220GHz of dark, optical, and delta $P_{sat}$.

5.12 Histograms for all wafers in the second-year focal plane split per band of $\Delta P_{sat}$ taken from subtracting the median measured $P_{sat}$ for optically-coupled dark bolometers for a particular wafer and band from the $P_{sat}$ measured for each dark bolometer. Because each wafer-band combination will only have a maximum possible of roughly 10-15 dark bolometers, the number statistics for this measurement are low.

5.13 Continued on next page
5.13 Optical loading for three wafers deployed in the second year focal plane of SPT-3G calculated by comparisons of $P_{\text{sat}}$ for optically-coupled bolometers in situ in the SPT-3G receiver with measurements of dark $P_{\text{sat}}$ for the same bolometers taken during testing in a dark configuration in a northern cryostat prior to deployment. Left panels: plotting per-bolometer dark and optical measured $P_{\text{sat}}$ as well as $\Delta P_{\text{sat}} = P_{\text{sat, dark}} - P_{\text{sat, opt}}$ as a function of bias frequency in the LC comb. Right panels: histograms of median per-bolometer delta $P_{\text{sat}}$, separated by band. The optically-loaded $P_{\text{sat}}$ measurements were drawn from single full-array tuning of the SPT-3G array, and therefore the Pole $P_{\text{sat}}$ values are presented without a measured error bar. The errors on the dark $P_{\text{sat}}$ data are taken from uncertainty in fitting the $P_{\text{sat}}(T_{\text{bath}})$ function in the $G$ measurement.

5.14 Histograms of intrinsic TES loop gain measured from data taken in a dark testing configuration prior to first-year deployment and calculated using $\mathcal{L} = \frac{\alpha P_{\text{elec}}}{G T_c}$. For reference, histograms of each of the four quantities that enter the loop gain calculation are also shown, although the loop gain calculation is done on a per-bolometer basis.

5.15 Histograms of signal-to-noise to the chopped, thermal calibrator source during measurements of $\tau_{\text{th, eff}}$ as a function of depth in the transition.

5.16 Measured effective thermal time constants for wafers W172, W174, W176, W177, W180 as a function of depth in the transition. Here time constants are measured via optical response to a chopped thermal source in situ in the SPT-3G receiver.

5.17 Measured effective thermal time constants for wafers W181, W187, W188, W201, W203 as a function of depth in the transition.
5.18 Improvement in median full-array overbiased noise level between first and second years of SPT-3G, with the primary improvement due to reduced current leakage from replacement of the high-input-inductance SQUIDs in the first year with newly-fabricated lower-input-inductance SQUIDs in the second year. Figure from (Bender et al., 2018).

5.19 Noise measured on the second-year focal plane in the overbiased state for a set of repeated full-array tunings taken over the course of roughly 10 days in February, 2018. Colors correspond to each wafer, which have been separated along the horizontal axis purely for visualization. Each point corresponds to a single LC readout comb, where the size of the point is scaled by the number of bolometers that were operational on that comb during a given full-array tuning.

A.1 Cold hardware readout mappings between LC channel and pixel for the focal plane deployed in the first-year for SPT-3G.

A.2 Cold hardware readout mappings between LC channel and pixel for the focal plane deployed in the second-year for SPT-3G.
Chapter 1

Introduction to SPT

The South Pole Telescope (SPT) is a 10-m millimeter-wavelength telescope located at the NSF Amundsen-Scott South Pole Station in Antarctica. The telescope was designed for mapping low-contrast sources with high sensitivity, such as the faint anisotropies in the Cosmic Microwave Background (CMB), in frequencies $95 - 220\ \text{GHz} \ (1.4 - 3.2\ \text{mm})$, with a roughly 1-arcmin angular resolution. The SPT telescope employs an off-axis Gregorian design to achieve a large diffraction-limited field of view, unobstructed optics, and low scattering [Padin et al., 2008; Ruhl et al., 2004; Carlstrom et al., 2011; Benson et al., 2014]. SPT’s location at the South Pole is one of the premier developed sites on the planet for mm-wavelength observations, due to relatively high altitude, low, stable levels of water vapor in the atmosphere [Bussmann et al., 2005], and a six-month night of stable observing conditions.

1.1 Science Motivation

With high angular resolution and multichroic cameras, SPT provides a unique, strong lever arm on the advancement of science goals in mapping temperature and polarization anisotropies in the CMB, as well as other high-angular-resolution science objectives in CMB observations and mm-wavelength astrophysics. Early in the universe’s history, just after the Big Bang, the universe was extremely dense and hot, resulting in the matter field being a fully-ionized plasma where the mean free path for photon scattering was small and therefore the radiation coupled strongly with the matter. As the universe expanded, it cooled, and roughly 400,000 years after the Big Bang (at
The universe cooled sufficiently for neutral atoms to form and the photons decoupled from the matter. These photons, now significantly redshifted to a blackbody temperature of 2.73 K, are observed in the current epoch as the CMB, and provide a snapshot of this moment, referred to as “recombination,” or the “surface of last scattering,” the last moment the photons interacted with the primordial matter field. Although the CMB is a highly uniform blackbody, small anisotropies at a level of $10^{-5}$ in temperature and $10^{-6}$ in polarization result from interactions with the plasma at the surface of last scattering. In addition, CMB photons traveling from the surface of last scattering to the point of observation in the current day, pass along lines of sight through the matter field of collapsed structure in the Universe, which also causes anisotropies in the CMB due to gravitational lensing of CMB photons.

Prior to recombination, acoustic oscillations in the plasma set up by gravitational attraction and counteracted by radiation pressure caused density perturbations in the matter which were imparted to the photon field causing temperature anisotropies in the photon field. The angular size and strength of the acoustic oscillations was sensitive to the geometric curvature of spacetime as well as the relative densities of baryonic and dark matter as well as radiation, and therefore measurements of the power spectrum of temperature anisotropies have proved to be a powerful probe of constraining cosmology (Hu & Dodelson, 2002). Local temperature quadrupoles also resulted in linear polarization of the photon field via Thomson scattering between the photons and free electrons in the ionized plasma. Any polarization field can be deconstructed into E and B modes, where the E modes represents the gradient, or “curl-free,” scalar modes, and B modes represent the “curl,” or tensor modes. Density perturbations via Thomson scattering can physically only generate E modes and not B modes. However, B modes are expected to be created in the universe through two different possible mechanisms. First, it’s theorized that if a period of rapid expansion, known as inflation, occurred immediately following the Big Bang, gravitational waves during inflation would have imparted a B-mode signal into the polarization spectrum of the CMB, which should peak at large angular scales with an amplitude expected to depend on the energy scale of inflation (Abazajian et al., 2015). Second, as CMB propagates through regions with collapsed
matter in between the surface of last scattering and its observation, gravitational lensing will also distort primordial E modes into B modes, known as “lensing” B modes, which are stronger in amplitude at small angular scales and may dominate the primordial B modes.

The combination of small-aperture full-sky CMB observations from space-based telescopes such as WMAP (Hinshaw et al., 2013) and Planck (Planck Collaboration et al., 2018) with large-aperture, and therefore fine-angular-resolution, ground-based telescopes such as ACTpol (Louis et al., 2017), and SPT/SPTpol (Henning et al., 2018) have made tremendous strides in mapping both temperature and E-mode polarization anisotropies from large angular scales to small, far into the damping tail, where acoustic oscillations were smoothed during recombination by the diffusion of photons from the plasma. An overview of the current state of observations is shown in Figure 1.1. Lensing B modes, with a signal several orders of magnitude weaker than the E modes, have been detected by instruments like BICEP2/Keck (BICEP2 Collaboration et al., 2016), POLARBEAR (POLARBEAR Collaboration et al., 2017), and SPTpol (Keisler et al., 2015), but with much lower signal-to-noise than the E-mode spectrum. A confirmed discovery of primordial B modes from inflation has yet to be made and more information is needed to discern how much of the measured signal is due to inflationary B modes and how much is due to possible foreground contamination. Mapping the CMB in a broader range of frequency bands is essential for enabling the separation of foregrounds from CMB signals since the two will have different spectral behavior.

Most ground-based instruments designed to measure B-mode polarization anisotropies take one of two approaches: small aperture, such as BICEP2 and Keck, and large-aperture, such as SPT, ACT, and POLARBEAR. Since the power spectrum of inflationary B modes is expected to peak at large angular scales, a telescope with a small aperture and optimized for possible systematics in extremely low-contrast observations can be advantageous. However, small-aperture telescopes will have little sensitivity to lensing B modes, and therefore may not be able to disentangle the two signals without external datasets. Large aperture telescopes may not be as optimal for detecting inflationary B modes due to the larger potential for systematics, but will be able to target small-angular-scale science, including lensing B modes as well as other small-angular-scale CMB and
millimeter-wavelength science targets.

SPT is well-positioned to map lensing B-modes with high precision out to small angular scales. Since lensing B modes map the influence of all collapsed matter along the line of sight from the surface of last scattering, measurements of the lensing B-mode power spectrum place constraints on the sum of neutrino masses and the expected number of light relativistic relics (Abazajian et al., 2016). Forecasts for SPT-3G achievable map depths indicate that SPT-3G combined with Planck and eBOSS (Dawson et al., 2016), may yield constraints on the sum of neutrino masses \( \sigma(\Sigma m_\nu) \lesssim 0.1 \) eV, potentially allowing for discerning between different hierarchies in neutrino mass (Benson et al., 2014; Abazajian et al., 2016). Furthermore, measurements of lensing B modes will enable SPT to separate or “de-lens” the lensing B mode signal from measurements of inflationary B modes, either in SPT data alone or in coordinated observations with BICEP2/Keck, which are currently mapping the same patch of sky as SPT-3G. Figure 1.1 shows forecasts for SPT-3G measurements of temperature, E-, and B-mode power spectra using expected map depths of 3, 2, 9 \( \mu \)K-arcmin in temperature at 95, 150, and 220 GHz, respectively (with polarization depths being \( \sqrt{2} \) higher) in a 1500 square-degree patch observed for five years (2018-2023) (Bender et al., 2018).

In addition to power spectrum measurements, SPT’s 1-arcmin beam and large-area surveys have and will continue to enable the pursuit of other small-angular-scale science. Surveys from SPT-SZ have discovered hundreds of galaxy clusters (Bleem et al., 2015), and SPT-3G is projected to discover thousands more (Benson et al., 2014). Galaxy clusters are detectable in CMB sky maps via the thermal Sunyaev-Zel’dovich Effect (Sunyaev & Zel’dovich, 1972), where CMB photons receive an energy boost via inverse Compton scattering off higher-energy electrons as the photon passes through the hot intracluster medium of a galaxy cluster. The CMB spectrum is shifted to higher frequencies by passing through the intracluster medium, resulting in flux decrements at the line-of-sight locations of the clusters in CMB maps at frequencies below 220 GHz, the null of the spectral distortion. SPT-3G is projected to observe to noise levels roughly 12, 8, and 7 times lower relative to SPT-SZ, although with a current target field area somewhat smaller than the SPT-SZ field. The SPT-3G survey will therefore enable detection of lower-mass clusters and therefore detection of
Figure 1.1: Current state of temperature and polarization CMB power spectrum measurements as well as forecasts for SPT-3G based on first- and preliminary second-year performance. Figure from Bender et al. (2018).

clusters out to higher redshifts. As the most massive collapsed structures in the universe, galaxy clusters provide a sensitive probe on the growth of structure and nature of dark energy, and the strength of the SPT-3G survey for cosmological implications will be augmented by overlapping coverage with the optical Dark Energy Survey (DES) (Wu et al., 2010), which is anticipated to measure tens of thousands of clusters and completed observations in January, 2019.

SPT has also demonstrated its capability to advance millimeter-wavelength astrophysics and has released two catalogs of compact, emissive sources, and Chapter 2 presents the third and final catalog release from the SPT-SZ 2500 square-degree survey. Compact, emissive sources observable in millimeter wavelengths fall generally into two categories of physical object: AGN and dusty star-forming galaxies. Large-area mm-wavelength surveys target generally mm-bright objects and provide a complement to all-sky radio surveys for AGN and early surveys of dusty galaxies that focused on small-sky-areas targeting faint sources (Holland et al., 1999). The Planck satellite has
mapped all-sky coverage in nine bands from 30 - 857 GHz and released the Planck Catalog of Compact Sources (Planck Collaboration et al., 2016a). As a space-based instrument, Planck has a relatively small 1.5-m aperture and therefore relatively large beam sizes meaning the Planck catalog probes to noise floors roughly an order of magnitude or higher than SPT (see Figure 1 of Planck Collaboration et al. (2016a)). With projected noise floors for a five-year survey with SPT-3G 12, 8, and 7 times lower than those of SPT-SZ, we expect that SPT-3G will find tens of thousands of compact sources and begin to overlap the flux ranges of extremely-faint populations of sources originally probed in pencil-beam surveys.

1.2 SPT History

Since the telescope’s construction in 2007, three different cameras have been installed and undertaken observations to map the primary and secondary anisotropies of the CMB. All three cameras utilized the same 10-m primary mirror but used different secondary optics. The first camera, SPT-SZ, observed from 2008-2011 with the main data product being a 2500-square-degree survey of CMB temperature anisotropies, observed in three frequency bands centered at 95, 150, and 220 GHz and mapped to a noise depth of approximately 36, 16, and 62 \( \mu \text{K-arcmin} \) in 95, 150, and 220 GHz, respectively (where K refer to equivalent temperature fluctuations in a CMB background, a 2.73 K blackbody) (Benson et al., 2014). The camera contained a 960-pixel array of transition-edge-sensor (TES) bolometers, coupled to the sky using feed-horn arrays. The pixels were arranged on the focal plane into six triangular wedges forming a hexagon, with each wedge sensitive in a single band. The band edges were chosen so as to overlap with windows of high atmospheric transmission and were defined on the low-frequency side using circular waveguide coupled to each bolometer and on the high-frequency side by low-pass metal mesh filters attached above each wedge (Schaffer et al., 2011). SPT-SZ utilized a cold secondary mirror, cooled to 4K, and the combined optics allowed for a simultaneous diffraction-limited field of view of roughly 1 deg. The detectors were read out using frequency-domain multiplexing (DfMUX), using a multiplexing factor of 8. The initial science goal of the 2500-square-degree survey was a large-area, nearly-redshift-
independent blind search for galaxy clusters using the Sunyaev-Zel’dovich effect, but the data has subsequently been used for a wide array of scientific applications, including deriving constraints on cosmology from measurements of the temperature power spectrum of the CMB, and blind surveys for compact, extragalactic sources, which motivate studies of the astrophysics of radio sources as well as high-redshift star-forming galaxies.

The second camera on SPT, SPTpol, was installed in the austral summer of 2011-2012 and observed the sky from 2012-2016. The SPTpol focal plane contained 1536 polarization-sensitive, feedhorn-coupled TES bolometers in two frequency bands: 95 and 150 GHz. Similar to SPT-SZ, the different frequency bands were separated into different pixels and occupied distinct locations on the focal plane, and the same, cold secondary mirror was utilized. The telescope was modified to reduce ground pickup by adding a 1-m guard ring around the primary mirror as well as side shields that extend from the edges of the guard ring to the end of the boom arm holding the camera (Henning et al., 2018). The SPTpol instrument was used to map primarily two fields: a 100 square-degree field and a 500 square-degree field each mapped to a depth at 150 GHz of roughly 9.4 $\mu$K-arcmin.

In the austral summer of 2016-2017, the third-generation camera, SPT-3G, was installed on SPT, with the goal of improving the mapping speed relative to SPTpol by a factor of 20 (Benson et al., 2014). Because TES bolometers have reached a stage of development where single bolometer noise performance is now limited by the arrival statistics of the photons being measured (“background-limited”), the only way to improve mapping speed is by increasing the number of pixels on the sky. The goal of SPT-3G is to increase the detector count to ~15,000, roughly an order of magnitude increase relative to SPTpol (Benson et al., 2014). Three main improvements have been implemented in order to accommodate the huge increase in detector count: 1) Each pixel for SPT-3G is multichroic as well as dual-polarization-sensitive. 2) The optics chain of the receiver has been redesigned to enhance the diffraction-limited area available on the focal plane. 3) The DfMUX multiplexing factor has been increased by more than a factor of 5, from 12x for SPTpol to 68x for SPT-3G. To enable multichroic sensitivity, each pixel employs a broad-band sinuous antenna coupled to the sky using a beam-defining hemispherical, anti-reflection-coated alumina
lenslet. Bands are defined using in-line three-pole quasi-lumped-element triplexer filters, making each pixel sensitive in two polarizations and three bands, centered at 95, 150, and 220 GHz, read out by six TES bolometers. Also to assist with maximizing the detector count on the sky, the optics for the SPT-3G receiver were redesigned to optimize the focal plane field-of-view. The primary mirror along with 1-m guard ring have been maintained, and we illuminate the same 8 meters of the primary, as used for SPT-SZ and SPTpol. The cryogenic secondary mirror has been replaced with a larger ambient-temperature secondary, which couples light through three 720-mm diameter alumina lenses cooled to 4-5 K in an “optics cryostat” mounted on the front of the detector receiver. The new secondary optics enlarge the field-of-view of the focal plane to 1.9 degrees (Anderson et al., 2018). The current planned survey strategy for SPT-3G is to observe a 1500-square-degree patch of sky for five years, 2018-2023, resulting in a map depth of 3, 2, 9 $\mu$K-arcmin in temperature at 95, 150, and 220 GHz, respectively (with polarization depths being $\sqrt{2}$ higher) (Bender et al., 2018).

1.3 Thesis Organization

This thesis is organized around three main topics: 1) Methods and results from the 2500 square-degree point sources survey using data taken with the first-generation camera on the South Pole Telescope (SPT), SPT-SZ, from 2008-2011. 2) Laboratory characterization of detectors designed for the third-generation camera for SPT, SPT-3G. 3) Post-deployment characterization of the detector properties and performance of the first- and second-year focal planes for SPT-3G.

To overview my contributions as described in this thesis, the analysis pipeline used for point source extraction from SPT-SZ maps was developed by two previous papers, Vieira et al. (2010) and Mocanu et al. (2013), which I then worked to adapt to suit the needs of the full 2500-square-degree survey. For SPT-3G testing and deployment, I undertook the design of the array-level wiring for SPT-3G detector wafers, based on design principles from POLARBEAR detector wafers. I undertook SPT-3G bolometer characterization at CU Boulder and also resonator testing at NIST. I assisted with a pre-deployment hardware test-build and deployed to the South Pole three times, first during an SPTpol summer, and twice during the first- and second-year deployments of SPT-3G.
In the first two years of SPT-3G deployment, I worked predominantly on array characterization, daily monitoring of array yield and stability, and low-level instrument diagnostics and systematics.

Chapter 2 is drawn from the draft of a paper in preparation, Everett et al., 2019, and bolometer characterization for the first-year focal plane of SPT-3G is drawn from a published conference proceedings, Everett et al. (2018).
2.1 Introduction

The South Pole Telescope (SPT) is a 10-m millimeter-wavelength telescope which has provided an immensely rich set of survey data. From 2008 - 2011, the SPT was used to conduct a 2500-square-degree survey of the southern sky in three bands centered at 95, 150, and 220 GHz with arcminute resolution. While the primary science goal of this survey, referred to as the SPT-SZ survey, was a search for galaxy clusters using the Sunyaev-Zel’dovich effect, the dataset is also ideal for finding compact, extragalactic sources. At 2500 square degrees and arcminute resolution, the full SPT-SZ survey provides an unprecedented lever arm on the statistics of these sources at moderately bright fluxes. The multifrequency nature of the dataset further provides the opportunity for population separation based on spectral characteristics of different types of sources.

Broadly speaking, the emission from extragalactic sources at millimeter (mm) wavelengths produces bright peaks at small angular scales with spectra that fall into two categories: sources whose flux increases with frequency, and sources whose flux is either nearly constant or decreasing with frequency. Flat- or falling-spectrum sources are consistent with active galactic nuclei (AGN), where the source of the flux is from acceleration of relativistic charged particles producing synchrotron radiation. Rising-spectrum sources are consistent with thermal emission from dusty star-forming galaxies (DSFGs), which are often dust-obscured in the optical, making the millimeter/submillimeter particularly useful for identifying and observing them.
Historically, the synchrotron population has been well-studied at radio wavelengths (a review of the current understanding of radio source populations from millimeter and radio surveys can be found in De Zotti et al. (2010)). The spectra of radio sources are generally characterized by a power law relating source flux, $S$, to frequency, $\nu$: $S \propto \nu^\alpha$. AGN-fueled radio sources can be roughly separated into two populations: those characterized as flat-spectrum sources with $\alpha > -0.5$ and those as steep-spectrum sources with $\alpha < -0.5$. In the currently accepted “unified model” (see De Zotti et al. (2010) for references), these two populations are actually the same type of physical object whose spectral appearance depends on the orientation of the observer relative to the axis of the characteristic jets emerging from the central black hole. In side-on observations relative to the jets, the optically-thin lobes create a steep component of the spectrum at radio frequencies, and the central black hole engine is obscured by the dusty accretion torus. For sight lines along the axis of the jet, the object appears as a flat-spectrum source also referred to as a blazar. Flat-spectrum objects can be divided further into BL Lacs and Flat Spectrum Radio Quasars (FSRQs), distinguished mainly by the presence of strong emission lines for FSRQs as compared with the featureless spectrum in the optical for BL Lac objects. This orientation allows a view of the base of the jet, the luminosity of which is subject to Doppler-boosting due to the high speed of the jet along the line of sight, and the appearance of flatness is caused by the superposition of multiple components of the jet which can peak in a relatively broad range of frequencies due to self-absorption of the components. This often causes the spectrum in reality to be more complicated than a simple power law. Steep-spectrum sources are typically extended, given that the emission is due to the radio jets, whereas flat-spectrum sources appear generally as compact, often unresolved even at arc-second resolution. Flat-spectrum sources are also known to be quite variable due to changes in the jet structure, growth of new components, etc, and these variations can occur on time scales from hours to years (De Zotti et al., 2010). This is often regarded as a characteristic of young objects which are rapidly evolving. Synchrotron self-absorption in compact regions can also result in sources that peak in the gigahertz range, termed GHz Peaked Spectrum (GPS) sources, which may be linked to late phases of AGN evolution characterized by inefficient accretion (De
The complexity of different processes involved in synchrotron sources makes it hard to classify their spectra effectively, but to simplest order, splitting into flat- vs. steep-index is still useful.

The characterization of dusty sources has progressed incredibly as mm- and submm-wave surveys have grown in size and resolving power in the last several decades. In the 1980s, the all-sky infra-red satellite IRAS discovered a population of 20,000 extra-galactic sources (Sanders & Mirabel, 1996). Most of these were at relatively low redshifts, less than approximately 0.3, with emission dominated by dust, and were classified as Luminous Infra-Red (IR) Galaxies (LIRGs) \((10^{11} < L_{IR} < 10^{12} \, L_\odot)\) and Ultraluminous IR galaxies (ULIRGs) \((10^{12} < L_{IR} < 10^{13} \, L_\odot)\), compared with typical spiral galaxies with luminosities around \(10^{10} \, L_\odot\) (Blain et al., 2002). Beginning in the late 1990s, observations with the Submillimeter Common-User Bolometer Array (SCUBA) instrument on the JCMT (Holland et al., 1999), at 450 and 850\(\mu m\), and later complemented by observations including the Max-Planck Millimeter Bolometer Array (MAMBO, Kreysa et al. (1998)) at 1.25 mm on the 30-m IRAM telescope, Bolocam (1.1mm, on the CSO, Glenn et al. (1998)), AzTEC (1.1mm, on JCMT, ASTE, and then the LMT, Wilson et al. (2008)), LABOCA (870\(\mu m\), on APEX, Weiss et al. (2009)), discovered a high-redshift component of the DSFG population, which were termed Submillimeter Galaxies (SMGs). These early surveys of SMGs covered relatively small areas, only a few square degrees at most, and as a result traced out populations of relatively dim sources. The advent of large-area and multi-band surveys allowed detections probing the brightest and rarest SMGs. This included the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST, Pascale et al. (2008)), which surveyed 10 square degrees at 250, 350, and 500\(\mu m\), the South Pole Telescope (SPT), which released its first survey from 100 square degrees in two bands (1.4 and 2.0mm) in 2010 (Vieira et al., 2010) and later 771 square degrees in three bands (1.4, 2.0, and 3.2 mm) in 2013 (Mocanu et al., 2013), and results from two surveys using the SPIRE camera at 250, 350, and 500\(\mu m\) on the Herschel Space Observatory: the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS, Eales et al. (2010)) and the Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al. (2010)), which have been expanded to cover areas up to 600 square
degrees Negrello et al. (2017); Nayyeri et al. (2016). The first released compact-source survey from the SPT, Vieira et al. (2010), detected a population of emissive sources that did not have counterparts in IRAS catalogues, meaning that these sources were not low-redshift U/LIRGs, and therefore were most likely at high redshift. Follow-up observations confirmed this, and indicated that they were indeed SMGs. Furthermore, follow-up observations of sources detected in early Herschel and SPT surveys using telescopes such as ALMA and the Submillimeter Array (SMA) have indicated that these objects are often detectable because their fluxes have been magnified by strong gravitational lensing by a massive object along the line of sight (Negrello et al., 2010; Vieira et al., 2013).

Observations of individual objects have further been complemented by a developing knowledge of the Cosmic Infrared Background (CIB), first detected by the COBE satellite in 1996 (Puget et al., 1996). It is now understood that the CIB is made up of the light from unresolved infrared galaxies, and the CIB contains about half of all the energy emitted by extragalactic sources (Lagache et al., 2005), under the scenario that light in the optical and UV from star-forming regions and dust-enshrouded galaxies are absorbed by dust and reradiated in the infrared.

Since these high redshift dusty galaxies are expected to trace out the bulk of cosmic star formation, and are obscured by dust in optical wavelengths, observations in (sub)millimeter wavelengths become necessary. (Sub)millimeter observations are also particularly powerful because the flux density of most sources benefits from strong negative K-correction (Blain, 1996). Since we observe these sources on the steeply-rising Rayleigh-Jeans side of the spectrum, as redshift increases, one observes an intrinsically brighter part of the spectrum. For observations at wavelengths longer than 500 µm, and for galaxies at $z > 1$, the intrinsic brightening of the source with frequency balances out the dimming due to increasing distance, and the flux density remains constant, or even grows for mm wavelengths. This allows a mm-/submm-band telescope to probe the same type of object detectable at $z \sim 0.5$ out to $z \sim 10$ (Blain et al., 2002; Blain & Longair, 1993).

Casey et al. (2014) provides a review of the current state of observations and understanding of DSFGs at high redshift, including SMGs, the best-characterized population of high-$z$ DSFGs.
Current observations of SMGs indicate that they have extremely high star formation rates, on order of hundreds to thousands of $M_{\odot}\text{yr}^{-1}$ as well as large stellar masses, $>10^{10} M_{\odot}$ (Casey et al., 2019), with luminosities comparable to local ULIRGs, $>10^{12} L_{\odot}$ (Simpson et al., 2014). While DSFGs are quite rare at low redshifts, their spatial density is 1000x higher at $z \sim 2$, although they are still rare even at high redshifts relative to other types of galaxies (such as Lyman Break Galaxies), making them difficult to detect in small-area surveys (Casey et al., 2019). Their redshift distribution peaks between $1 < z < 3$, though this is dependent on the wavelength of observation (longer wavelengths probe higher redshift sources) and on the availability of spectroscopic follow-up observations (Casey et al., 2014), and constraining the population of SMGs at redshifts greater than 3 is complicated by their scarcity and difficulty in accurately measuring redshifts (Casey et al., 2019). Although the strong negative K-correction makes high-$z$ SMGs bright enough for discovery, it also makes accurately determining the redshift more difficult (Casey et al., 2019). Observations indicate that, like local ULIRGs, the high rates of star-formation may be triggered by major mergers (Simpson et al., 2014), or SMGs may be gas-rich massive disk galaxies undergoing high star-formation (Casey et al., 2019). Dynamical timescales, constrained via observations of a few high-$z$ objects, but mostly from studies of ULIRGs, are thought to be on order 100-200 Myr, much shorter than for normal type galaxies. Although these time scales are longer than for local ULIRGs, this is likely because SMGs have elevated gas fractions (Casey et al., 2014). High star-formation rates and relatively short dynamical times indicate that SMGs are undergoing a starburst phase and may therefore be the progenitors of local massive ellipticals (see Simpson et al. (2014) for references). However, it should be noted that given the observational cost of follow-up observations, detailed understanding of SMGs has generally been limited to observations of the brightest and most extreme objects, and the relationship and evolution of high-$z$ DSFGs as a whole relative to the “main sequence” of normal galaxies is not well-understood (Casey et al., 2014). Understanding the full range of populations of DSFGs at high redshift and therefore the cosmic history of star formation is the goal of current study, both from the direction of exploring the non-lensed population in small-area but deep observations with ALMA (Hatsukade et al., 2018), and large-area surveys observing
to increasing depth, particularly at wavelengths > 1 mm which will probe the highest redshift populations, with instruments such as SPT (Casey et al., 2019).

Detailed follow-up observations with instruments like the Atacama Large Millimeter Array (ALMA), have made tremendous strides in developing detailed understandings of high-z DSFGs; however, observations are not yet able to fully constrain detailed models of SMG SED fitting, and studies of ULIRGs and ULIRG SED templates have often been used as proxies to understand their high-redshift counterparts (Blain et al., 2002). The IR/submm/mm part of the spectral energy distribution (SED) for these galaxies is fit generally with a modified blackbody spectrum, \( S(\nu, T_d) \propto \kappa(\nu) B_\nu(\nu, T_d) \) where \( \kappa \propto \nu^\beta \) is the dust grain absorption cross section per unit mass (Bianchi, 2013), or dust emissivity, which given the lack of resolved images for SMGs, is assumed to follow a volume-averaged and therefore power-law description (Blain et al., 2002). This yields a two-parameter fit for the dust temperature, \( T_d \), and the dust emissivity spectral index, \( \beta \) (Kovács et al., 2006). While this model is not perfect, and is known, for example, to not accurately reproduce the Wien side of the spectrum (Magnelli et al., 2012), most SMG SEDs do not have enough data points to warrant more complicated models, and even within this simplified framework, \( T_d \) and \( \beta \) are degenerate (Blain et al., 2002). Best-fitting temperatures for SMGs fall in the range of 30-40 K (Kovács et al., 2006; Blain et al., 2002; Casey et al., 2014).

In this work, we present results from the full 2500 sq. degree area of the SPT-SZ survey; this analysis is an extension on the work of two previous papers: Vieira et al. (2010) (hereafter V10), and Mocanu et al. (2013) (hereafter M13), and builds on the same analysis pipeline. V10 developed the source-finding pipeline and applied it to a single field observed in 2008 in two frequencies, ra5h30dec-55. M13 expanded that analysis to 5 fields, two observed in 2008 and three in 2009 (771 square degrees in total), and added a third frequency. In this current paper, we add 1759 square degrees of previously unanalyzed data and include additional data for two fields which were re-observed in 2010 and 2011. We adjust the previous pipeline to be compatible with the goals of the full survey (full area coverage) and work to optimize elements in the pipeline chain. Sections 2.2 and 2.3 present an overview description of the data and analysis pipeline. Section 2.4
2.2 Observations

The South Pole Telescope (SPT), a 10-meter telescope designed for observations in millimeter wavelengths, is located at the geographic South Pole (Carlstrom et al., 2011). The telescope was designed to measure low-contrast sources such as CMB anisotropies with high sensitivity, and has a roughly 1-arcmin angular resolution at 150 GHz, with a 1-degree diffraction-limited field of view. The first camera for the SPT, SPT-SZ, contained a 960-pixel array of transition-edge-sensor bolometers, with sensitivity in three bands centered at 95, 150, and 220 GHz (3.2, 2.0, and 1.4 mm), with bandwidths of approximately 31, 37, and 49 GHz, respectively. The pixels on the focal plane were arranged into 6 triangular wedges with each wedge sensitive in a single band, forming a hexagon.

The SPT-SZ survey represents the culmination of four years of observations, 2008-2011, of roughly 2500 square degrees on the sky. The sky area covered spans the region in the southern hemisphere from roughly declination (decl.) -65 to -40 degrees and from right ascension (R.A.) 20$^h$ to 7$^h$. Over the duration of the survey, the composition of the receiver changed slightly. In 2008, the focal plane was composed of three 150 GHz wedges, two 220 GHz wedges, and a single 95 GHz wedge, but the 95 GHz wedge failed to produce science-quality data. For 2009, one 220 GHz wedge was swapped for another 150 GHz wedge, and the 95 GHz wedge was upgraded to an improved-quality wedge, resulting in four 150 GHz wedges, and one each of 220 GHz and 95 GHz. The composition of the focal plane then remained the same for 2009, 2010, and 2011.

The full 2500 sq. degree area was split into 19 contiguous fields which were observed independently. The characteristics of each field are presented in Table 2.1. In observing a given field, the telescope started in one corner, scanned back and forth across the sky in constant elevation and then took a step in elevation and repeated until it had covered the desired area in that field.
Scan speeds in azimuth varied between 0.25 and 0.42 deg/sec. Between observations, the telescope initial starting position was dithered to achieve uniform coverage of each field. Only data from the constant-speed portion of each scan is used in the map for that particular observation. The three 2009 fields, \texttt{ra21hdec-50}, \texttt{ra3h30dec-60}, and \texttt{ra21hdec-60}, and one 2008 field, \texttt{ra23h30dec-55}, were observed using a lead-trail scan strategy, in which the field is split into two halves, left and right. The two halves were observed independently, delayed such that due to sky rotation, the second half had drifted so that the two halves were observed over the same azimuth range. This allows for the possibility of the removal of ground-synchronous contamination. However, ground contamination in those fields was measured to be negligible, so the lead and trail portions are simply coadded in this analysis. The rest of the fields were observed using a simple scan in azimuth, except for the \texttt{ra21hdec-50} field, for which a portion of the observations used an elevation scan, where the telescope scans up and down in elevation while allowing the field to drift through the field of view in azimuth. Techniques for analyzing this field are discussed in detail in M13. The observation strategy for each field was designed to produce as close as possible a uniform-depth survey across the full area, except for two fields, \texttt{ra5h30dec-55} and \texttt{ra23h30dec-55}, both of which were observed originally in 2008 and then re-observed in either 2010 or 2011, to add data at 95 GHz which was unavailable in 2008 and nominally to observe to twice the depth of the 2008 survey in 150 GHz.

2.3 Data Reduction and Analysis

The following section describes the steps in the analysis pipeline from timestream data for individual bolometers to source catalogs. These steps include: filtering of each bolometer’s timestream data for each scan; forming a single-observation map by coadding each bolometer’s contribution to map pixels, and then forming a single map for each field by coadding all single-observation maps; constructing masks to define the high-weight regions of the fields for source-finding; developing an optimal filter to amplify the signal-to-noise for detecting compact sources; extracting sources separately for each band using a CLEAN algorithm; and finally, forming a single multi-band catalog,
<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>R.A.</th>
<th>Decl.</th>
<th>∆R.A.</th>
<th>∆Decl.</th>
<th>Eff. Area (deg$^2$)</th>
<th>No. sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA5H30DEC-55</td>
<td>2008/2011</td>
<td>82.5</td>
<td>-55.0</td>
<td>15</td>
<td>10</td>
<td>89</td>
<td>3x3</td>
</tr>
<tr>
<td>RA23H30DEC-55</td>
<td>2008/2011</td>
<td>352.5</td>
<td>-55.0</td>
<td>15</td>
<td>10</td>
<td>108</td>
<td>3x3</td>
</tr>
<tr>
<td>RA21HDEC-60</td>
<td>2009</td>
<td>315.0</td>
<td>-60.0</td>
<td>30</td>
<td>10</td>
<td>150</td>
<td>6x3</td>
</tr>
<tr>
<td>RA3H30DEC-60</td>
<td>2009</td>
<td>52.5</td>
<td>-60.0</td>
<td>45</td>
<td>10</td>
<td>225</td>
<td>8x3</td>
</tr>
<tr>
<td>RA21HDEC-50</td>
<td>2009</td>
<td>315.0</td>
<td>-50.0</td>
<td>30</td>
<td>10</td>
<td>193</td>
<td>6x3</td>
</tr>
<tr>
<td>RA4H10DEC-50</td>
<td>2010</td>
<td>62.5</td>
<td>-50.0</td>
<td>25</td>
<td>10</td>
<td>166</td>
<td>5x3</td>
</tr>
<tr>
<td>RA0H50DEC-50</td>
<td>2010</td>
<td>12.5</td>
<td>-50.0</td>
<td>25</td>
<td>10</td>
<td>152</td>
<td>5x3</td>
</tr>
<tr>
<td>RA2H30DEC-50</td>
<td>2010</td>
<td>37.5</td>
<td>-50.0</td>
<td>25</td>
<td>10</td>
<td>155</td>
<td>5x3</td>
</tr>
<tr>
<td>RA1HDEC-60</td>
<td>2010</td>
<td>15.0</td>
<td>-60.0</td>
<td>30</td>
<td>10</td>
<td>140</td>
<td>6x3</td>
</tr>
<tr>
<td>RA5H30DEC-45</td>
<td>2010</td>
<td>82.5</td>
<td>-45.0</td>
<td>15</td>
<td>10</td>
<td>105</td>
<td>3x3</td>
</tr>
<tr>
<td>RA6H30DEC-55</td>
<td>2011</td>
<td>97.5</td>
<td>-55.0</td>
<td>15</td>
<td>10</td>
<td>82</td>
<td>3x3</td>
</tr>
<tr>
<td>RA23HDEC-62.5</td>
<td>2011</td>
<td>345.0</td>
<td>-62.5</td>
<td>30</td>
<td>5</td>
<td>65</td>
<td>6x2</td>
</tr>
<tr>
<td>RA21HDEC-42.5</td>
<td>2011</td>
<td>315.0</td>
<td>-42.5</td>
<td>30</td>
<td>5</td>
<td>118</td>
<td>6x2</td>
</tr>
<tr>
<td>RA22H30DEC-55</td>
<td>2011</td>
<td>337.5</td>
<td>-55.0</td>
<td>15</td>
<td>10</td>
<td>73</td>
<td>3x3</td>
</tr>
<tr>
<td>RA23HDEC-45</td>
<td>2011</td>
<td>345.0</td>
<td>-45.0</td>
<td>30</td>
<td>10</td>
<td>221</td>
<td>6x3</td>
</tr>
<tr>
<td>RA6HDEC-62.5</td>
<td>2011</td>
<td>90.0</td>
<td>-62.5</td>
<td>30</td>
<td>5</td>
<td>65</td>
<td>6x2</td>
</tr>
<tr>
<td>RA3H30DEC-42.5</td>
<td>2011</td>
<td>52.5</td>
<td>-42.5</td>
<td>45</td>
<td>5</td>
<td>185</td>
<td>8x2</td>
</tr>
<tr>
<td>RA1HDEC-42.5</td>
<td>2011</td>
<td>15.0</td>
<td>-42.5</td>
<td>30</td>
<td>5</td>
<td>126</td>
<td>6x2</td>
</tr>
<tr>
<td>RA6H30DEC-45</td>
<td>2011</td>
<td>97.5</td>
<td>-45.0</td>
<td>15</td>
<td>10</td>
<td>112</td>
<td>3x3</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2530</td>
<td></td>
</tr>
</tbody>
</table>

Note. — Locations and sizes of the fields included in this work. For each field we give the center of the field in Right Ascension (R.A.) and Declination (Decl.), the extent of the field in Right Ascension and Declination, the number of sectors the field is divided into (see Section 2.3.3), the effective field area as defined by the apodization mask.
taking into account the effect of flux biases and overlap regions between fields.

2.3.1 Timestream Filtering and Mapmaking

The response of each detector is recorded at 100 Hz as time-ordered data (TOD) as the telescope scans across the sky. We apply a set of filters to the TOD to remove high-frequency noise above the Nyquist frequency and low frequency noise due to atmosphere. The filtering we apply in this work is very similar to that in M13. The data are low-pass filtered in Fourier space above $\ell = 37500$ to remove noise on scales smaller than the Nyquist frequency of the chosen map pixel size, 0.25 arcmin. To mitigate atmospheric noise, we apply a first-order polynomial subtraction and a high-pass filter below $\ell = 246$. Since atmospheric noise will be spatially coherent on the size scale of the detector wedges, we also remove a mean across each wedge of the receiver from all well-performing bolometers at each time step.

The filtered TOD for each bolometer are then coadded into 0.25 by 0.25 arcmin pixels by inverse-variance weighting, adding contributions from bolometers to each pixel to form a single map per observation. The weights for each bolometer are calculated from the power spectral density of each detector’s TOD in the range from 1 to 3 Hz. We use a flat-sky approximation for each field and apply an oblique Lambert equal-area projection. This choice of projection is important for source-finding because it preserves the source shape across the full area of the map. However, it also produces complications in the analysis, since the scan direction rotates with pixel location in the map. The ramifications of this are discussed in Section 2.3.3.

To make final coadded maps from all the observations, we apply several cuts (which have been previously shown to be useful for SPT data ([Schaffer et al., 2011]), based on the mean weights and mean RMS of the uniform-weight region of each single-observation map. We cut on excessively high median weights which occurs when a bolometer’s TOD has anomalously low noise. In the past, this has been shown to correspond to poor bolometer behavior, such as when detectors latch or change operating point due to shifts in the amount of loading ([Schaffer et al., 2011]). For maps with reasonably good weather conditions, the weights scale well with the RMS of the map; however,
for poor weather days, $1/f$ noise dominates the RMS and the 1-3 Hz range is no longer a good estimate of the weight that should be assigned to that bolometer. Therefore, we also perform a cut on observations where the map RMS does not scale properly with the median weight in the map. The single-observation maps that survive the cuts are coadded by inverse-variance-weighting each pixel to form a single coadded map per field and per band.

To calibrate the maps, we use both a relative and absolute calibration. The relative calibration of the TOD from one observation to the next is done through repeated observations of the galactic HII region RCW38 and reference from a thermal calibrator source installed in the bolometer optical path \cite{Schaffer2011}. The absolute calibration is determined from comparisons of the SPT power spectrum band powers to those from \cite{Planck2016} in the $\ell$ range from 682 to 1178. This results in fractional errors in temperature of 1.05%, 1.15%, and 2.24% in 95, 150, and 220 GHz, respectively.

The pointing model used for constructing maps is based on regular measurements of galactic HII regions in addition to data recorded by sensors on the telescope measuring temperature, linear displacement and tilt. To check the global astrometry, we fit for a global pointing offset per field using the positions of the brightest sources in all three bands in each field to source locations in the Australia Telescope 20 GHz (AT20G) Survey catalog \cite{Murphy2010}, which has an RMS positional accuracy of 1 arcsec. We correct the global pointing of each field center until the iterated correction is smaller than the residual scatter, and we find the RMS residual pointing scatter for the on-average 26 brightest sources in each field to be 4.3 arcsec in declination and 4.6 arcsec in R.A.*cos(declination).

### 2.3.2 Mask Construction

Each field is analyzed separately in our pipeline for extracting sources. We then cross-match the single-field catalogs at the end, accounting for places where fields overlap, to form a single catalog for the survey. Field masking is needed to exclude low signal-to-noise edges due to turn-around regions of the scan strategy and non-uniform array coverage between bands on the focal
plane. However, we also want to define masks such that we have continuous coverage of the full 2500 square-degree survey area. This requires that we define separate masks per band for each field, because different bands occupy physically offset locations in different wedges on the focal plane and therefore observe slightly offset regions on the sky. In principle, this choice only adds slightly more complicated bookkeeping for cataloging sources, since now a source detected on the edge of one field in one band could be detected in an adjacent field in a different band. To achieve continuous coverage, we also need to extend the field masks to lower signal-to-noise regions compared with M13, making the noise level within each field slightly less uniform. The masked areas for each field are shown in Figure 2.1.
Because detectors sensitive in each band occupied physically offset locations on the focal plane, the different bands observed slightly shifted areas on the sky, and in order to achieve full coverage while optimizing using the highest-weight region of each field, separate masks were used for each field for each band, meaning that for adjacent fields, a source may be detected in one field in one band and in an adjacent field in a different band.
2.3.3 Optimal Filtering for Source Extraction

Since sources we detect are expected to be unresolved by the telescope (except for nearby sources), a source in our maps should manifest in the maps as an SPT beam with the time-stream filtering applied. We can improve our signal-to-noise for detecting objects with an expected source shape using an appropriate optimal filter. The filter takes advantage of knowledge of the source shape and the noise in the region of the map where the source is located, which includes residual atmosphere, instrument noise, and the primary anisotropies of the CMB, which acts as a source of noise for the detection of compact, extragalactic sources. The first component needed in constructing the source profile is the beam, which is measured using a combination of observations of Jupiter and Venus, as well as the brightest point sources in the fields. The main lobes of the beams are measured to be well-described by Gaussian functions with FWHM of 1.7, 1.2 and 1.0 arcmin for 95, 150 and 220 GHz, respectively. The sidelobes of the beams are downweighted in the filter, and therefore are unimportant for the point source analysis pipeline. To model the source profile, we insert a beam into a noiseless map, and then reobserve the source once for each single-observation map using the characteristics of the telescope’s performance for that particular observation and the time-stream filtering. The Fourier-domain version of this source profile is used as the transfer function for our maps. All the single-observation transfer functions are then coadded into a single transfer function for the coadded map.

Following formalism set up in Tegmark & de Oliveira-Costa (1998) and Haehnelt & Tegmark (1996), to maximize the signal-to-noise of sources in the map, we filter the map using an appropriately normalized version of the signal-to-noise of the source. We apply the optimal filter, $\psi$, in the Fourier domain given by:

$$\psi = \frac{\tau^T N^{-1} \tau}{\tau^T N^{-1} \tau},$$

(2.1)

where $\tau$ is the transfer function and $N$ is the 2D noise PSD, resulting in a filtered map still in units of temperature. In addition to the source profile, we also need to characterize the noise around each source. To do this, we find the power spectral density (PSD) of the noise of the coadded map...
by averaging 100 versions of difference maps. Each difference map is constructed by multiplying a randomly-chosen half of the individual observation maps by -1 and adding them. The 2D power spectrum of the Fourier transform of each difference map are then averaged to generate a single 2D noise PSD for the coadded map. Because differencing two individual observation maps cancels out the contribution to the noise from the CMB anisotropies, we add back in a power spectrum of the primary CMB anisotropies using a model of ΛCDM with best-fit parameters from WMAP7 and the SPT from Keisler et al. (2011).

However, the construction of the optimal filter is complicated by two characteristics of the SPT data. Because of the telescope’s location at the South Pole, the scan direction is always along constant declination. This means that the effect of time-stream filtering is anisotropic in the maps, and we have essentially have an anisotropic beam. We account for the smearing of the beam in the scan direction by calculating the transfer function and applying the transfer function during source extraction. But, for point source work, we use an area-preserving projection, which causes the scan direction to rotate with respect to the axes of the pixel orientation of the maps. Therefore, our anisotropic beam in the map rotates with respect to the pixel \( x-y \) location. The second characteristic of the SPT data is that the noise in the maps varies with declination. Because the telescope scans the same distance in azimuth in the same amount of time regardless of elevation, but this distance corresponds to less physical distance at higher (more negative) declination, the result is a noise level with a gradient in declination through our maps, with slightly less noise at higher declination. To account for these two position-dependent complications, we divide up each field in a number of sectors which are small enough that an assumption of zero source rotation and noise uniformity is reasonable. We then calculate separate transfer functions and noise PSDs for each sector independently, construct a single optimal filter for each sector, and extract sources separately per sector. Further description of the process for creating these data products and their salient features can be found in the SPT 2008 data release paper (Schaffer et al., 2011). The number of sectors per field is shown in Table 2.1.

Essentially, splitting up each field into sectors is a compromise between computation time
and accuracy. We test that the sizes of our sectors are appropriate, i.e. that the measured flux of sources is unaffected by the size of the sector we choose, by applying the transfer function and noise PSD from adjacent sectors to a sector where the effects of noise and scan rotation angle are the most severe, and check that the resultant change in the fluxes of the sources in that sector are below the noise level of the sector. We also test that the noise in different sectors does not differ by more than 5%.

We found in creating and testing our optimal filter that there was residual noise due to incomplete averaging in the creation of the PSD. This resulted in excess noise in the source extraction template, resulting in excess noise in the optimally-filtered maps. To mitigate this effect, we apply a smoothing kernel to the optimal filter in the Fourier domain. To test that the strength of the filtering is optimal, we sweep through a range of kernel size while monitoring the noise. As we apply a stronger and stronger smoothing to the filter, we see that the noise level in the optimally filtered-map reduces, indicating that the excess noise being introduced by the filter is being diminished. But, applying stronger smoothing past a certain point eventually causes the noise level to once again rise, as real noise information in the PSD will begin to be cut, and the filter becomes a less realistic description of the actual signal-to-noise in the map and therefore less optimal. We take the minimum noise level as our optimized smoothing kernel size. For the test field used to optimize the filter smoothing, employing this technique reduced the noise floor in the filtered map by 10.5%, 8%, and 0.6% at 95, 150, and 220 GHz, respectively. The optimization of the filter smoothing kernel for the field RA4h10dec-50 is shown in Figure 2.2.

### 2.3.4 Source Extraction Algorithm

After optimally filtering the map, we locate and extract source fluxes by using a CLEAN algorithm [Högström 1974]. CLEANing was developed originally for radio interferometry, where uneven baseline sampling and a finite number of antennae produce incomplete sampling of the Fourier domain. In turn, this effect produces sidelobes on the beam (a so-called “dirty beam”), which is analogous to the wings on the SPT beam due to time-stream filtering. The CLEAN
Figure 2.2: Excess noise due to incomplete averaging in the difference maps that are used to generate a 2D noise PSD was mitigated by applying a smoothing kernel to the PSD. The size of smoothing kernel was optimized by increasing the amount of smoothing (corresponding to using a smaller kernel radius) while monitoring the noise floor. Initially the noise floor decreased as excess noise was removed; eventually applying a stronger and stronger smoothing, the noise floor began to increase again, corresponding to removing real signal from the PSD. The smoothing kernel size corresponding to the minimum noise floor was chosen. Kernel optimization for one field, RA4H10DEC-50, is shown.

The algorithm detects and removes sources iteratively using a template source profile, which allows for the detection of fainter sources hidden underneath the dirty-beam wings of brighter sources. The source template we employ for CLEANing takes into account that we have optimally filtered the map, however, technically this optimal filter is only optimal for a source located at the center of a sector (which is where the simulated beam was placed when calculating the transfer functions for each sector). For sources off center in the sector, this optimal filter is at a slightly incorrect rotation angle. In order to form a template for each source, $\tau'$, we rotate the source profile (which is the map space version of the transfer function, $\tau$) to the correct rotation angle for the $x$-$y$ pixel location in the sector, and then convolve it with the optimal filter for that sector (which is not
rotated). Effectively, our source template (in the Fourier domain) is given by,

$$\tau' = \psi \tau,$$  \hspace{1cm}  (2.2)

where $\psi$ is the optimal filter function. Each sector of a field has been filtered separately, so we also perform the cleaning separately per sector and then unite the catalogs of detected sources from all fields. Since sources have long wings in the scan direction due to time-stream filtering, we need to account for the possibility of false detections from the wings of sources bleeding into a sector from sources just outside the sector. We do this by defining a sector pixel mask to outline the source-finding area for each sector and a second mask which covers a larger area than this sector mask. We define the larger masks such that the extra space on the left and right sides relative to the sector mask edges will be wider than the wings on all but the very obviously brightest sources, which we check by hand if they occur at the edge of a sector. The CLEAN algorithm is applied to the area of the larger mask for each sector, but only the sources that are within the smaller sector pixel mask are saved into the catalog.

To better account for non-uniformity in noise level across each sector, we construct a scaled noise map using the weight map for each field’s coadded map. We apply the optimal filter for each sector to the inverse of the weight map, and then scale each sector’s RMS noise by the square-root of the ratio of each sector’s median weight to it’s filtered weight map. In essence, we construct a local scaled-noise map, which can be used to construct a local signal-to-noise map when combined with the optimally-filtered map. Thus, rather than assume a single noise value per sector when CLEANing, we take into account any local noise non-uniformity and CLEAN down to a locally-determined signal-to-noise threshold. The most noticeable differences resulting from the implementation of this method arise along the edges of the map, which are noisier than the RMS noise of the sectors which include these regions, and fields which were observed with a lead-trail observing strategy and have low-noise strips where the lead and trail observations overlap.

The steps of the CLEANing are as follows:

(1) Find the location of the brightest pixel in a given sector in the optimally-filtered map.
(2) Rotate the source profile for that sector by the appropriate rotation angle for that \(x\)-\(y\) pixel location, and convolve it with the optimal filter for that sector. This is the source template.

(3) Subtract the source template, scaled to the flux of the pixel and multiplied by a loop gain coefficient. The loop gain is a multiplicative factor between 0 and 1 to account for non-ideal characteristics of the CLEANing pipeline, such as imperfections in the source model, extended sources, and finite pixelization in the map. We choose a loop gain of 0.1.

(4) Find the next brightest pixel in the map and repeat the process until all pixels in the map have significance below the chosen signal-to-noise detection threshold, in this case 4.5 times the scaled RMS noise of that pixel location.

Because the CLEANing is performed with a loop gain, bright sources will be broken up into multiple brightest pixels during the CLEANing. Once the CLEANing is finished (i.e. no pixels in the map remain above the chosen significance threshold), the pixels found by the CLEAN are associated into sources using a radius of association that is brightness-dependent. All of the pixels associated with a single source are used in a centroiding process to find the source’s position. The post-CLEAN map, with all sources removed, is called a residual map, and will be used in later steps of the analysis.

After locating sources in the map, we convert from units of CMB temperature fluctuations to units of flux. Optimally filtering the map is equivalent to fitting the map with a source shape, and the value of the brightest pixel of each source can be used to calculate the integrated source flux. Specifically, we calculate the flux of each source by stacking all of the CLEAN components removed for a given source onto the residual map and taking the maximum in a cutout region. The maps are calibrated in units of CMB temperature fluctuations, so we convert to flux units using

\[
S[Jy] = T_{\text{peak}} \cdot \Delta \Omega_f \cdot 10^{26} \cdot \frac{2k_B}{c^2} \left( \frac{k_B T_{CMB}}{h} \right)^2 \frac{x^4 e^x}{(e^x - 1)^2},
\]

where \(x = h \nu / (k_B T_{CMB})\), and \(\Delta \Omega_f\) is the effective solid angle under a filtered source template,
given by

$$
\Delta \Omega_f = \left[ \int d^2 k \, \psi(k_x, k_y) \, \tau(k_x, k_y) \right]^{-1}.
$$

(2.4)

We inspect detected sources for obvious spurious detections, such as false sources created by the effect of the timstream filtering on bright galaxy clusters and spurious detections very close to extremely bright sources. We also inspect for extended sources, discussed in more detail in Section 2.4.7. Obvious false detections are trimmed; for the sake of completeness in the catalog, information on extendedness is not used to remove any sources, but is retained as a flag in the catalog.

### 2.3.5 Flux Biases and Three-band Flux Deboosting

The raw fluxes in our catalogs are subject to several biases, which must be carefully considered before the fluxes can be used for population statistics. The first is due to the fact that the underlying source number count populations are steep functions of flux. We expect the noise in the map to be Gaussian, but since there are many more dim sources than bright sources, it is much more likely that a detection at a given significance is a dim source on top of a positive noise fluctuation than a bright source on top of a negative noise fluctuation. Therefore, more sources below a significance threshold will be bumped above the threshold and detected as sources due to noise than will be bumped below, resulting in a positive flux bias which most strongly affects low signal-to-noise sources as a fraction of source flux. This bias is closely related to Eddington bias, although that term is generally applied to counts as a function of flux rather than the fluxes of individual objects (Mocanu et al., 2013). When applied to individual sources, we refer to this bias as “flux boosting” and its correction as “flux de-boosting.”

A second bias is due to the fact that we estimate source flux based on peak pixel brightness. A positive noise fluctuation near a source will pull the detected peak position away from the true position and also return a higher flux, whereas a nearby negative noise fluctuation will not have nearly as strong a corresponding opposite effect on either the returned position or flux (Austermann et al., 2010). For a significance threshold of $S/N_{\text{meas}} = 4.5$, this is a roughly 5% effect and will be less important for all higher-significance detections (see e.g. Vanderlinde et al. (2010)). We
therefore neglect this bias in this work.

Finally, a third bias arises from the fact that for sources that we detect only in one or two bands but not all three, the flux(es) for the source in the non-detected band(s) will be subject to a slight negative bias. This is due to the fact that we measure source flux in the non-detection band(s) using a source position determined from a band where the source is detected, and positional uncertainty biases the flux low. This bias is expected to be small given the small positional uncertainty for a 4.5σ detection. We calculate that a 1σ positional offset would result in a flux underestimate of 5%, and therefore neglect this bias.

2.3.5.1 Bayesian Flux Deboosting

One standard method for dealing with flux deboosting in mm and submm surveys is the application of a Bayesian approach, where a posterior probability distribution is calculated given prior knowledge about the underlying source populations (Coppin et al., 2005). The usual Bayesian posterior distribution can be expressed as

$$P(S_{\text{true}}|S_{\text{meas}}) \propto P(S_{\text{meas}}|S_{\text{true}}) P(S_{\text{true}}),$$

(2.5)

where $P(S_{\text{true}}|S_{\text{meas}})$ is the posterior likelihood, expressing the probability of the true source flux $S_{\text{true}}$ given the measured value $S_{\text{meas}}$. $P(S_{\text{meas}}|S_{\text{true}})$ is the likelihood, expressing the probability of measuring a flux $S_{\text{meas}}$ given that the true flux of the source is $S_{\text{true}}$. Most simply, the likelihood is taken to be a Gaussian with width given by the map noise. $P(S_{\text{true}})$ is the prior, which expresses previous knowledge about the population of sources being detected, which in our case is proportional to the differential number counts as a function of flux, $dN/dS$.

Crawford et al. (2010) present an argument for slightly altering the expressions above to account for the fact that we expect the number of sources to rise steeply with decreasing flux and the reality that the telescope observes the sky with some finite resolution (which we further pixelate when creating a map). Therefore, there is a confusion limit due to faint sources coexistent in a single pixel which contributes to the noise of each detection. The standard Bayesian approach can
be modified slightly to account for this:

\[
P(S_{\text{max}}|S_{\text{meas}}) \propto P(S_{\text{meas}}|S_{\text{max}}) P(S_{\text{max}}),
\]

where now the posterior, \( P(S_{\text{max}}|S_{\text{meas}}) \), gives the probability that the highest flux source contributing to the pixel brightness is \( S_{\text{max}} \) given the measured flux of \( S_{\text{meas}} \) in that pixel. Similarly, \( P(S_{\text{meas}}|S_{\text{max}}) \) expresses the likelihood that \( S_{\text{meas}} \) will be measured given that the brightest source contributing to that pixel brightness has flux \( S_{\text{max}} \). The likelihood includes the uncertainty in the flux due to the presence of fainter sources. The prior, \( P(S_{\text{max}}) \), is still expressed by the differential number counts, \( dN/dS \), but now multiplied by an exponential suppression at low flux representing the probability that no other sources brighter than \( S_{\text{max}} \) exist in that pixel.

### 2.3.5.2 Simultaneous Three-band Deboosting

Also presented in Crawford et al. (2010) is the framework for expanding the single-band deboosting presented above to a deboosting of fluxes for sources detected in multiple bands simultaneously. Crawford et al. (2010) expands the analysis from one to two bands, and M13 presents the extension to three bands. We use the same method for deboosting as in M13 and present an overview of the methodology below, see M13 for further details.

The goal of multiband deboosting is to estimate the posterior probability for the flux of the source in multiple bands using its measured flux in one or more bands and any prior information known. The simplest way to write this would be

\[
P(S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}} | S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}}) \propto P(S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}} | S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}}) \cdot P(S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}}),
\]

which would express the 3-dimensional posterior probability distribution for the true flux for the detected source in the three bands, given the measured fluxes for that source in three bands. For
the multiband prior, one could assume that the priors for each band are independent and therefore could be separated as

\[ P(S_{\text{max}}^{95}, S_{\text{max}}^{150}, S_{\text{max}}^{220}) = P(S_{\text{max}}^{95}) P(S_{\text{max}}^{150}) P(S_{\text{max}}^{220}). \]  

(2.8)

However, in general this assumption would only be accurate if the three bands probed completely separate populations of sources with no overlap. In general, while more synchrotron sources are detected in 95 GHz, and 220 GHz is a stronger probe of dusty sources, there is certainly population overlap between the bands.

To accommodate this issue, we can express the prior as the combination of a prior on flux for one band (for example 150 GHz), and two priors describing the power law behavior connecting two fluxes as a function of frequency:

\[ S_{95} = S_{150} \left( \frac{\nu_{95}}{\nu_{150}} \right)^{\alpha_{95-150}} \]

\[ S_{220} = S_{150} \left( \frac{\nu_{220}}{\nu_{150}} \right)^{\alpha_{150-220}}. \]  

(2.9)

Note that the effective band centers for SPT depend slightly on the assumed spectral index of the source. We assume a flat spectral index of zero, which gives effective band centers of 97.6, 152.9, and 218.1 GHz. M13 found that source fluxes are not affected significantly by making this assumption. Through a change of variables, then, we can express the three-flux prior in terms of one flux and two spectral indices (\(\alpha\)’s):

\[ P(S_{\text{max}}^{95}, S_{\text{max}}^{150}, S_{\text{max}}^{220}) = P(S_{\text{max}}^{150}, \alpha_{\text{max}}^{95-150}, \alpha_{\text{max}}^{150-220}) \left( \frac{d\alpha_{\text{max}}^{95-150}}{dS_{\text{max}}^{95}} \right) \left( \frac{d\alpha_{\text{max}}^{150-220}}{dS_{\text{max}}^{220}} \right) \]  

(2.10)

where the \( \frac{d\alpha_{\text{max}}}{dS_{\text{max}}} \) can be found from Eqn. 2.9.

We then make the assumption that the prior written in this way is made up of three independent components:

\[ P(S_{\text{max}}^{150}, \alpha_{\text{max}}^{95-150}, \alpha_{\text{max}}^{150-220}) = P(S_{\text{max}}^{150}) P(\alpha_{\text{max}}^{95-150}) P(\alpha_{\text{max}}^{150-220}). \]  

(2.11)

By separating them, we are assuming that the spectral indices are independent of flux and the two spectral indices are not correlated with each other. Strictly speaking, we know that this assumption
of independence is also incorrect – fainter sources tend to have more dust-like spectral indices. More fundamentally, simply changing variables does not change the issue of the priors being correlated, since the amount of information contained in the priors has stayed the same. However, since we are interested in measuring $\alpha$ in this analysis, expressing the priors in this way allows us to place weak flat priors on both $\alpha$s between the physically motivated range of $-3 \leq \alpha \leq 5$, allowing the intrinsic population characteristics the emerge.

We now have for the 3-dimensional posterior on fluxes:

$$ P(S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}} | S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}}) \propto P(S_{95}^{\text{max}} | S_{150}^{\text{max}}, S_{220}^{\text{max}}) \cdot P(S_{150}^{\text{max}} | S_{95}^{\text{max}}, S_{220}^{\text{max}}) \cdot P(S_{220}^{\text{max}} | S_{95}^{\text{max}}, S_{150}^{\text{max}}) \cdot P(\alpha_{95-150}^{\text{max}}) \cdot P(\alpha_{150-220}^{\text{max}}) \cdot \frac{d\alpha_{95-150}^{\text{max}}}{dS_{95}^{\text{max}}} \cdot \frac{d\alpha_{150-220}^{\text{max}}}{dS_{220}^{\text{max}}} \cdot dS_{95}^{\text{max}} \cdot dS_{150}^{\text{max}} \cdot dS_{220}^{\text{max}} \quad (2.12) $$

The likelihood, $P(S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}} | S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}})$, is given by a multivariate Gaussian

$$ P(S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}} | S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}}) = \frac{1}{\sqrt{(2\pi)^3 \text{det}(C)}} \exp\left(-\frac{1}{2} \mathbf{r}^T \mathbf{C}^{-1} \mathbf{r}\right) \quad (2.13) $$

The noise covariance $\mathbf{C}$ represents the map noise due to instrument noise and atmosphere, beam calibration, and (correlated) absolute calibration from Planck.

The residual vector, $\mathbf{r}$, is given by:

$$ \mathbf{r} = [S_{95}^{\text{meas}} - S_{95}^{\text{max}}, S_{150}^{\text{meas}} - S_{150}^{\text{max}}, S_{220}^{\text{meas}} - S_{220}^{\text{max}}] \quad (2.14) $$

For the flux prior, we estimate the number counts $dN/dS$ based on a sum of synchrotron and dusty population models. Synchrotron populations are calculated using the De Zotti et al. (2005) model at 150 GHz and extrapolated to the other two bands. Dusty populations are estimated by use of Negrello models (private communication) for 150 and 220 GHz, and an extrapolation of the Negrello et al. (2007) prediction at 850 $\mu$m to 95 GHz (3.2 mm) using a typical spectral index of 3.1 calculated from the relatively high-redshift and luminous ULIRG Arp 220 ($z \sim 3$) and 2.0 calculated for low-redshift IRAS sources ($z < 0.3$). This is the same method as employed in M13.

There is an asymmetry introduced in our current deboosting algorithm, namely, that one band is chosen to have much stricter prior information applied to it through the flux prior, and
the other two bands have much less restrictive priors applied through loose \( \alpha \) priors. Therefore, for any given source, with flux information in three bands, the amount of deboosting each band’s flux receives depends on the choice made in selecting which band the flux prior is applied to. In Crawford et al. (2010) and M13, this band is termed the “detection band” but this is slightly confusing terminology, since a given source could in fact be detected simultaneously in all three bands or some combination of bands. To avoid this confusion, here we employ the term “flux-prior band” to refer to the band which has the flux prior applied as opposed to a prior on \( \alpha \). In practice, the deboosted fluxes reported in the catalog are calculated using the band with the highest significance detection in raw flux as the flux-prior band. For number counts, we use the band for which we are calculating number counts as the flux-prior band and then restrict to only sources with a detection in that band.

Since we are interested in calculating posterior distributions for \( \alpha \)’s in addition to fluxes, we calculate in parallel the posteriors for one flux and two \( \alpha \)’s:

\[
P(S_{150}^{\text{max}}, \alpha_{95-150}, \alpha_{150-220}^{\text{max}}|S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}}) \propto P(S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}}|S_{150}^{\text{max}}, \alpha_{95-150}^{\text{max}}, \alpha_{150-220}^{\text{max}}) \cdot P(S_{150}^{\text{max}}, \alpha_{95-150}^{\text{max}}, \alpha_{150-220}^{\text{max}}).
\]

(2.15)

The prior is identical to that used for three fluxes, and the likelihood is very similar:

\[
P(S_{95}^{\text{meas}}, S_{150}^{\text{meas}}, S_{220}^{\text{meas}}|S_{95}^{\text{max}}, S_{150}^{\text{max}}, S_{220}^{\text{max}}) = \frac{1}{\sqrt{(2\pi)^3 \det(C)}} \exp(-\frac{1}{2} r^T C^{-1} r),
\]

(2.16)

the same as before, but where the residual vector is now:

\[
r = \left[ S_{95}^{\text{meas}} - S_{95}^{\text{max}} \left( \frac{\nu_{95}}{\nu_{150}} \right)^{\alpha_{95-150}}, S_{150}^{\text{meas}} - S_{150}^{\text{max}}, S_{220}^{\text{meas}} - S_{220}^{\text{max}} \left( \frac{\nu_{220}}{\nu_{150}} \right)^{\alpha_{150-220}} \right].
\]

(2.17)

The likelihood values are identical for the corresponding locations in the different parameter spaces.

From our 3-dimensional posterior probability distributions, we marginalize over two of the three parameters in the posterior to find the corresponding 1-dimensional posteriors for a parameter of interest. We then integrate the PDFs to the 16%, 50%, and 84% levels in the cumulative distribution to calculate the best-fit values and 1-\( \sigma \) error bars.
2.3.6 Radial cross-match method

There are several instances in the analysis pipeline where a cross-match method is employed: cross-matching between the 19 SPT fields within a given band, cross-matching between SPT bands, and cross-matching between the SPT catalog and external catalogs. The same general principle is applied in each case, while the details that differ will be discussed topically in following sections. A cross-match criterion involving only a radial offset is appropriate when the source densities of the two groups of sources under comparison are comparable or, in the case of cross-matching with external information, the source density of the external catalog is similar or lower than the SPT catalog, and the positional uncertainty is small relative to the typical distance between sources. An appropriate cross-matching radius can then be chosen either analytically or empirically using the measured source density, and depending on the application, either all of the sources within the radial distance are considered associated (in the case of cross-matching between SPT fields for the same band), or the closest candidate within the radial criterion, if one exists, is considered associated (in the case of cross-matching between SPT bands and between the SPT catalog and external catalogs). Selecting a radial threshold that is excessively large will result in falsely associating physically unrelated objects, whereas a radial threshold that is too small risks missing true associations that are shifted in position due to map noise or residual pointing error. Further details of the cross-matching between SPT detections to form a single three-band full-survey-area catalog can be found in the following subsection, and details of cross-matches with external catalogs and redshift information are further detailed in Sections 2.4.6 and 2.4.8.

2.3.7 Catalog generation

To be included in the source catalog, we require that a source must exceed the 4.5 sigma detection threshold in raw flux signal-to-noise in at least one band. To form a united single SPT catalog including all fields and bands, we first cross-match across all 19 fields for detections in a single band. About 10% of the full survey area falls in overlap regions covered by multiple fields,
and we throw out repeat detections in these regions. To do this, we concatenate all fields’ detections in each band and employ a radial cross-match as discussed in Section 2.3.6 to find all associated sources, keeping the detection that comes from the map with the lowest noise at that location and throwing out the others. To determine the cross-match radius, we use the analytic formalism in Appendix B of Ivison et al. (2007) which takes into account the measured beam FWHM for that band and the source signal-to-noise to yield a positional error calculated analytically. Assuming there is equal and uncorrelated error in both positional directions, we use $2\sigma$ positional error for a $4.5\sigma$ detection to cross-match, corresponding to 38.4, 27.2, and 22.6 arcsec for 95, 150, and 220 GHz, respectively. (Note: in reality the positional error is correlated in the two orthogonal directions in the map when cross-matching source positions, so assuming errors are uncorrelated is not technically true). We test that this is an appropriate radius by comparing to the actual distribution in nearest-neighbor separations of source detections within each single field and also check that we don’t end up associating (and therefore removing) sources detected within the same field. Employing a radius that is too large risks hurting the completeness of the catalog by removing true detections of distinct objects. For a crossmatch distance of $2\sigma$, we falsely flag and remove one source each from 95 and 150 GHz and none from 220 GHz. These numbers don’t change if we restrict to $1.5\sigma$ of the positional error, so we conclude that $2\sigma$ is not too large to falsely remove too many real sources.

We additionally remove all sources that lie in regions with overlapping coverage from multiple fields where the source is detected in a field with a higher noise level but not detected in an overlapping field with lower noise, as all of these detections are very likely false. This step removes roughly 60 sources in each band, which is 3.5% of sources in 220 GHz, and a smaller percentage for 95 and 150 GHz. We check that the distribution in signal-to-noise of sources trimmed is sensible, i.e. that almost all trimmed sources are near the detection threshold of $4.5\sigma$, and therefore likely to be false detections due to map noise.

The next step in creating a multi-band catalog is to cross-match across the SPT bands. We employ a radial cross-match method and use a 30 arcsec radius of association, which is chosen
similarly to above using the analytical positional uncertainty of our sources calculated from the formalism in Ivison et al. (2007). For the band with the widest beam (1.7 arcmin at 95 GHz), 30 arcsec is roughly a $1.5\sigma$ positional error for a $4.5\sigma$ detection. Since the source densities in all three SPT bands are quite low relative to the 30 arcsec association radius, the expected rate of random association of two unrelated sources between bands is also very low. Using just the full-survey average source density, the probability of random association is 0.024%, 0.034%, and 0.012% for 95, 150, and 220 GHz, respectively.

At this step we also remove any sources with incomplete coverage across the three bands. Because the masks of usable area for each field cover physically offset regions of the sky for the three bands, some area of the survey at the edges will be covered only by one or two bands, and for the sake of consistency, we trim any sources detected in these areas. This removes 115 sources from the final catalog, or about 2% of the catalog.
Figure 2.3: Upper panels: raw (left) and deboosted (right) fluxes for 150 GHz vs 95 GHz for all sources in the catalog. Lower panels: raw (left) and deboosted (right) fluxes for 220 GHz vs 150 GHz. Colors and symbols show cross-matches with external catalogs and black crosses indicate sources detected by the SPT-SZ survey with no counterparts in external catalogs. Dashed lines show expected spectral indices for synchrotron and dusty populations, and dotted lines in the right panels show bounds applied as priors on spectral index for the deboosting. The vertical and horizontal clusters of sources at relatively low flux show the 4.5σ detection thresholds, which are different for each field, and for example, show two clusters at different flux levels in 220 GHz because we combine data from two fields observed initially in 2008 and then reobserved to substantially deeper depth in 150 GHz and 220 GHz later with the rest of the catalog, which is more uniform.
Figure 2.4: Summed normalized posterior distributions for spectral indices 95-150 GHz (left) and 150-220 GHz (right) from the deboosting, choosing for each spectral index only sources with detections above 5σ in both bands spanned by that index. As expected, the distribution for $\alpha_{\text{max}}^{95-150}$ shows a single peak at $\alpha_{\text{max}}^{95-150} \sim -0.75$, since synchrotron sources are expected to dominate at 95 GHz, especially for bright, and therefore high-signal-to-noise, sources. The distribution for $\alpha_{\text{max}}^{150-220}$ shows distinct peaks for synchrotron and dusty populations and we select the minimum at $\alpha_{\text{max}}^{150-220} = 1.51$ as the threshold for applying a categorization for each source in the catalog.
Figure 2.5: Upper panels: raw (left) and deboosted (right) $\alpha_{150-220}$ vs $\alpha_{95-150}$, where colors and symbols indicate flux brightness. Dotted box indicates the bounds of the prior on spectral index applied during deboosting, and dotted horizontal and vertical dashed lines indicate $\alpha_{150-220} = 1.51$, the minimum of the 150-220 GHz summed posterior and the corresponding separation index between dusty and synchrotron in 95-150 GHz from reexamining the distributions of summed spectral index posteriors after single-population separation. These separation lines are used to categorize sources into four quadrants of “falling,” “rising,” “peaking,” and “dipping.” The typical error for a source at the 4.5σ detection threshold is shown in the lower left corner of the deboosted spectral index plots. Lower panels: Left: deboosted $\alpha_{150-220}$ vs $\alpha_{95-150}$, where colors and symbols indicate cross-matches with external catalogs, and black crosses indicate SPT sources with no cross-matches in external catalogs. Right: Measured spectral indices for ten stars detected in the catalog, overplotted on the rest of the catalog, shown by grey crosses.
2.4 Catalog: Description and Characterization

2.4.1 Single-band and Multi-band Catalogs

We find that our 3-band integrated catalog for the full 2530 square degrees of survey area contains 2772 sources detected above 4.5 $\sigma$ at 95 GHz, 3906 at 150 GHz, and 1431 at 220 GHz. Cross-matching across SPT bands, this yields a multi-band catalog with 4841 total sources detected at a minimum of 4.5$\sigma$ in at least one band. The noise levels for individual matched-filtered maps are shown in Table 2.2; taking the median noise level across all fields, 4.5$\sigma$ corresponds to detections above 9.8, 5.8, and 20.4 mJy in 95, 150, and 220 GHz, respectively. Of the 4841 sources in the catalog, 721 sources are detected at $\geq 4.5\sigma$ in all three bands. 1659 are detected only in 95 GHz and 150 GHz, and 167 are detected only in 150 GHz and 220 GHz. 392 are detected only in 95 GHz, 1359 are detected only in 150 GHz, and 543 are detected only in 220 GHz. Of all the detections in the catalog, roughly 8% have fluxes in different bands drawn from multiple different fields, which is consistent with about 10% of the area of the survey falling in overlap regions covered by multiple fields. Similarly, of all the sources detected above 4.5$\sigma$ in all three bands, about 9% have fluxes drawn from multiple fields. We compare raw fluxes and deboosted fluxes in the combined catalog in Figure 2.3. Overplotted are expected values for spectral indices between the bands, and we see that for the most part, sources follow the characteristic lines for dusty and synchrotron sources. Similarly, we plot $\alpha_{95-150}$ vs. $\alpha_{150-220}$ for both raw spectral indices and deboosted values in Figure 2.5. We note in these plots, that spectral index does seem to correlate with source brightness, as expected, where the brightest sources are synchrotron in behavior. We also note that while there are sources where $\alpha_{95-150}$ correlates with $\alpha_{150-220}$, there are also numerous sources with spectral indices which are not correlated, indicating sources with a spectral break, which will be discussed further in Section 2.6.
2.4.2 Single-population Separation

To explore the distributions in spectral indices that we find from deboosting and to separate sources into populations based on spectral index, we normalize each source’s posterior probability distribution for $\alpha$, such that the integral of the marginalized posterior over all possible values of $\alpha$ is unity, and then sum all the posteriors from different sources. In Figure 2.4, we show these distributions for sources with signal-to-noise greater than or equal to 5.0 in both of the bands that a particular spectral index spans. We restrict to higher signal-to-noise sources for this part of the analysis to provide a cleaner population separation.

From Figure 2.4, we see that the posteriors for $\alpha_{95-150}^{\text{max}}$ show only the presence of a synchrotron population peaking at roughly $\alpha_{95-150}^{\text{max}} \sim -0.75$. As shown in Figure 2.5, synchrotron sources do dominate the high signal-to-noise sources in general and dusty sources, with a positive spectral index, are much more likely to be below the detection threshold at 95 GHz. In contrast, the posteriors for $\alpha_{150-220}^{\text{max}}$ show a double-peak in the distribution, representing contributions from both dusty and synchrotron populations. Once again, the synchrotron peak is stronger since we are restricting to relatively high signal-to-noise detections, which are synchrotron-dominated.

We take the minimum of our summed posterior distribution on $\alpha_{150-220}^{\text{max}}$ as the dividing line to produce separate catalogs of synchrotron and dusty sources. From Figure 2.4, this produces a population separation at $\alpha_{150-220}^{\text{max}} = 1.51$. To classify each source as either dusty or synchrotron, we find the probability for each source that $\alpha_{150-220}^{\text{max}} > 1.51$ from each source’s marginalized posterior. If the probability that a source has $\alpha_{150-220}^{\text{max}} > 1.51$ is less than 50%, we classify the source as synchrotron, and conversely, if the the probability that a source has $\alpha_{150-220}^{\text{max}} > 1.51$ is greater than or equal to 50%, the source is classified as dusty.

2.4.3 Catalog Description

The columns in our catalog are described as follows; sources in the catalog are listed in order of strongest-significance detection across all bands.
(1) Source I.D.: Source IAU identification

(2) RA: Right ascension (J2000) in degrees

(3) DEC: Declination (J2000) in degrees

(4) $S_{95}^{\text{meas}}/N_{95}$: Raw signal-to-noise in 95 GHz

(5) $S_{95}^{\text{meas}}$: Raw flux in 95 GHz, [mJy]

(6) $S_{95}^{\text{max}}$: Deboosted flux in 95 GHz taken from integrating 50% of the posterior PDF, with 16% and 84% taken as 1-\(\sigma\) error bars, [mJy]

(7) $S_{150}^{\text{meas}}/N_{150}$: Raw signal-to-noise in 150 GHz, [mJy]

(8) $S_{150}^{\text{meas}}$: Raw flux in 150 GHz, [mJy]

(9) $S_{150}^{\text{max}}$: Deboosted flux in 150 GHz taken from integrating 50% of the posterior PDF, with 16% and 84% taken as 1-\(\sigma\) error bars, [mJy]

(10) $S_{220}^{\text{meas}}/N_{220}$: Raw signal-to-noise in 220 GHz, [mJy]

(11) $S_{220}^{\text{meas}}$: Raw flux in 220 GHz, [mJy]

(12) $S_{220}^{\text{max}}$: Deboosted flux in 220 GHz taken from integrating 50% of the posterior PDF, with 16% and 84% taken as 1-\(\sigma\) error bars, [mJy]

(13) $\alpha_{95-150}^{\text{meas}}$: Spectral index between 95 GHz and 150 GHz as calculated from the raw 95 and 150 GHz fluxes.

(14) $\alpha_{95-150}^{\text{max}}$: Spectral index between 95 and 150 GHz taken from integrating 50% of the posterior PDF from the deboosting algorithm. 1-\(\sigma\) error bars from integrating 16% and 84% of the posterior PDF.

(15) $\alpha_{150-220}^{\text{meas}}$: Spectral index between 150 GHz and 220 GHz as calculated from the raw 150 and 220 GHz fluxes.
(16) $\alpha_{150-220}^{\text{max}}$: Spectral index between 150 and 220 GHz taken from integrating 50% of the posterior PDF from the deboosting algorithm. 1-$\sigma$ error bars from integrating 16% and 84% of the posterior PDF.

(17) Type: Classification of a source as either synchrotron or dusty depending on the fraction of the integrated 150-220 GHz spectral index posterior above the threshold of $\alpha_{150-220}^{\text{max}} > 1.51$. For $P(\alpha_{150-220}^{\text{max}} > 1.51) \geq 0.5$, the source is classified as dusty, for $P(\alpha_{150-220}^{\text{max}} > 1.51) < 0.5$, the source is classified as synchrotron.

(18) External counterparts: Flag on sources with an associated detection in one of the external catalogs we cross-match. See Section 2.4.6.

(19) Extendedness: Flag on sources that by either method of extended flagging appear to be extended or are multiple members of the same source at physically offset locations due to being extended. See Section 2.4.7.

2.4.4 Completeness

The completeness of the catalog for a given band is defined as the ratio of the number of sources we detect using the source-finding algorithm compared with the true number of sources in the map for a given flux. Due to the presence of noise in the maps, sources near the detection threshold may be missed by the source-finder if they happen to be coincident with a negative noise fluctuation which pulls their flux below the detection threshold. Completeness is important not only for the robustness of the catalog, but also for calculating number counts, discussed in the following section. The completeness is calculated in practice by performing the source-finding on a known population of sources at fixed flux values. We add a set of 100 simulated sources at a chosen flux level to random locations in the residual map (the optimally-filtered map post-CLEANing, which is a good approximation to noise plus a background of sources below the detection threshold of the CLEANing). The source profile used is the real-space version of the transfer function (i.e. a beam with the timestream filtering applied) for the sector which contains the coordinates randomly.
chosen for the source, rotated to the proper angle. We then run the source-finder and cross match
the returned detections with the known inputs. We repeat this process for a broad range of flux
levels. The completeness as a function of flux is then given by $f_{\text{compl}}(S) = N_{\text{recovered}} / N_{\text{input}}$. Since
the noise in our maps is to a good approximation Gaussian and sources are rare enough that the
noise dominates the distribution of flux in the map, we would expect the completeness to follow an
error function of the form

$$f_{\text{compl}}(S) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{S}^{\infty} e^{-(S'-S_0)^2/2\sigma^2} dS' \quad (2.18)$$

where $S_0$ is the detection threshold, in this case 4.5 times the mean RMS noise in the map for each
band. Since it becomes computationally expensive to evaluate the completeness at many flux levels,
we fit the error function to our data and use it as a model of our completeness. Since repeating
the process of injecting and searching for sources is computationally expensive, we estimate errors
on our completeness values for the fit by using binomial statistics. We repeat this process for each
band separately.

During the CLEANing process, we extract negative sources as well as positive sources. We
expect negative flux detections in 95 and 150 GHz due to the presence of galaxy clusters which
interact with the CMB via the thermal Sunyaev-Zel’dovich (SZ) effect (see Bleem et al. (2015)
for a recent review and catalog release of clusters detected in 2500 square-degrees of the SPT-
SZ survey; and Sunyaev & Zel’dovich (1972) for background on the SZ effect). CMB photons
are shifted to higher energies as they upscatter through the hot intracluster medium resulting in
a characteristic spectral shift toward higher frequencies. 220 GHz is at the null of this spectral
shift, so the CMB is unaltered by the SZ effect at that frequency. Compact clusters with high
significance can overlap and therefore cancel out emissive sources, which we do not account for in
the completeness calculation. Using an assumed cosmological model and cluster mass function as
well as SPT cluster selection functions, M13 calculated an expectation of one cluster large enough
to cancel a 4.5\(\sigma\) emissive source per ten square degrees of SPT-SZ survey, which corresponds to
roughly 10-20 clusters per field or roughly 250 total in the full SPT-SZ survey. Given the relatively
low point source density in the SPT maps above the detection threshold, the likelihood of purely random overlap and cancellation is less than 1% per field for 150 GHz, the band with the highest source density, and even though it is known that point sources and clusters have some preference for clustering, the effect on the completeness due to cluster overlap is expected to be small.

Flux levels averaged over all sectors per each field and band for 50% and 95% completeness are shown in Fig. 2.2. The median 95% completeness across all fields is 12.89, 7.60, and 26.83 mJy at 95, 150, and 220 GHz, respectively.

2.4.5 Purity

The purity of the catalog as a function of source signal-to-noise is defined as the fraction of sources at that signal-to-noise or higher that are expected to be false detections due to noise in the map. To quantify the purity of the catalog, we estimate the number of detections above a given threshold in a simulated noise-only map and compare those with the number detected above the same significance in the real maps. We generate simulated noise maps from difference maps, which contain instrument noise and residual atmosphere. The method for generating difference maps is discussed in Section 2.3.3. To the noise realizations we add contributions from the power spectrum of primary anisotropies in the CMB, which is also a source of noise for our source detections. These noise fluctuations have a power spectrum determined from the best fit ΛCDM model to combined WMAP7 and SPT data (Keisler et al., 2011). We also include an estimate of the thermal SZ effect, as well as contributions from the CIB in terms of a Poisson and clustered component. The component of the noise that we add to our simulations to account for the SZ effect is a Gaussian random field with power spectrum given by fitting measurements in Shirokoff et al. (2011). Massive clusters were masked before this power spectrum was measured, so they are not included in the model. More fundamentally, massive clusters are non-Gaussian and affect the source-finding in a very non-Gaussian manner. Therefore the model accounts for noise due to diffuse thermal SZ signal only.

Running the source-finder on these simulated maps, we calculate the purity as a function of
<table>
<thead>
<tr>
<th>Name</th>
<th>95 GHz</th>
<th>150 GHz</th>
<th>220 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS (mJy)</td>
<td>50% c. (mJy)</td>
<td>95% c. (mJy)</td>
</tr>
<tr>
<td>RA5h30dec-55</td>
<td>2.25</td>
<td>9.76</td>
<td>13.33</td>
</tr>
<tr>
<td>RA23h30dec-55</td>
<td>2.17</td>
<td>9.43</td>
<td>12.87</td>
</tr>
<tr>
<td>RA21hdec-60</td>
<td>1.89</td>
<td>8.20</td>
<td>11.20</td>
</tr>
<tr>
<td>RA3h30dec-60</td>
<td>1.93</td>
<td>8.30</td>
<td>11.34</td>
</tr>
<tr>
<td>RA21hdec-50</td>
<td>2.18</td>
<td>9.44</td>
<td>12.89</td>
</tr>
<tr>
<td>RA4h10dec-50</td>
<td>1.87</td>
<td>8.15</td>
<td>11.13</td>
</tr>
<tr>
<td>RA0h50dec-50</td>
<td>2.24</td>
<td>9.72</td>
<td>13.27</td>
</tr>
<tr>
<td>RA2h30dec-50</td>
<td>2.15</td>
<td>9.17</td>
<td>12.52</td>
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<tr>
<td>RA1hdec-60</td>
<td>2.14</td>
<td>9.25</td>
<td>12.64</td>
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<tr>
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<td>2.35</td>
<td>10.35</td>
<td>14.13</td>
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<td>RA6h30dec-55</td>
<td>2.22</td>
<td>9.55</td>
<td>13.04</td>
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<td>RA23hdec-62.5</td>
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<td>RA21hdec-42.5</td>
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<td>9.80</td>
<td>13.29</td>
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<tr>
<td>RA22h30dec-55</td>
<td>2.29</td>
<td>10.16</td>
<td>13.88</td>
</tr>
<tr>
<td>RA23hdec-45</td>
<td>2.18</td>
<td>9.56</td>
<td>13.05</td>
</tr>
<tr>
<td>RA6hdec-62.5</td>
<td>2.14</td>
<td>9.08</td>
<td>12.40</td>
</tr>
<tr>
<td>RA3h30dec-42.5</td>
<td>2.11</td>
<td>9.11</td>
<td>12.44</td>
</tr>
<tr>
<td>RA1hdec-42.5</td>
<td>2.21</td>
<td>9.44</td>
<td>12.89</td>
</tr>
<tr>
<td>RA6h30dec-45</td>
<td>2.17</td>
<td>9.20</td>
<td>12.56</td>
</tr>
</tbody>
</table>

Note. — RMS noise for the matched-filtered maps, averaged across all sectors; 50% and 95% completeness levels; and purity levels at 4.5σ.
signal-to-noise to be

\[ f_{\text{pure}} = 1 - \frac{N_{\text{false}}}{N_{\text{total}}} \]  

(2.19)

Massive clusters in the real maps will contribute to impurity in the source-finding because the timestream filtering causes these objects to have positive wings, which can be detected as false sources. However, these false detections are easy to identify and quite rare in the real maps. We remove them from the catalog by hand, and a total of six sources are removed. Thus there is no need to include them in the purity simulations.

Table 2.2 shows purity values averaged over all sectors per field and per band for detections \( \geq 4.5 \sigma \). The median purity for the full survey is 94.4%, 94.8%, and 83.4% at 95, 150, and 220 GHz, respectively.

### 2.4.6 External Associations

To further characterize the nature of sources in the SPT catalog, we cross-match with seven external catalogs, ranging from in wavelength from radio to X-ray, work done by Lizhong Zhang and Joaquin Vieira at the University of Illinois, Urbana-Champaign. These include:

- The Sydney University Molonglo Sky Survey (SUMSS, \cite{Mauch_2003}) at 843 MHz
- The Parkes-MIT-NRAO (PMN) Southern Survey (\cite{Wright_1994}) at 4850 MHz
- The Australia Telescope 20-GHz Survey (AT20G, \cite{Murphy_2010})
- The Infrared Astronomical Satellite Faint Source Catalog (IRAS-FSC, \cite{Moshir_1992}) at 12, 25, 60, and 100 \( \mu \text{m} \)
- The Infrared Astronomical Satellite AKARI, IRC Point Source Catalog (\cite{Yamamura_2010}) at 9 and 18 \( \mu \text{m} \), and the FIS Bright Source Catalog (\cite{Ishihara_2010}) at 65, 90, 140, 160 \( \mu \text{m} \)
- The Wide-field Infrared Survey Explorer (WISE) AllWISE Source Catalog at 3.4, 4.6, 12 and 22 \( \mu \text{m} \) (WISE, \cite{Wright_2010})
<table>
<thead>
<tr>
<th>Survey Name</th>
<th>Band</th>
<th>Beam size</th>
<th>$\Sigma$ [1/deg$^2$]</th>
<th>$r_{assoc}$ [arcmin]</th>
<th>X-matches</th>
<th>P(random) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>95 GHz (3.2 mm)</td>
<td>1.7 arcmin</td>
<td>1.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 GHz (2.0 mm)</td>
<td>1.2 arcmin</td>
<td>1.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>220 GHz (1.4 mm)</td>
<td>1.0 arcmin</td>
<td>0.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUMSS</td>
<td>843 MHz (36 cm)</td>
<td>45 arcsec</td>
<td>26.75</td>
<td>0.8</td>
<td>3517</td>
<td>1.49</td>
</tr>
<tr>
<td>PMN</td>
<td>4850 MHz (6 cm)</td>
<td>4.2 arcmin</td>
<td>1.75</td>
<td>2.5</td>
<td>1833</td>
<td>0.95</td>
</tr>
<tr>
<td>AT20G</td>
<td>20 GHz (1.5 cm)</td>
<td>4.6 arcsec</td>
<td>0.32</td>
<td>1.0</td>
<td>819</td>
<td>0.03</td>
</tr>
<tr>
<td>IRAS</td>
<td>12, 25, 60, 100 $\mu$m</td>
<td>11-88 arcsec</td>
<td>4.72</td>
<td>1.5</td>
<td>317</td>
<td>0.92</td>
</tr>
<tr>
<td>AKARI-FIS</td>
<td>65, 90, 140, 160 $\mu$m</td>
<td>24-59 arcsec</td>
<td>0.87</td>
<td>1.5</td>
<td>217</td>
<td>0.17</td>
</tr>
<tr>
<td>AKARI-IRC</td>
<td>9, 18 $\mu$m</td>
<td>3.3-6.6 arcsec</td>
<td>5.18</td>
<td>0.5</td>
<td>56</td>
<td>0.11</td>
</tr>
<tr>
<td>WISE</td>
<td>3.4, 4.6, 12, 22 $\mu$m</td>
<td>6.1-12 arcsec</td>
<td>45.32</td>
<td>0.7</td>
<td>732</td>
<td>1.94</td>
</tr>
<tr>
<td>RASS</td>
<td>0.1-2.4 keV</td>
<td>3.53</td>
<td>1.5</td>
<td>447</td>
<td>0.69</td>
<td></td>
</tr>
</tbody>
</table>
• The ROSAT All-Sky Survey (RASS) Bright Source Catalog (Voges et al. 1999) and Faint Source Catalog (Voges et al. 2000) at X-ray energies 0.1-2.4 keV

Each external catalog is cross-matched with positions of SPT point sources in the catalog using a radial association criterion, as overviewed in Section 2.3.6. An appropriate radius for association is determined for each external catalog by looking at the distributions of source separations, selecting a radius such that the probability of a random, false association is approximately 1% and no greater than 2%. The chosen radius for each catalog can be found in Table 2.3. For most of the external catalogs, the density of sources is low enough that confusion within the SPT beam size is not an issue. For WISE, which has the highest source density, confusion becomes a problem for cross-matching with the detections in the shorter-wavelength WISE bands. Therefore, we restrict the source density in the WISE sources we cross-match with by applying a cut on the WISE catalog using the W4 22 µm band, and restricting to only cross-matching with WISE sources that have W4 flux greater than 5 mJy. We experimented with a more complex cross-matching scheme, incorporating source flux and number density, but found that a simple radial cross-match achieved comparable results.

Figure 2.6 shows an overview of the SPT survey relative to surveys we cross-match with, including survey depths, as well as reference spectral energy distributions for dusty star-forming galaxies and flat-spectrum synchrotron sources. Spectral energy distributions for dusty sources at varying redshifts show how powerful the mm-wavelength range is for detections of high-redshift objects due to negative K-correction. Table 2.3 gives an overview of each survey and the number of cross-matches with the SPT catalog. A comparison of cross-matches per catalog, including cross-match overlap between surveys for the total SPT catalog as well as dusty and synchrotron subpopulations is illustrated in Figure 2.7. The most ubiquitous cross-match for the SPT catalog is with the SUMSS survey in the radio, where 71% of SPT sources have cross-matches in SUMSS. SUMSS is especially useful for cross-matches with synchrotron-dominated sources since the wide-field radio survey has full coverage of the SPT area and is complete to a depth of 6 mJy/beam at
5σ. For dusty sources, IRAS is particularly useful for identifying low-redshift dusty galaxies, but both WISE and AKARI overlap IRAS cross-matches considerably, as shown in Fig. 2.7.

Of the 4841 sources in the catalog, 1107 have no cross-matches with external catalogs. 85% of these are detections in only one band, mostly in 150 GHz-only or 220 GHz-only; 10 sources with no cross-matches in external catalogs have detections in all three bands.

Figure 2.6: A comparison of survey depths for SPT and wide-field surveys used to cross-match with the SPT source catalog. Blue curves show example spectral energy distributions (SEDs) for dusty star-forming galaxies and their high-redshift component, SMGs, which are an Arp220 SED shifted in redshift. Red curves show two example synchrotron SEDs for different types of flat-spectrum sources.
Figure 2.7: Venn diagram showing an overview of cross-matches with external catalogs, including cross-match overlap between external catalogs.
2.4.7 Extended Sources

We expect that all extragalactic sources with redshifts greater than $z \sim 0.05$ will be unresolved in the maps, given the instrumental beam size of roughly 1 arcmin. There is a chance that very nearby sources or bright AGN with extended radio lobes may be resolved in the maps. We take a two-pronged approach to flagging extended sources: first, we fit a cutout around each detected source to a model constructed from the beam profile convolved with a non-symmetric 2D Gaussian and compare the $\Delta \chi^2$ of the fit to a model containing only the beam. Based on looking at the fields with the most obvious extended sources, we use a threshold of $\Delta \chi^2 \geq 7$ to flag sources as extended in the catalog. Second, to ensure that we are catching all sources that are detected as multiple detections of the same source in the CLEANing, we run a by-eye check of all sources within close proximity to other detections and flag sources that appear to be multiple detections at physically offset locations of the same, extended source. Each source flagged as possibly being a multiple detection of the same, extended object, is cross-checked with external catalogs to determine if the detections are indeed from the same object or from distinct objects that appear in our maps with close proximity. For the sake of completeness, we leave all detections in the catalog, but indicate the likelihood that a source is extended. In calculating the number counts, we calculate multiple versions of the counts, including using the extendedness information from both flagging methods. Fluxes for extended sources will be lower limits on the true flux, since the CLEANing is unable to accurately return flux for sources that do not look like our chosen source profile.

2.4.8 Redshift associations

Redshifts for SPT catalog sources are identified wherever possible using the following method:

1) Identify all sources in the NASA/IPAC Extragalactic Database (NED) with measured redshifts within 5 arcmin of each SPT source.

2) Develop a separation criterion for associating sources using the distributions of positional offsets from all potential cross-matches within 5 arcmin. 0.6 arcmin is used as radial
cross-match criterion, and SPT sources are cross-matched with the nearest candidate if a candidate is present within the radial criterion.

The redshift cross-match information is used to aid in removing extended sources from the number counts, as discussed further in Section 2.4.10 and applied in Section 2.5. The redshift cross-match method was developed and cross-match undertaken by Lizhong Zhang and Joaquin Vieira at the University of Illinois, Urbana-Champaign.

Figure 2.8: Plotting deboosted $\alpha_{150-220}^{\max}$ for sources with measured redshifts, coloring by cross-matches with external catalogs. Because redshifts are drawn from a variety of different sources, we don’t attempt to quantify the completeness function of the redshift cross-matching with the SPT catalog; rather, this figure is only to give an illustration of the known redshift information for the catalog. A few individual sources in this plot warrant additional comment. Two sources with measured redshifts $>3$ that have no cross-matches in external catalogs are not included in the “SPT-SZ lensed candidate list” because both appear with a dipping spectrum in the SPT bands, due to blending of the lensed object with either its foreground lens or an unrelated source along the line of sight. An additional source with measured redshift $>3$ appears in the plot above with a cross-match with an IRAS detection, this cross-match is most likely a false association of two unrelated objects that fall just within the association radius. Finally, one source with a measured high redshift in the lensed candidate list has a cross-match with an X-ray detection in RASS; the X-ray detection is of the galaxy cluster which is the lens for the high redshift object.
2.4.9 Star identification

A small but interesting sub-population in the catalog are ten stars, identified primarily using their cross-matched IRAS flux at 12 µm. As shown in Figures 2.5 and 2.9, the stars are not clearly identifiable using SPT data alone: their flux in SPT bands does not set them apart from other SPT sources and their spectral indices in SPT wavelengths span both synchrotron and dusty populations. However, looking at cross-matched flux in IRAS at 12 µm, these sources have considerably higher flux than other sources in the SPT catalog.

Nine of the ten stars identified in the SPT catalog are red giants on the Asymptotic Giant Branch (AGB), most of which are late-type M stars. The remaining star is * β Pic, which has a well-known dusty circumstellar disk [Sheret et al., 2004; Riviere-Marichalar et al., 2014]. The primary selection effect in our catalog is a bias toward the largest-surface-area and most-luminous stars that have sufficient flux at mm wavelengths to be detected in the SPT data. Many of the stars identified in the SPT data are Mira variables or closely related to Miras, known to be very large and luminous. Miras and other red giants are relatively cool, with surface temperatures of order a few thousand Kelvin, and therefore their stellar flux follows a blackbody distribution peaking around 1-a few µm [Bedding et al., 1997; Whitelock et al., 1997]. Dusty galaxies as well as flat- and steep-spectrum synchrotron sources have spectra that rise as a function of wavelength for wavelengths shorter than ~ 100 µm, as shown in Figure 2.6 whereas stars have spectra that are falling between λ = a few µm to ~ 100 µm. Therefore, the ratio of IRAS 60 µm to IRAS 100 µm flux should be less than one for non-stellar objects and greater than one for stars. This ratio can be used to with relative success to identify stars, as shown in the right panel of Figure 2.9 but we find that high IRAS 12 µm flux on its own is a more effective criterion. In theory, it should be possible to use cross-matches with WISE at wavelengths shorter than the IRAS bands to more clearly identify stars, since stars should be even brighter at shorter IR wavelengths than IRAS, closer to the peak of the stellar SED; however, most of the stars observed in the SPT sample are so bright that the WISE flux measurements are saturated and unreliable.
Three sources in the SPT catalog have cross-matches with sources in IRAS with fluxes at 12 $\mu$m comparable to the stars but are not identified as stars, as can be seen in Fig. 2.9. Looking at each of these objects individually by hand and comparing with data in external surveys, two appear to be likely false cross-matches due to blends of multiple objects superimposed in the SPT maps along the line of sight, making accurate cross-match identification difficult. A third SPT object appears in the catalog as a repeat cross-match with the IRAS source identified as V* RZ Sgr, due to either being a blend of unrelated objects along the line of sight near V* RZ Sgr or possibly a multiple detection of V* RZ Sgr itself, which is known to have an extended circumstellar shell resolved in IRAS, with a measured radius at 60 $\mu$m of 4.3 arcmin (Young et al., 1993).

Figure 2.9: Flux at 12 $\mu$m in IRAS is shown to be the best way to separate stellar objects from the rest of the SPT compact sources. Stars cannot be identified as stellar objects using SPT data alone, as indicated by the left and center plots which show that stars do not show separation from the bulk of the SPT source population in $\alpha_{150-220}$ or flux at 150 GHz. Stars with fluxes detectable in the SPT catalog are primarily red giants on the AGB branch, with SEDs that peak at $\sim$ 1- a few $\mu$m, and therefore the ratio of their fluxes at 60 and 100 $\mu$m should set them apart from dusty galaxies and synchrotron sources, which have SEDs that are rising with increasing wavelength in IR wavelengths. The right plot shows that this ratio is relatively effective at identifying stars, but that high flux at 12 $\mu$m alone is sufficient and just as effective. Three SPT sources appear to be cross-matched with IRAS objects with comparable 12 $\mu$m flux as the stars but are not identified as stars. In the case of two of these objects, they appear to be false associations due to blends of unrelated objects along the line of sight. In the case of the third, it appears to be a repeat cross-match with the IRAS detection associated with V* RZ Sgr, which may be due to superposition of unrelated objects or repeat detections of V* RZ Sgr, measured to have an extended circumstellar shell in IRAS at 60 $\mu$m (Young et al., 1993).
2.4.10 Cut selection criteria

To assist with comparing number counts with models and to further characterize source populations within the catalog, we develop three source cuts using extendedness and external cross-match information. Because source fluxes are measured in maps that have been optimally filtered assuming sources are unresolved by the SPT beam, sources that are flagged as extended or measured in the SPT maps as multiple detections will have fluxes that are systematically underestimated and therefore may bias the number counts. We therefore develop two cuts to flag them for removal when calculating the number counts.

First, in the extended cut, or “ext cut,” we flag all objects flagged as extended or detected as multiple detections but confirmed to be a single object, using the methods described in Section 2.4.7. Sources identified as stars are also removed in the counts for this cut, since they are not included in the models we compare the counts to. The extended cut removes 131 sources from the catalog as a whole, 37 of these are classified as synchrotron-dominated and 94 as dust-dominated.

Second, we develop a cut to flag all low-redshift objects, using the redshift cross-match information discussed in Section 2.4.8. Because the extended source flag used in the “ext cut” involves in part a by-eye inspection of individual sources, a method was sought to remove extended objects more systematically. All extended sources appear large enough in the SPT maps to be resolved by the SPT beam, and therefore should all be relatively local and removable by cutting all objects with low measured redshift. However, cutting below a redshift threshold will remove additional sources as well. The “z cut” trims all sources flagged as stars and all sources with cross-matched redshifts $z \leq 0.1$, resulting in flagging 460 sources from the full catalog, of which 251 have a synchrotron classification and 209 have a dusty classification. Looking at the distributions of source angular sizes for SPT sources with NED identifications, we expect that the cut threshold of $z < 0.1$ will correspond roughly to cutting objects with angular sizes $\gtrsim 1$ arcmin, roughly the size of the SPT beam. We verify that all sources flagged by “ext cut” are included in those sources flagged by the “z cut.”
To more cleanly select sources in the catalog that are likely to be lensed SMGs, we develop a list of “SPT-SZ SMG lensed candidates” using more strict criteria than the “z cut” and “ext cut” source lists. For this cut, we apply the same redshift criterion to dusty sources as the “z cut,” but also exclude any remaining detections with IRAS cross-matches. IRAS detections are unlikely to be high-redshift objects, since dusty objects will be observed on the Wien side of the spectrum in the IRAS bands, which will shift to an intrinsically dimmer portion of the spectrum with increasing redshift, in addition to reduced flux from greater distance. Furthermore, a cut on IRAS objects has been used successfully in previous SPT analyses as a proxy for trimming low-redshift objects [Vieira et al. 2010; Mocanu et al. 2013]. We also trim SPT detections that are measured as “dipping” in the three SPT bands, meaning that they are sources with a dusty spectral index between 150 and 220 GHz, but a synchrotron spectral index between 95 and 150 GHz. We note that there are a couple dipping sources from Vieira et al. (2010) and Mocanu et al. (2013) with follow-up observations that confirmed that they are high-redshift lensed objects and either appear to have “dipping” spectral behavior in the SPT bands due to superposition of the high redshift object with its foreground lens or are a superposition of unrelated objects along the line of sight. However, it is expected that for the most part, dipping sources will have significant synchrotron emission and therefore are less likely to be high redshift lensed galaxies, and therefore we exclude them from our candidate list. The cross-matched list of lensed candidates with already-measured redshifts is shown in Figure 2.8. We find a total of 499 sources in the “lensed candidate” list, of which 73 have detections above 4.5σ at both 150 and 220 GHz.

2.5 Number counts

In addition to supplying a catalog of detected sources, we seek to calculate the expected number counts in each of our bands as a function of flux. The number counts provide a characterization of mm-wave source populations at different wavelengths, and can be used to constrain models of galaxy population evolution.

To characterize the number counts at each of our three frequencies, we employ a bootstrap
Figure 2.10: Differential number counts of emissive sources in 2530 square degrees of the SPT-SZ survey. Ten sources identified as stars have been removed. Total counts are shown in black, synchrotron-dominated counts are in green, and dust-dominated counts are in blue and purple. Two versions of the dust-dominated counts are shown: cutting extended sources, “cut ext” and cutting all objects with measured redshift below 0.1, “z cut.” The total and synchrotron-dominated counts have the “ext cut” applied. Details of the cuts can be found in Section 2.4.10.
method developed in [Austermann et al. (2009)]. For each band, we select only the sources in the catalog that are detected above 4.5\(\sigma\) in that particular band. For each source, using our chosen band as the flux prior band for deboosting, we select 50,000 triplets of source fluxes from the 3-dimensional flux posterior probability distribution for that source. Effectively this creates 50,000 mock catalogs. We resample each catalog by drawing fluxes with replacement for a number of sources that is a Poisson deviate of the true catalog size. We then calculate for each catalog the number of sources in each flux bin to find the differential number counts, and determine 16th, 50th, and 84th percentiles of the distribution of \(dN/dS\) within each flux bin. The number counts are corrected for completeness in each bin using the simulations in Section 2.4.4. We plot our calculated number counts in Figure 2.10. We do not explicitly correct for purity in the number counts, since that will be accounted for by the deboosting which has generated the posteriors we draw from. The posteriors include fluxes below the detection threshold, and when drawing fluxes at random, there is a chance that fluxes below the detection threshold will be chosen. When this occurs, we remove them from the number counts calculation.

Figure 2.10 shows total source counts per band as well as synchrotron and dusty population counts. The single-population counts are generated using a probabilistic classification, where we calculate the corresponding \(\alpha_{150-220}^{\text{max}}\) for each of the 50,000 flux resamplings of each source. We then calculate the probability that each resampling will be classified as dusty or synchrotron using the same cut as for the catalog sources, and associate it with the counts for its assigned population. Therefore, for a single source in the catalog, if it has a probability \(p\) of having \(\alpha_{150-220}^{\text{max}} \geq 1.51\), it will fall into the dusty source counts \(p\) fraction of resamplings and will fall into the synchrotron source counts \(1 - p\) fraction of resamplings. Looking at Figure 2.10 as we might expect, the synchrotron counts dominate at all frequencies, but dusty sources are much more prominent at 220 GHz than in the other two bands, and exceed the synchrotron counts at the very lowest flux levels. The dust-dominated counts shown in Fig. 2.10 are shown with two different cuts applied: “ext cut” and “z cut.” Because the “ext cut” and “z cut” counts for the synchrotron counts are quite similar, as shown in Fig 2.13, we only show “ext cut” versions for the total and synchrotron-dominated counts.
2.6 Discussion of results

2.6.1 Source catalog characteristics

Of the 4841 sources in the catalog, 3991 (82.4%) are classified as synchrotron sources, and 850 (17.6%) as dusty sources, based on the probability that their $\alpha_{150-220}^{\text{max}}$ from deboosting is less or greater, respectively, than 1.51, the minimum of the summed posterior distribution of $\alpha_{150-220}^{\text{max}}$, as discussed in Section 2.4.2. 1107 sources in the catalog, or about 23%, have no cross-matches in external catalogs, and of those, 603 are classified as synchrotron and 504 as dusty. 936 or 85% of the sources in the catalog with no external cross-matches are detected in only one band by SPT, and 171 (15%) are detected in at least two bands.

Looking at Figure 2.5, we see that while a majority of sources in the catalog fit into the paradigm of two populations, dusty and synchrotron, with similar spectral indices between 95–150 GHz and 150–220 GHz, we also see some sources with a spectral break. To categorize different types of behavior, we look at the distributions of $\alpha_{95-150}^{\text{max}}$ for dusty and synchrotron sources, and see that $\alpha_{95-150}^{\text{max}} = 0.5$ forms a relatively natural population separation, although this is a somewhat soft threshold. Using $\alpha_{95-150}^{\text{max}} = 0.5$ and $\alpha_{150-220}^{\text{max}} = 1.51$ as population separations, we divide the plots in Fig. 2.5 into four quadrants: “rising,” “falling,” “dipping,” and “peaking,” though we stress that since the population break lines do not fall along $\alpha = 0$, the behavior of a source in one of the quadrants may not be as simple as the name suggests. For example, a source in the “peaking” quadrant may have flux that rises with band between all three frequencies but with a spectral index shallow enough that the source was characterized as synchrotron.

2.6.1.1 Synchrotron sources

Using this categorization, we find that of the 3991 sources categorized as synchrotron, 3249 sources fall into the “falling” category, sources that we expect to have their flux dominated by
synchrotron emission and likely are characteristic synchrotron sources: FSRQs, BL Lacs, or steep-spectrum sources. Considering all sources classified as synchrotron, we find a median $\alpha_{95-150}^{\text{max}}$ of -0.6, which steepens slightly for median $\alpha_{150-220}^{\text{max}}$ to -0.72. Restricting to synchrotron sources detected at greater than 5.0$\sigma$ at 150 and 220 GHz, these median spectral indices flatten slightly to median $\alpha_{95-150}^{\text{max}} = -0.64$ and median $\alpha_{150-220}^{\text{max}} = -0.6$. These numbers are the same if we restrict to only synchrotron sources in the “falling” quadrant.

From models of synchrotron number counts, we expect that in our observing bands, synchrotron sources for the flux ranges spanned by the SPT catalog should be dominated by flat-spectrum sources, either FSRQs for sources with fluxes $\gtrsim 15$ mJy, or BL Lacs for sources with fluxes $\lesssim 15$ mJy, although steep spectrum sources are expected to assume a larger portion of the synchrotron population at lower flux ranges as well (Tucci et al., 2011). Flat-spectrum sources are expected to have spectral indices $\alpha > -0.5$, but Tucci et al. (2011) posits that the spectra of FSRQs will feature a spectral break which becomes more prominent at higher observing frequencies. For the “C2Ex” model version from Tucci et al. (2011), which is expected to be the model version in Tucci et al. (2011) that best predicts synchrotron number counts at our observing frequencies, the frequency at which the spectral break is predicted to occur is below our observing bands for all but the few very highest-flux sources in our catalog. Therefore, in the SPT bands, it’s likely that FSRQs will appear as steep-spectrum sources, post-spectral break. In contrast, according to the Tucci et al. (2011) model, BL Lacs are expected to feature a spectral break at observing frequencies higher than the SPT bands, and therefore, BL Lacs should appear as flat-spectrum sources, but their population will be balanced out somewhat in the lower flux ranges by steep-spectrum sources. Therefore, we might expect that relatively high flux synchrotron sources in the SPT catalog will appear with moderately steep spectral indices in our bands, and lower fluxes are likely to have a wider distribution of spectral indices, which may peak between flat- and steep- depending on the balance between FSRQs, BL Lacs, and steep-spectrum sources. Looking at the SPT catalog, we find this to be generally true: synchrotron sources with fluxes greater than 50 mJy in at least two bands have a moderately steep median spectral index $\alpha_{95-150}^{\text{max}} = -0.6$, which is the same regardless of if we
restrict to sources in the “falling” quadrant or include all synchrotron-classified sources. Looking at synchrotron sources in the lower range of flux probed by the SPT-SZ catalog, $S_{150} < 20\text{mJy}$, but still detected above $4.5\sigma$ at 150 and 220 GHz such that they will have well-measured spectral indices, we find the same median $\alpha_{95-150}^{\text{max}}$ but with a wider distribution. We also note, however, that the width of the distribution in $\alpha_{95-150}^{\text{max}}$ will necessarily be wider for lower-flux sources just due to larger scatter from noise.

These median spectral indices are slightly steeper than those found by M13 (median $\alpha_{150-220}^{\text{max}} = -0.48$ for synchrotron sources detected at greater than $5\sigma$ at 150 and 220 GHz), likely due to the fact that while the full SPT-SZ survey area is relatively uniform in noise level, most of 14 fields newly added to the full 2500-square-degree analysis were slightly less deep relative to the fields from M13, and therefore, on average, the distribution of sources extracted in the 2500 square-degree analysis will shift to a slightly higher flux level relative to the M13 (we find fewer lower-flux sources because the noise levels are slightly higher) and therefore the full 2500 square-degree catalog is likely to be slightly more dominated by FSRQs.

Sources in the “peaking” quadrant are classified as synchrotron and have a flat, or falling index between 150 GHz and 220 GHz, but a rising spectral index between 95 GHz and 150 GHz. In the SPT catalog, there are 742 sources in this quadrant. Physically, we might expect sources to fall in this category if they are AGN with significant self-absorption. Gigahertz peaked-spectrum (GPS) sources are synchrotron sources that peak generally in the range 500 MHz-10 GHz [O’Dea 1998] due to either self-absorption of synchrotron or to free-free absorption in the ionized outskirts of the source [Dallacasa et al. 2000]. High Frequency Peakers (HFPs) peak at frequencies above 5 GHz, and are considered to be smaller and therefore younger given the measured correlation between source size and turnover frequency and the understanding that these sources expand as they age [Dallacasa et al. 2000]. HFPs still generally peak at only tens of GHz, but this may be due to selection effects of the bands used to detect them [Dallacasa et al. 2000]. We would also expect that CMB would fall in this quadrant, and therefore, this quadrant may also contain false detections of CMB features. Of the source in the SPT-SZ survey that fall in the “peaking”
quadrant, 88% are single-band detections in 150 GHz only, indicating that many have relatively low flux, given the noise threshold is lowest for 150 GHz and sources just barely detected at 150 GHz may be below the noise threshold at 90 and 220 GHz, and meaning their flux deboosting is quite uncertain. About half of the “peaking” sources have cross-matches in SUMSS; only about 6% have cross-matches in IRAS.

2.6.1.2 Dusty sources

Looking at all 850 dusty-classified sources, we find median spectral indices of $\alpha_{95-150}^{\text{max}} = 1.72$ and $\alpha_{150-220}^{\text{max}} = 2.72$, which steepen to $\alpha_{95-150}^{\text{max}} = 2.28$ and $\alpha_{150-220}^{\text{max}} = 3.24$ when considering only sources detected above 4.5\(\sigma\) at both 150 and 220 GHz. They also steepen to $\alpha_{95-150}^{\text{max}} = 2.08$ and $\alpha_{150-220}^{\text{max}} = 2.80$ when considering only dusty sources in the “rising” quadrant (684 sources), and $\alpha_{95-150}^{\text{max}} = 2.60$ and $\alpha_{150-220}^{\text{max}} = 3.24$ for sources in the “rising” quadrant detected above 4.5\(\sigma\) at both 150 and 220 GHz. For the list of lensed SMG candidates, we find median spectral indices of $\alpha_{95-150}^{\text{max}} = 2.04$ and $\alpha_{150-220}^{\text{max}} = 2.64$, which steepen to $\alpha_{95-150}^{\text{max}} = 3.20$ and $\alpha_{150-220}^{\text{max}} = 3.24$ for lensed SMG candidates detected above 4.5\(\sigma\) at 150 and 220 GHz.

From Casey et al. (2014), we expect dusty galaxies observed at relatively high observing frequency such that we are probing the Rayleigh-Jeans side of the spectrum to follow a modified Blackbody spectrum, $S_\nu \propto \nu^\beta B_\nu(\nu, T_d) \propto \nu^{\beta+2}$, where $\beta$, the dust emissivity spectral index is often assumed to be 1.5 and measured to be in the range 1-2 for starburst galaxies. Thus, we expect to find measured spectral indices for dusty sources in the range $\alpha = 3-4$, and we find the SPT catalog to be relatively consistent with this, especially for dusty sources with well-measured spectral indices (detected at both 150 and 220 GHz).

We find 166 sources in the “dipping” quadrant, which are dusty-classified sources with typically greater flux at 95 and 220 GHz relative to 150 GHz. We expect these sources to be nearby spiral galaxies or ULIRGs (Mocanu et al., 2013) such that they look like synchrotron sources but with an extra dusty component causing additional flux at 220 GHz. About 70% of the sources in the “dipping” quadrant have cross-matches in external catalogs, especially SUMSS, and most of
the brightest “dipping” sources have cross-matches in SUMSS, IRAS, and WISE, as expected for nearby galaxies.

Most sources in the “dipping” quadrant don’t have a strong preference of falling in that quadrant: many are detections in only 95 GHz or only 220 GHz, meaning they have high uncertainties on their deboosted spectral indices, or they are relatively close to the threshold of a different quadrant. Using the posterior distributions for $\alpha_{95-150}^{\text{max}}$ and $\alpha_{150-220}^{\text{max}}$ to calculate a probability for each source to be deboosted into the dipping quadrant, of the five sources with greater than 90% likelihood of being in the dipping quadrant, two are part of objects detected as multiple counts in the source-finding, indicating that they are extended, and therefore likely low-redshift and possibly have greater uncertainty on their measured flux from not optimally matching the source profile used to extract them. One of the five sources is part of an extended galactic source.

We would also expect that galactic HII regions should fall in the “dipping” quadrant. The sources in the catalog that cross-match with galactic HII regions are mostly divided between the “rising” and “dipping” quadrants. However, most of these sources are quite extended and therefore are detected in the catalog in multiple source detections, making their measured fluxes relatively inaccurate.

2.6.1.3 Millimeter-wavelength star characterization

Millimeter wavelength observations of cool stars can provide interesting insight into the nature of these objects. The baseline expected flux measured at mm-wavelengths is due just to observing the tail of the stellar blackbody radiation, where the stars detectable by SPT are those that are large and bright enough that despite observing the SED in a wavelength range where the flux is many orders of magnitude below the star’s peak output, it is still detectable above the SPT noise level. However, excess mm-wavelength emission above the stellar SED or a spectral break from the expected $\nu^2$ of the stellar blackbody may indicate the presence of dust or potentially stellar winds, though the effects of winds are likely to be subdominant to dust because the stellar atmosphere will be optically thin at millimeter wavelengths [O’Gorman et al. (2017) and conversations with
Figure 2.11 shows SEDs for the ten stars identified in the SPT-SZ catalog, including fluxes drawn from a variety of external catalogs that have been fit with a blackbody function. Of the ten stars in the SPT-SZ catalog, * P Dor, * bet Gru, * pi.01 Gru, V* R Hor, V* X Pav, and V* NU Pav show flux in the SPT bands consistent with blackbody fits to the stellar SED. The other four stars identified in the SPT data have somewhat different spectral behavior from following the tail of the stellar blackbody. Two stars show excess emission but similar spectral indices: * β Pic and V* RZ Sgr. * β Pic is well-known to have a distinctive dusty debris disc with a median dust temperature of 79 K (Riviere-Marichalar et al., 2014), and shows strong excess flux in the SPT bands relative to the expected stellar SED and a spectral index slightly steeper than the expected $\nu^2$ of the stellar blackbody, likely due to dust modification of the blackbody spectrum. V* RZ Sgr shows an excess of flux in mm-wavelengths but with a typical blackbody spectral index. It is known to have an optical nebula (Whitelock, 1994) and a circumstellar shell large enough to be resolved by IRAS at 60 μm (Young et al., 1993), and therefore the extra emission observed in the SPT bands is consistent with the significant presence of dust.

Two stars show spectral indices distinctly different from the stellar blackbody: V* RR Tel and del02 Gruis. V* RR Tel and shows quite flat spectral indices as well as excess flux in SPT bands. This star is known to be a symbiotic nova, with a red giant in mutual orbit with a white dwarf (Ivison et al., 1995), and its distinct spectrum may indicate the presence of significant stellar winds (Güdel, 2002) or the effect of ionization from the white dwarf. del02 Gruis, a red giant, also has a relatively flat measured spectral index in SPT bands, but it is detected in the SPT maps only at 150 GHz, and therefore its spectral indices are considerably more uncertain.
Figure 2.11: Spectral energy distribution for the ten stars detected in the SPT-SZ catalog drawing fluxes from a variety of external catalogs from the literature. To disentangle how much of the flux in mm-wavelengths is due to the stellar emission relative to possible excess emission from dust, the SEDs have been fit (grey dashed lines) with a model assuming a blackbody spectrum for the stellar emission. The model is a two-parameter fit for effective temperature, $T_{\text{eff}}$, and angular diameter. Although the data used for each star’s fit depended on available data in the literature, the data included in the fit is predominantly AKARI IRC and FIS, IRAS, and 1.25 – 60 µm from DIRBE (Hauser et al., 1998). The fit data is selected to include mainly IR and near-IR in order to constrain $T_{\text{eff}}$, which sets the peak wavelength of the stellar-only part of the emission and therefore test for excess at mm-wavelengths in the Rayleigh-Jeans tail of the spectrum. Fluxes reported by WISE are not included in the fit, as it is expected that WISE will be saturated for sources of these flux levels (Cutri et al., 2013). Error bars on the fit assume a flat fractional 5% error on the fit data. For stars with available measurements of $T_{\text{eff}}$ and angular diameter in the literature, those values were used as starting parameters for the fit.
Figure 2.12: Number counts of SPT synchrotron-dominated sources. All sources in the catalog that are identified as stars have been removed from the catalog prior to the counts calculation. Additionally, sources flagged by the “ext cut,” which cuts sources identified as extended have been removed. A comparison of the effects of different cut versions on the number counts can be found in Figure 2.13. Overplotted are the De Zotti et al. (2005) and the Tucci et al. (2011) models, which have not been fit to the SPT data.

Figure 2.13: Number counts of SPT synchrotron-dominated sources, showing a comparison of different cut versions. All sources in the catalog that are identified as stars have been removed from the catalog prior to the counts calculation. Three cut versions are shown: 1) only stars have been removed, “no cuts.” 2) Cutting all stars and all sources flagged as extended or detected as multiple detections and confirmed to be from a single object, “ext cut,” and 3) cutting all sources with measured redshifts $z < 0.1$, “$z$ cut.”

### 2.6.2 Number counts characterization

#### 2.6.2.1 Synchrotron population

Differential number counts per band for synchrotron-dominated sources are shown in Fig. 2.12 along with comparison to two models: De Zotti et al. (2005) and Tucci et al. (2011), neither of which have been fit to the SPT counts. The SPT counts shown are calculated using the method
described in Section 2.5 on the SPT source population with the “ext cut” flagged sources removed. Plots comparing non-cut and different cut versions of the synchrotron counts are shown in Fig. 2.13; since the “ext cut” and “z cut” synchrotron counts are quite similar, we choose to only plot the “ext cut” counts for synchrotron sources in plots in the body of the paper.

The De Zotti et al. (2005) cosmological evolution model includes separate components for multiple synchrotron populations: steep spectrum radio sources and two populations of flat-spectrum sources (blazars): flat-spectrum radio quasars (FSRQs) and BL Lacs, as well as other more exotic but less dominant populations such as Advection-Dominated Accretion Flows, GHz-peaked radio sources, dusty star-forming galaxies and the SZ-effect. It describes each population with a comoving luminosity function extrapolated to higher frequencies using a simple power law ($\alpha = -0.1$) for flat-spectrum sources and some spectral steepening for steep-spectrum sources.

Similar to De Zotti et al. (2005), the Tucci et al. (2011) model extrapolates source counts using spectral behavior measured at low radio frequencies (5 GHz). But the extrapolation is developed using characteristics of the physical mechanisms of emission for different populations, focusing specifically on flat-spectrum sources which dominate the number counts at cm- to mm-wavelengths and fluxes brighter than $\sim 10$ mJy. The emission from flat-spectrum sources originates mainly from self-absorbed and shock-heated jet components in the optically-thick, compact, core regions of the AGN. As high-energy electrons leave the core and are injected into the jets, they lose energy due to synchrotron emission, and depending on the balance of injection rate and cooling, the spectrum of their synchrotron emission must steepen above some frequency. Furthermore, the apparent size of the optically-thick AGN core reduces with increasing observing frequency such that at higher observing frequencies, the emission will become dominated by the optically-thin jet, with a correspondingly a steeper spectrum (Tucci et al., 2011). Therefore, at some frequency in the range 10-1000 GHz, where the particular value of the break frequency depends on the size of the core and other physical characteristics of the source emission, the spectrum of emission from flat-spectrum sources will break and steepen for higher frequencies. Correspondingly, the number counts at higher observing frequencies for models that include a spectral break will be lower than
models without a break, and the amount of reduction depends on the break frequency and post-break spectral index. This effect is most prominent for higher flux sources, because the brighter fluxes are more strongly dominated by flat-spectrum sources. The SPT-SZ counts are compared with the “C2Ex” version of the Tucci et al. (2011) model, which is the version that best fits data at frequencies \( \gtrsim 100 \) GHz, as confirmed mainly with comparison to Planck ERCSC counts, which has strong constraining power at the highest flux ranges due to full-sky coverage.

While historically the De Zotti et al. (2005) model has been broadly successful in extrapolating to higher frequencies (De Zotti et al., 2010), because the De Zotti et al. (2005) model does not include a spectral break for flat-spectrum sources, we expect that it will become less of a good fit to the counts relative to the Tucci et al. (2011) model with increasing observing frequency and increasing source flux. Looking at Fig. 2.12 while the De Zotti et al. (2005) model is in moderate agreement with the SPT-SZ counts at 95 GHz, it becomes an increasingly poor fit to the counts at higher frequencies, particularly at high fluxes, where FSRQs will dominate. The Tucci et al. (2011) model is a reasonably good fit to the data at all three SPT-SZ frequency bands, particularly for fluxes \( \gtrsim 100 \) mJy. Below this flux level, both the De Zotti et al. (2005) and Tucci et al. (2011) models tend to somewhat underestimate the counts. For these observing frequencies, at flux levels below approximately 10 mJy, the contribution to the number counts from FSRQs becomes comparable or even subdominant to other components of the AGN population, mainly BL Lacs and steep-spectrum sources, and the slight underestimate of the models may be due to the physics included in modeling those subpopulations. However, we note that because the SPT counts are drawn from repeated resamplings from the posterior distributions from deboosting, flux information from a single source will scatter into multiple flux bins in the number counts, especially for flux ranges near the SPT noise threshold where the posterior distributions are wider due to noise. Therefore, the SPT number counts in adjacent bins will be somewhat correlated, particularly at lower fluxes.
Figure 2.14: Number counts of SPT dust-dominated sources. All sources identified as stars have been removed from the catalog prior to the counts calculation. Additionally, two cuts have been applied to the source populations feeding into the counts calculation: 1) all sources with measured redshifts $z < 0.1$, “z cut,” and 2) all sources identified as being extended, “ext cut.” Overplotted are the [Béthermin et al. (2012)] and [Cai et al. (2013)] models, including lensed and total counts versions, neither of which have been fit to the SPT counts. Plots showing a comparison of the two cuts along with counts calculated with no cuts applied are shown in Figure 2.15.

Figure 2.15: Number counts of SPT dust-dominated sources, showing a comparison of different cut versions. All sources identified as stars have been removed from the catalog prior to the counts calculation. Four cut versions are shown: 1) only stars have been removed, “no cuts.” 2) Cutting all stars and all sources flagged as extended or detected as multiple detections and confirmed to be from a single object, “ext cut,” 3) cutting all sources with measured redshifts $z < 0.1$, “z cut,” and 4) “lensed candidate SMG” list, cutting all sources with measured redshifts, IRAS cross-matches, or dipping spectral behavior in the SPT bands.

2.6.2.2 Dusty and SMG source populations

Differential number counts per band for dust-dominated sources are shown in Fig. 2.14 with comparisons to two representative models: [Béthermin et al. (2012)] and [Cai et al. (2013)], including lensed and unlensed versions. None of the models considered here have been fit to the SPT number...
Fully-integrated forward-evolution models linking primordial density fluctuations to late-time galaxy counts, underpinned by physical characteristics and describing the full richness of current galaxy datasets are not yet achievable. Therefore, most models combine forward-physical and backward-phenomenological components to describe different populations of the observable galaxy population, including late-type warm (starburst) and cold (normal) galaxies, as well as lensed and unlensed spheroids and protospheroids. From the Cai et al. (2013) model, while late-type galaxies are expected to dominate the differential number counts at 95 GHz, the dusty SPT differential counts at 150 and 220 GHz are expected to be dominated by lensed sources for all but the very highest fluxes. Furthermore, because low-redshift sources are explicitly trimmed by the redshift cut, we expect the “z cut” SPT counts shown in Fig. 2.14 will be dominantly SMGs, and therefore should agree better with lensed components of models. Because extended sources should all be at low redshift, trimming them should also make the “ext cut” counts agree better with lensed models compared with models including lensed and unlensed components, but since fewer sources are trimmed from this cut version, the counts will be slightly higher than the “z cut” counts.

The Béthermin et al. (2012) model includes main sequence and starburst galaxies as the two main components of the model, using one SED per component from libraries from Herschel. Because phenomenological or hybrid models are limited by lacking physical underpinnings describing the evolution of the luminosity function, instead the Béthermin et al. (2012) model is based on two distinct star-formation mechanisms and their evolution, one for each galaxy component, based on the work in Sargent et al. (2012). The contribution from strong gravitational lensing is accounted for by applying a magnification factor to the luminosity function. Both the unlensed and lensed versions of the models generally underpredict counts at 95 GHz. The lensed Béthermin et al. (2012) model is consistent with SPT number counts at lower flux ranges in 150 and 220 GHz, but overestimate at higher fluxes, and the total model overestimates the counts in 150 and 220 GHz for almost all flux bins.

The Cai et al. (2013) model is a hybrid model, combining a physical, forward model for
spheroidal galaxies and backward-evolution model for late-type galaxies, based on observations that early-type galaxies are dominated by older stellar populations, while late-type galaxies have younger stellar populations. They improve on previous models by considering components of the flux for protospheroidal galaxies from star formation and central AGN in a unified way, rather than being considered separately. Protospheroidal galaxies are modeled using Granato et al. (2004), and low-z galaxy populations are considered in two populations: “warm” starburst galaxies and “cold” late-type galaxies. A magnification factor is applied to account for strong lensing of high-redshift protospheroidals, which dominates at the flux ranges and wavelengths where SPT observes. Similar to the Béthermin et al. (2012) total and lensed models, the Cai et al. (2013) models, both total and lensed versions, underestimate counts at 95 GHz. Lensed and total versions of the model are in relatively good agreement to the SPT counts at lower flux ranges in 150 and 220 GHz, but the total version of the model overestimates the counts considerably at higher flux ranges, and the lensed version moderately overestimates the counts at higher fluxes.

We note that while the SPT dusty number counts at 150 and 220 GHz agree relatively well with models, the counts at 95 GHz exceed both models under comparison. In a reanalysis of SPT point source number counts from Mocanu et al. (2013), Mancuso et al. (2015) fit SEDs to bright 95-GHz SPT sources using data from a wide range of wavelengths from radio to infrared. They found that several SPT sources with relatively bright 95 GHz fluxes classified as dusty galaxies by the SPT analysis pipeline classification have potentially unclear identification when considering broader wavelength information and may indeed not be dusty galaxies. We note that the exact classification of these sources remains somewhat unclear and they all have well-measured dusty spectral indices between 150 and 220 GHz; three of these sources have “dipping” behavior in SPT bands, indicating the possible presence of both synchrotron and dusty emission, and may be affected by blending of nearby objects, which can make it difficult to cross-match in external catalogs. Nevertheless, because we classify sources into dusty and synchrotron categories using a statistical resampling of each source’s posterior distribution on spectral index, but the number counts of the synchrotron population dominates that of the dusty population, we may see leakage
of synchrotron sources into the dusty-classified population, as Mancuso et al. (2015) suggests. We note that the SPT classification pipeline we employ relies only on the measured SPT fluxes, which is essential given that low signal-to-noise sources in the SPT catalog may not have cross-matches in external catalogs, and it may be that using only information from SPT bands is not sufficient to classify sources distinctly enough that the populations in the SPT-only catalogs are identical to the populations probed by current models.

Figure 2.16 shows an overview of all the different source populations present in the SPT-SZ catalog. The plot shows cumulative 220 GHz counts, including total, synchrotron-only, and dusty-only components. Contributions to dusty counts are considered in three components: low-z LIRGs, SMG lensed candidates, and unlensed high-z sources, with empirical counts from the SCUBA-2 instrument (Geach et al., 2017). SPT number counts for low-z dusty sources have been calculated using sources that are trimmed by the “z-cut,” and because we know the flux measurements for these sources is biased too low, their calculation is shown more for illustration than as a quantitative comparison. Nevertheless, they agree relatively well with the Béthermin et al. (2011) model. The Negrello et al. (2007) lensed-only model agrees well with number counts calculated from our lensed candidate list; however, we note that the Negrello et al. (2007) model was tuned to match empirical number counts at 850 µm, and therefore is more fine-tuned than the other models compared with in Figure 2.14.

2.6.3 Comparison with previous SPT-SZ point source results

As the third and final compact source data release from SPT-SZ, the full 2530 square-degree analysis covers a factor of 3.3 times the area of the previous release, M13, including 1759 square-degrees of previously unanalyzed data. Due to alterations of the source-finding pipeline and differences in mask areas to aid full survey coverage, the five sky fields covered by the previous two analyses, V10 and M13, have be reanalyzed in the current analysis, and for RA5h30dec-55 and RA23h30dec-55 which were originally observed in 2008 and then reobserved in 2010 and 2011 to add 95 GHz coverage and greater depth at 150 and 220 GHz, we have incorporated the previously
Figure 2.16: An overview of $N(>S)$ for 220 GHz, showing counts for SPT total counts, synchrotron-dominated source counts, and dusty-dominated counts split into high-redshift and low-redshift populations, where we expect that the high-redshift population best represents SMGs.

unanalyzed 2010 and 2011 data. Although a large majority of the sources extracted in the five reanalyzed fields are consistent with past reported catalogs, there are slight differences in sources extracted between M13, V10, and the current analysis. These differences are due mostly to the lower noise in 150 GHz for ra5h30dec-55 and ra23h30dec-55 and the slightly different treatment of map noise used for source detection in the current analysis, as discussed in Section 2.3.4. We confirm that the sources that differ generally have signal-to-noise values very close to the detection threshold.

As expected, the increase in sky area with generally comparable noise level also reduces the error bars on the calculated number counts and adds a few flux bins of counts that were either upper limits or missing from M13. The error bars on the uncut version of the counts, which are most directly comparable to the M13 counts, reduce roughly by a factor of 50%, consistent with the amount of area increase.

The smaller error bars allow the SPT number counts to be more constraining of the param-
eters of galaxy evolution models. For the synchrotron counts, the Tucci et al. (2011) model more clearly agrees with the number counts than the older De Zotti et al. (2005) model, as shown in Fig. 2.12, whereas the M13 counts showed a weaker preference between models, particularly at 95 and 150 GHz. Since the main difference between the two models is the inclusion of a spectral break for FSRQs, the greater constraint shows a clear preference for the presence of a spectral break, although the counts are not constraining enough to provide much further information on the models, such as the break frequency, which might further constrain the AGN core size. Similarly, the smaller error bars for the dusty counts, will provide clearer constraints particularly on parameters governing lensed sources, such as the expected lensing magnification factor, such as in Figure 2. of Bonato et al. (2014).

2.7 Conclusion

We present a catalog of 4841 compact sources with fluxes measured at 95, 150, and 220 GHz, identified in the SPT-SZ survey from observations taken with the South Pole Telescope from 2008-2011. The SPT-SZ survey was observed in 19 independent fields, and each field has been analyzed separately, with masks chosen so as to provide full survey coverage in all three bands with a total covered area of 2530 square degrees. Single-band and single-field catalogs were then concatenated and cross-matched to form a single multi-band catalog. Sources have been identified and fluxes measured using a matched-filter approach, assuming sources are unresolved by the SPT beam. Sources in the catalog have detections with a significance of $4.5\sigma$ or higher in at least one band, representing detections above roughly 9.8, 5.8, and 20.4 mJy at 95, 150, and 220 GHz, respectively, though specific detection limits per band are specific to each field. Purity and completeness have been calculated per field, with median purity values across the survey for detections above $4.5\sigma$ of 94.4%, 94.8%, and 83.4%, and median 95% completeness at flux levels of 12.9, 7.6, and 26.8 mJy, for 95, 150, and 220 GHz, respectively. Because the source populations have number counts that are a steep function of flux, the fluxes for the detected source population suffer from a positive flux bias, and we employ a Bayesian deboosting method to
correct this bias. Compact emissive, extragalactic sources observed in mm-wavelengths physically correspond to broadly two distinct populations: 1) active galactic nuclei, which emit primarily through synchrotron radiation, and 2) dusty star-forming galaxies, which emit via thermal radiation by dust, many of which are at high redshift and magnified by strong lensing. Because the two populations have different dominant emission mechanisms, which have distinctly different spectral behavior, we use each source’s measured flux in three frequency bands to separate the cataloged sources into synchrotron and dusty populations. Using a bootstrap method, we calculate number counts for the total population as well as synchrotron- and dusty-only populations. We cross-match the catalog with seven external catalogs, including surveys from radio, IR, and X-ray wavelengths, and cross-match with available redshift information. This work represents the final data release for compact sources observed in the SPT-SZ survey, building on previously-published results in Vieira et al. (2010) and Mocanu et al. (2013).
Chapter 3

Introduction and Overview of SPT-3G

3.1 SPT-3G Instrument overview

Bolometers for mm-wavelength observations of the CMB have achieved background-limited noise performance, meaning that the primary way to improve measurements of the CMB is by increasing the number of detectors observing the sky. To achieve its ambitious science goals, SPT-3G increased the detector count on the sky by roughly an order of magnitude relative to the previous generation instrument on SPT, SPTpol, from \( \sim \) 1500 detectors to \( \sim \) 15,000. To this end, SPT-3G has three primary improvements relative to SPTpol in order to accommodate the increase in detector count: 1) SPT-3G employs multichroic, polarization-sensitive, pixels so that the light from each broad-band antenna is measured in three bands (centered at 95, 150, and 220 GHz) and two polarizations. 2) The optics chain of the telescope has been redesigned to increase the diffraction-limited field of view from 1.2 degrees for SPTpol (George et al., 2012) to 1.9 degrees for SPT-3G (Anderson et al., 2018). 3) The DfMUX multiplexing factor has been increased from 12x for SPTpol to 68x for SPT-3G.

The receiver for SPT-3G is comprised of two cryostats, an optics cryostat and a detector cryostat, which are held in optical alignment with a support structure of trusses made from thermally-isolating G-10 at that interface. The detector cryostat contains the millikelvin stage holding the ten detector wafers with cold readout towers as well as SQUID amplifiers cooled to 4 K. The optics cryostat mounted on the front of the detector cryostat contains the cooled refracting optics chain discussed further in Section 3.1.1 below. An overview diagram of the two cryostats
is shown in Figure 3.1 showing the main cooled optical elements and location of the focal plane. The optics and detector cryostats each employ a continuously-running PT415 pulse tube cryocooler made by Cryomech, which maintain steady 4 K head temperatures of 3.5 K and 3.2 K for the optics and detector cryostats, respectively, during sky observations.

Figure 3.1: Model cutaway of the optics and detector cryostats. From Anderson et al. (2018).

### 3.1.1 Optical Design

SPT-3G employs the same 10-m primary with 1-m guard ring as SPTpol, and replaces the cooled SPTpol secondary mirror with an ambient-temperature ellipsoidal secondary combined with a flat tertiary to couple light into the optics cryostat holding a set of refracting lenses made from amorphous aluminum oxide (alumina) that reimage the light onto the focal plane. The optics cryostat contains an HDPE window, an alumina IR shader at 50 K, and three 720-mm-diameter alumina reimaging lenses (Benson et al. 2014). The optics cryostat also contains a cold Lyot stop.
with a 9 icm metal mesh low-pass filter cooled to 4.5 K to reduce stray light from scattering and
to terminate some optical power from the sky to reduce optical loading on the focal plane. In the
SPTpol optics, the cold secondary was over-illuminated, terminating considerable optical power on
HR 10 at 10 K \cite{George2012}. For SPT-3G, the secondary and tertiary mirrors are under-
illuminated and the Lyot stop is colder, resulting in comparable optical loading (1–2 pW) from the
SPT-3G warm secondary, tertiary, and stop as from the cold secondary for SPTpol \cite{Anderson2018}. The left panel of Figure 3.2 shows a ray trace of the SPT-3G optics. The new secondary
and tertiary as well as the optics and detector cryostats (which weigh a combined \sim 1300 lbs) are
held by a new optics bench, as shown in the right panel of Figure 3.2, from Bender et al. \cite{Bender2018},
which has 6-axis movement control to adjust instrument focus.

At the focal plane, light is coupled to the sinuous planar antennas in each pixel using hemi-
spherical alumina lenslets each with roughly 5-mm diameter. The lenslets are constructed in hexag-
onal arrays of 271 lenslets each, mounted to the detector wafer, and cooled to \sim 250 mK.

Given the large number of refracting optical elements, and the relatively high index of re-
fraction of alumina of $n \approx 3$ (and therefore relatively large reflection coefficient at each alumina-air
boundary), optimizing transmission at each interface with anti-reflection (AR) coatings becomes
greatly important. During the first year of SPT-3G deployment, the three large alumina lenses
were deployed with a two-layer thermal-spray-based AR coating with good transmission at 95 and
150 GHz but with suboptimal performance at 220 GHz. For the second year of SPT-3G, this AR
coating was replaced with a three-layer thermally-bonded coating of PTFE with LDPE used as an
adhesion layer, as detailed in Nadolski et al. \cite{Nadolski2018}. Three layers with different densities of PTFE
allows for a smoother transition between the high spectral index of alumina and air, increasing
transmission over a broader range of frequencies. The hemispherical alumina lenslets also employ a
similar three-layer PTFE AR coating thermally-molded in a monolithic sheet, one for each lenslet
wafer. FTS measurements made on sample AR-coated alumina pucks at the University of Califor-
nia Berkeley of spectral transmission indicate that our expected transmission at each air-alumina
interface in the three SPT-3G bands will be better than 0.99, 0.98, 0.77 at 95, 150, 220 GHz,
3.1.2 Expected optical loading

The expected total optical power reaching the focal plane as well as the photon noise from that optical power provide critical constraints on detector design parameters, and for CMB experiments such as SPT-3G, the photon background is generally dominated not by the CMB but by emission from the atmosphere, as well as from optical elements in the optics chain of the receiver. Table 3.1 gives an overview of expected dominant optical loading for SPT-3G bolometers. For photon sources with a blackbody spectrum, such as the CMB, atmosphere, or optical elements, the expected photon loading illuminating a detector with spectral response $\varsigma(\nu)$ is given by

$$P_{\text{ext}} = \eta \sum_i \epsilon_i \tau_i \int_\nu A\Omega \frac{B(\nu, T_i)}{2} \varsigma(\nu) d\nu,$$

where $B(\nu, T_i)/2$ is the Planck blackbody spectral radiance for a single polarization and...
source temperature $T_i$. $\eta$ is the bolometer optical coupling efficiency; $\epsilon_i$ is the emissivity of the $i$th source and $\tau_i$ is the product of transmissivities of all elements in between the $i$th source and the bolometer.

The expected loading shown in Table 3.1 assumes an overall 85% bolometer optical efficiency with an additional 50% efficiency due to single-polarization sensitivity per bolometer. Because the bolometer, sinuous antenna, and lenslet are all at the subkelvin stage bath temperature of order 250 mK, they each contribute negligibly to the optical loading, < 0.01 pW.

### 3.2 SPT-3G bolometer and pixel design

The focal plane for SPT-3G is made up of ten 6-in-diameter hexagonal modules, each containing a silicon detector wafer with 269 lithographed pixels. The foundation of each detector wafer is a monolithic 150-mm-thick silicon wafer on which is deposited a 1 µm-thick layer of low-stress silicon nitride, $\text{Si}_3\text{N}_4$. The next layer, of 300-nm-thick layer of niobium, serves as the ground plane for the wafer and the material for the antenna arms, and a 500-nm-thick layer of silicon oxide, $\text{SiO}_x$, on top of that serves as the dielectric for Nb microstrip connecting all circuit elements in each pixel and from each pixel to the edge of the wafer. Quasi lumped-element filters in the microstrip transmission lines define the bandpass frequencies of each bolometer, where the band centers are then fixed by the dielectric thickness, and must be carefully designed and tested to avoid band overlap with water vapor emission and absorption lines in the sky atmosphere (Posada et al., 2018).

Each 6.8-mm pixel comprises a broad-band, polarization-sensitive sinuous antenna and six TES bolometers, measuring two orthogonal polarizations in three frequency bands centered at 95, 150, and 220 GHz, with bandwidths of roughly 23, 38, and 47 GHz, respectively. All structures within in each pixel are constructed using stepper-based lithography. An overview of the pixel architecture for SPT-3G is shown in the labeled SEM image in Figure 3.3 from Posada et al. (2015). The sinuous antenna (Duhamel, 1987) is log-periodic in the repeated, scaled pattern of the antenna arms, allowing it to have broadband frequency sensitivity with relatively flat impedance (Suzuki et al., 2012). As shown in Figure 3.3, the niobium arms of the antenna (light in color in Figure 3.3...
Table 3.1. Expected SPT-3G Optical Loading

<table>
<thead>
<tr>
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<th>Temp [K]</th>
<th>95 GHz</th>
<th>150 GHz</th>
<th>220 GHz</th>
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<tr>
<td></td>
<td>$\epsilon_i$</td>
<td>$\eta_i$</td>
<td>Power [pW]</td>
<td>$\epsilon_i$</td>
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<td>Lyot stop</td>
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<td>0.05</td>
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<td>Aperture Lens</td>
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<td>0.08</td>
<td>0.91</td>
<td>0.06</td>
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<td>Field Lens</td>
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<td>0.91</td>
<td>0.09</td>
</tr>
<tr>
<td>Alumina Filter</td>
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<td>0.03</td>
<td>0.96</td>
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<td>0.99</td>
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<tr>
<td>Flat Tertiary</td>
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<td>0.01</td>
<td>0.99</td>
<td>0.34</td>
</tr>
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<td>0.01</td>
<td>0.99</td>
<td>0.34</td>
</tr>
<tr>
<td>Primary</td>
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<td>0.01</td>
<td>0.98</td>
<td>0.28</td>
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<td>0.0</td>
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</tr>
<tr>
<td>Cumulative</td>
<td></td>
<td>0.14</td>
<td>5.09</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Note. — From intra-collaboration communication. Assumes an overall 85% bolometer optical efficiency with additional 50% efficiency for single-polarization sensitivity per bolometer. Values in this table are predictions for the second year of SPT-3G deployment and include predicted increases in optical throughput from improved AR coatings deployed in the second year.
compared with dark regions where the niobium has been etched away) act as the ground plane for niobium microstrip, which is separated from the ground plane by a 500 nm thick dielectric layer of SiO$_x$. The niobium microstrip couples each antenna to the bolometers with in-line three-pole quasi-lumped-element triplexer filters to define the frequency bandpass for each bolometer ([Posada et al., 2015]). Each signal is then terminated on a thermally-isolated island suspended over the bath by four, thin legs of low-stress silicon nitride (Si$_3$N$_4$). As shown in Figure 3.4, the niobium microstrip leads terminate in a 20 Ω Ti-Au load resistor on the island which converts the optical signal to heat and a Ti-Au TES measures the corresponding rise in temperature. Extra heat capacity on the TES island is provided by 700–850 nm thick non-superconducting palladium. A XeF$_2$ etch is used to remove the silicon substrate underneath each TES island, leaving each island suspended and allowing it to float in temperature above the rest of the wafer. The geometry of the legs controls the thermal conductivity of the TES island. As can be seen in Figure 3.4, niobium microstrip from the GHz part of the circuit, the antenna and in-line filters, runs to the on-island load resistor along one set of legs. For the MHz part of the circuit, including the TES and RLC resonance DfMUX circuit, niobium microstrip from the TES runs to the edge of each pixel and then to the edge of each wafer to be connected to the cold DfMUX readout mounted on the backside of each detector module. Details of the fabrication methods, recipe, and optimization can be found in [Posada et al., 2015], [Posada et al., 2016], and [Posada et al., 2018]. The specific fabrication architecture and target design parameters for each deployed wafer for the first, second, and third years of SPT-3G can be found in Table 3.2.

As can be noted in Table 3.2, target fabrication parameters changed somewhat, particularly between first-year and second-year deployment, as the on-sky performance of the first-year focal plane was more fully-characterized during deployment. Measurements of optical power present on the focal plane during first-year deployment, which are discussed in greater detail in Section 5.4, replaced theoretical expectations and allowed for better fine-tuning of target $P_{sat}$ values. As will be discussed further in Chapter 5, targets for transition temperature, $T_c$, of the TES bolometers was shifted downward, which reduces noise from thermal fluctuations in the thermally-isolating
legs, and target normal resistance, $R_n$, also shifted downward to reduce readout noise.

Detector wafers for SPT-3G were fabricated at Argonne National Laboratory, where considerable work in optimizing bolometer design as well as fabrication methods specific to SPT-3G wafers was done in the years leading up to and during SPT-3G deployment. Fine-tuning of fabrication techniques in response to measured detector characterization both in stateside cryostats as well as focal plane characterization after deployment on SPT is also reflected in the changes in design and target parameters. Fabrication techniques to control the XeF$_2$ etch were shown to be influential in determining the resultant $T_c$ and $P_{sat}$ (Ding et al., 2018). Controlled heat treatment has been shown to adjust the $T_c$ of Ti-Au TESs (intra-collaboration communication), and some heating was applied to wafers W136 and W139, deployed in 2017, but ultimately TES geometry was used as the dominant method for adjusting TES $T_c$ for subsequently fabricated wafers. For the first year of SPT-3G deployment, each TES was made up of a Ti-Au bi- or quad-layer, which were swapped in the second year of deployment for all Ti-Au-Ti-Au quad-layer TES architecture. The quad-layer devices have a thin Ti-Au buffer layer in between the 100–200 nm thick Ti layer and the substrate underneath (Ding et al., 2017). The Au layer on the top of the TES serves to protect the TES during the final fabrication steps and during long-term deployment of the array, and the bottom Au layer has been shown to reduce scatter in measured $T_c$ wafer-to-wafer as well as tighten the superconducting transition width, due to buffering the Ti off of the substrate (Ding et al., 2017; Carter et al., 2018). The bottom Ti layer acts as a adhesive layer between Au and the substrate (Carter et al., 2018). Studies of TES geometry using non-released films revealed that relative thicknesses of the quad layers controls the expected $T_c$ of the quad-layer film and its normal resistance can be modified nearly independently by changing the TES width (Carter et al., 2018). However, we note that while these principles work generally for TESs on released islands, the interdependence of $T_c$, $R_n$, and $P_{sat}$ with geometry and fabrication techniques seems to be somewhat more complicated, as noted from comparisons of measured parameters on the wafers deployed for SPT-3G and their design specifications.
Figure 3.3: SEM images of (left) SPT-3G pixel overview and (right) sinuous antenna and bolometer island architecture. From Posada et al. (2015) and intra-collaboration communication with Chrystian Posada.

Figure 3.4: SEM images from Posada et al. (2015) and intra-collaboration communication with Chrystian Posada of (left) close-up images of thermally-isolated bolometer island and (right) TES island architecture.
Table 3.2. Summary of Deployed SPT-3G Wafer Design Targets

<table>
<thead>
<tr>
<th>Deployed Wafers</th>
<th>TES thickness Ti/Au/Ti/Au [nm]</th>
<th>TES width [µm]</th>
<th>SiOx thickness [nm]</th>
<th>target $R_n$ [Ω]</th>
<th>target $T_c$ [mK]</th>
<th>target $P_{sat}$ [pW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>W136*</td>
<td>0/0/200/30</td>
<td>20</td>
<td>490</td>
<td>1.2</td>
<td>510</td>
<td>12.5</td>
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<tr>
<td>W139*</td>
<td>0/0/200/30</td>
<td>20</td>
<td>509</td>
<td>1.2</td>
<td>510</td>
<td>15.0</td>
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<tr>
<td>W142</td>
<td>5/5/200/20</td>
<td>20</td>
<td>522</td>
<td>2</td>
<td>550</td>
<td>16.8</td>
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<tr>
<td>W147</td>
<td>5/5/200/20</td>
<td>15</td>
<td>522</td>
<td>2</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>W148</td>
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<td>15</td>
<td>516</td>
<td>2</td>
<td>550</td>
<td></td>
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<tr>
<td>W152</td>
<td>5/5/160/20</td>
<td>20</td>
<td>510</td>
<td>2</td>
<td>550</td>
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<td>515</td>
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<tr>
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<td>2</td>
<td>550</td>
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<td>20</td>
<td>520</td>
<td>2</td>
<td>550</td>
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<td>2018</td>
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<td>1.7-1.8</td>
<td>420-430</td>
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<tr>
<td>Deployed Wafers</td>
<td>TES thickness Ti/Au/Ti/Au [nm]</td>
<td>TES width [µm]</td>
<td>SiOx thickness [nm]</td>
<td>target $R_n$ [Ω]</td>
<td>target $T_c$ [mK]</td>
<td>target $P_{\text{sat}}$ [pW]</td>
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</tbody>
</table>

Note. — TES geometry and target parameters from intra-collaboration communication for wafers deployed in the first, second, and third years of SPT-3G. For third-year deployment, wafers 187 and 201 were swapped for 204 and 206. Target $P_{\text{sat}}$ based on expected optical loading and design principle of $P_{\text{elec}} \sim P_{\text{opt}}$, with assumed 85% bolometer opt eff. * W136 and W139 had 5 min heat treatment applied at 185 C. ** Wafer 206 TES material was AlMn, all other wafers made with TiAu.
3.3 SPT-3G wafer design and focal plane layout

3.3.1 SPT-3G wafer layout

In order to evenly sample the linear polarization of the CMB sky signal, each detector wafer is populated with alternating pairs of pixels where the sinuous antennae are clocked at 45 deg relative to each other in order to measure Stokes Q and U parameters on the sky. The sinuous antenna is known to have a slight polarization wobble, and pairs of pixels alternate between left-handed and right-handed versions of the antenna to mitigate any bias from this effect (Suzuki, 2013; Posada et al., 2015). Therefore, each detector wafer is populated with four types of pixels: QA, QB, UA, UB, as shown in Figure 3.5 from Posada et al. (2015), arranged in horizontal rows across each wafer.

![Figure 3.5: SEM image showing the four variations in pixel architecture used to populate each detector wafer. Antenna clocking by 45 degrees is used to evenly sample polarization on the sky, and left- and right-handed versions of the sinuous antenna are used to account for a slight polarization wobble in the sinuous antenna response. Image from Posada et al. (2015).](image)

To aid in wafer characterization both in testing prior to deployment and during focal plane characterization after deployment, wafers are fabricated with a set of “dark” pixels where some part of the microstrip for a given bolometer has been disconnected so the bolometer receives no optical power. These dark pixels then enable characterization of optical and non-optical electrothermal properties on the wafer and in the receiver. For the first year deployment, there were six dark pixels (and therefore a total of 36 dark bolometers per wafer), one each along each edge of the wafer, where
the microstrip connecting from antenna to TES island was disconnected during fabrication. Since most stateside cryostats did not have the readout hardware capacity to connect to wiring on all six sides of a given wafer, typically one or two sides at most were tested, and the fabrication masks were changed to locate the dark pixels to be all along the outer edge of a single side of the wafer. In addition, for wafers W180 and higher, the wafers were fabricated with two distinct types of dark pixels: pixels where the termination resistor on the TES island is absent, resulting in the GHz circuit being disconnected, and pixels where the Nb cross-over step in fabrication has not been deposited, disconnecting four of the six bolometers in a pixel. Therefore, for second-year deployment wafers, W172, W174, W176, W177 also had 36 dark bolometers (no termination resistor), W180 and W181 had the same set of 36 dark bolometers but also an additional 16 bolometers that were dark from lacking cross-over structures. W187, W188, W201, W203, W204, W206 had dark bolometers all along one edge of the wafer, with 24 dark bolometers with no termination resistor and 16 dark bolometers from lacking cross-overs.

3.3.1.1 Array-level wiring layout

Multichroic pixels and an emphasis on close-packing of pixels on each detector wafer results in a complex task of routing wires to and from every bolometer on the wafer. Two wires each for six bolometers per 269 pixels per wafer yields a total of 3228 wires that must be mapped from the interior of the wafer to bond pads at the wafer edge to be connected with cold readout. Microstrip lines from the interior of each pixel are traced to niobium pads at the edge of the 5.9 mm circular footprint defining each pixel, which in turn connect to a circular ring of Nb microstrip, connecting then onward to bundles of microstrip routed in a hexagonal pattern to each edge of the wafer. Initial design concepts for the array-level wiring were based on detector wafers for the POLARBEAR instrument (Suzuki et al., 2016) and were adapted for SPT-3G detector wafers. The left panel of figure 3.6 shows an overview SEM image of a fabricated wafer and the microstrip wiring bundles. The combination of using circular rings connected to array-level bundles allows for maximal symmetry in the array-level wiring design and consistency in bolometer ordering at
the edge of the wafer. The QA, QB, UA, UB ordering on the wafer is structured in horizontal rows across the wafer, but the hexagonal nature of the wafer leads to a design based on rotational symmetry in six triangular sections, one for each edge. Therefore, a separate set of circular rings is drawn for each of the six triangular sections and these then act as an interface between the interior pixel design and the array-level bundling. The array-level bundling is therefore completely rotationally symmetric for all edges of the wafer with the exception of one edge where the wiring layer has been adjusted to enable reading out the central pixel of the wafer. The finished array-level wiring design is shown in the right panel of Figure 3.6. Employing this system of interfacing the two symmetries means that every pixel has its bolometers read out in the same order at the edge of the wafer, simplifying the readout bookkeeping. The ordering is detailed in Figure 3.7.

![Figure 3.6: Left: SEM image from Posada et al. (2015) showing pixel interiors and array-level wiring bundles. Right: Drawing of the final layout for the array-level wiring layer.](image)

Fitting the requisite number of wires in was a challenge, and we use 5 μm wide niobium microstrip with 5 μm separation in order to achieve this. Figure 3.8 shows example regions of tightest constriction in the array-level wiring design. Thin wire width with narrow separation in turn produces a tight constraint on fabrication fidelity. Components in the interior of each pixel are lithographed using a stepper, but given the large mask size for the array-level wiring feature, the
Figure 3.7: Drawing close-up of the architecture of the array-level wiring and bolometer readout order for each pixel at the edge of the wafer.

Figure 3.8: Drawing close-up of the array-level wiring showing areas of closest wiring constriction, resulting in the need for 5 µm wire width with 5 µm spacing.
array-level wiring was designed for lithography using a contact aligner. While the contact aligner was employed with relative success for the fabrication of some wafers for SPT-3G deployment, it was discovered that defects resulting from the contact aligner lithography caused low wafer yield, and therefore, this step was replaced with a non-contact laser lithography method [Posada et al., 2018].

### 3.3.2 Module assembly and focal plane layout

Each silicon detector wafer is paired with a silicon lenslet wafer, holding a set of hemispherical alumina lenslets with a monolithic AR coating, as detailed in Section 3.1.1. The two wafers are oriented such that the detector wafer is back-illuminated by incoming sky radiation through the lenslets. Alignment of the two wafers is accomplished using an IR microscope and they are then held in alignment with an invar support frame, where invar is chosen in order to accommodate the differential thermal contraction between the silicon of the wafers and the metal, either copper or aluminum, used for the mounting plate for focal plane. The detector wafer is wirebonded to flexible cables made of polyimide and copper, which connect to cold readout PCB boards holding monolithic capacity and inductor (LC) chips mounted in towers stood off the back of each invar holder, as illustrated in Fig. 3.9. Due to the necessary small size and close-packing of wirebond pads on each wafer edge, as shown in Fig. 3.7, the wirebonding necessitates use of a deep-access automatic wirebonder. The wafer alignment, module assembly, and wirebonding for all SPT-3G wafers is done at Fermilab National Laboratory, and assembled modules (without cold readout) are then shipped to stateside test beds or hand-carried to Antarctica for deployment.

### 3.4 Millikelvin stage description

For the bolometers to have high and linear responsivity, the bath temperature of the focal plane must be held stably below the $T_c$ of the TES transition. A closed-cycle $^4$He-$^3$He-$^3$He adsorption refrigerator made by Chase Research Cryogenics with three-stage cooling is used to hold the focal plane stably at around 270 mK with intermediate buffering stages at 350 mK and 1 K
prior to thermal sinking at 4K by the pulse tube cooler. The three-temperature-stage design of the millikelvin stage holding the focal plane is shown in Figure 3.10 and further detail of the stage mechanical and thermal design can be found in Sobrin et al. (2018). Each temperature stage is thermally isolated by carbon fiber reinforced legs. The ten detector modules combined with cold electronics and focal plane mounting plate weigh of order 23 lbs, and the millikelvin stage must not only minimize thermal conductivity between the temperature stages, but also be strong enough to support the load and vibration-insensitive to avoid excessive microphonic heating or vibration. For the first and second years of SPT-3G deployment, the sub-kelvin stages hold times at base temperature were 22-24 hours with a 4 hour fridge re-cycling duration, yielding an 85% observing efficiency.

### 3.5 SPT-3G readout overview

SPT-3G employs a frequency-domain multiplexing (DfMUX) readout system in order to reduce the heat load on the focal plane from biasing and sensing of order 15,000 detectors. Given
the order-of-magnitude increase in bolometer count relative to SPTpol, the multiplexing factor was also increased by a factor of $\sim 5$. For the first year of SPT-3G, we employed a 64x multiplexing factor which was upgraded to 68x in subsequent years. In the DfMUX scheme, each bolometer is AC-voltage-biased in a series-resonant RLC circuit where the capacitance is varied to change the resonant frequency. All bolometer channels in a single comb are connected in parallel, thus summing their input and output along a single pair of wires. A comb of sine-wave carrier voltage biases tuned to each bolometer’s resonant frequency is supplied and the output from all bolometers on a comb is summed and amplified by a series-array Superconducting Quantum Interference Device (SQUID) at 4K. The SQUID acts as a very sensitive magnetometer, sensing changes in the magnetic field from the summed current as it flows through the SQUID inductance coil to ground. Because the applied AC bias fluctuates at frequencies much higher than the bolometer response time, the bolometers see a constant RMS voltage bias \cite{Dobbs2012}. Because the SQUID has limited dynamic range and non-linear response, a set of “nuller” sine waves, identical but inverted relative to the carrier is supplied to cancel out the carrier, leaving only the sky signal which modulates the current through each TES in symmetric sidebands relative to each carrier frequency \cite{deHaan2012}.  

Figure 3.10: Left: Model diagram of the millikelvin stage assembly overviewing the temperature stages. Right: Photo of the first-year focal plane with mylar RF shielding prior to installation in the SPT-3G receiver during first-year deployment.
For the readout circuit employed in DfMUX for previous SPT instruments, the “nulling” signal was static in amplitude and the SQUID was operated in a negative feedback flux-locked loop, further linearizing its response. Combining the sky-modulated carrier signal with inverted nuller in principle will leave just the sky modulation, which is then read out using digital demodulators at room temperature.

In transitioning from the readout needs of SPTpol to those of SPT-3G, the large increase in multiplexing factor and therefore much wider and higher range of bias frequencies used was a challenge for the flux-lock-loop feedback method, since strong negative feedback must be provided across the full range of bias frequencies without significant phase shifts. Furthermore, bolometers in the comb that latch (i.e., slip into the superconducting branch of their transition and therefore see a large increase in current) can cause the negative feedback on the SQUID loop to go unstable (de Haan et al., 2012). Therefore, operating with many more channels in the comb makes stable operation of the SQUID feedback more difficult. To remedy these issues, SPT-3G employs a method known as Digital Active Nulling (DAN), where the nulling comb is not longer static in amplitude, but instead is actively modulated in a narrow bandwidth around each bolometer’s resonance, actively canceling both the carrier sine wave and the sky-signal sidebands. Because the active nulling ensures the SQUID will stay in the linear regime of its output, the flux-lock loop is no longer necessary. However, it is beneficial to maintain a long-time-constant integral feedback loop on the SQUID output to prevent drifts (Bender et al., 2014). Using DAN, therefore, allows for much higher multiplexing factors, relaxed restrictions on stray inductance, and therefore wire length, and improved operating stability, all of which are necessary for SPT-3G operation. A diagram of the readout scheme is shown in Figure [3.11] and more information on the integration and performance of the readout system can be found in Bender et al. (2018).

Although the cold component of the readout, the parallel inductor and capacitor circuit, necessarily grew in size with the increased multiplexing, to make the cold readout manageable in size, we employ monolithically-fabricated inductor-capacitor chips where a full comb of LC channels is incorporated into a single monolithic chip, rather than individually-soldered elements. The
inductors and inter-digitated capacitors are lithographed on silicon chips, fabricated at Lawrence Berkeley National Lab (Rotermund et al., 2016). The cold readout is connected to the SQUID amplifiers at 4 K via low-thermally-conductive and low-stray-inductance NbTi stripline; details of the design and fabrication can be found in Avva et al. (2018). A sample LC resonance comb is shown in Figure 3.11.

The SQUIDs used for SPT-3G were fabricated at NIST with typical yield > 99% (Anderson et al., 2018). During the first year of deployment, it was discovered that excess readout noise was being introduced for channels at high bias frequencies due to the high SQUID inductance of ~ 300 nH creating a current divider between the SQUID circuit and LRC circuit at the point where the active nulling is done. Noise introduced in the readout chain downstream of the SQUID is fed back in to the active nulling and depending on the ratio of impedance between the SQUID and the LRC circuit, some current (and noise) leaks into the LRC circuit and to ground via the bias resistor (Anderson et al., 2018; Bender et al., 2018). For the second year of deployment, this excess noise was mitigated by the development of low-inductance SQUIDs at NIST with input inductances closer to 60-80 nH, which has resulted in a reduction in readout noise and most significantly, a tightening of the distribution in noise between bolometers and reduction in excessively-noisy bolometers (Bender et al., 2018).
Figure 3.11: Top: Schematic diagram of DAN readout circuit (Bender et al., 2018). Bottom: Sample comb of LC resonances from 64x DfMUX employed in the first year of SPT-3G deployment.
Chapter 4

Hardware testing for SPT-3G deployment

4.1 Introduction

The ambitious science goals of SPT-3G necessitated the development of detector design as well as fabrication techniques to provide deployable detector wafers. Testing cryostats at universities and national labs that are part of the SPT-3G collaboration in the U.S. and Canada, including the University of Colorado at Boulder (CU), have been utilized to test detectors prior to deployment to facilitate detector research and development, feed back testing results to fabrication for improvements and fine tuning, and to predict the performance of the deployed SPT-3G array.

The main cryostat at CU used for SPT-3G detector testing was built by High Precision Devices (HPD), and employs a pulse tube cooler to reach a “4 K” base temperature of 2.5 K, and an Adiabatic Demagnetization Refrigerator (ADR) to further cool the detectors to a base temperature of roughly 300 mK, but with the capability of testing between $\sim 90 - 800$ mK. The cryostat has a zotefoam window at 300 K, which allow the detectors to look out of the cryostat toward testing apparatus in the room, while the amount of optical power entering the cryostat is limited by several bandwidth-limiting filters at 4 and 50 K and an optical-power-attenuating neutral density filter (NDF) at 4 K so as to not saturate the detectors, which have been designed for expected optical loading conditions in the SPT-3G receiver at the South Pole. The CU cryostat can be used in mainly two configurations: “dark,” where the window is capped internally in the cryostat at 4 K, useful for measuring the inherent electrothermal properties of the detectors, and “optical,” where the detectors are positioned in the cryostat such that they look out of the window.
to external testing equipment, useful for characterizing the optical sensitivity of the bolometers and their behavior under optical load.

Because the deployment of SPT-3G involved overhauls in detector development, readout capability, as well as optical and thermal design of the receiver, testing at CU focused primarily on characterization of SPT-3G detectors and therefore operated primarily in a mode of testing SPT-3G wafers using cold and warm readout from SPTpol, since the readout chain was well-characterized from previous years of SPTpol detector characterization. SPTpol cold readout (12x mux factor) has significantly more limited yield relative to SPT-3G DfMUX (68x mux), so while testing was restricted to a relatively small portion of detectors on a full wafer, using well-characterized readout allowed wafer testing and feedback to fabrication to proceed rapidly while the development SPT-3G readout was ongoing.

In this chapter, we focus on presenting methods employed at CU for characterizing wafers for SPT-3G deployment, focusing on bolometer parameters important to determining expected performance post-deployment and therefore feeding back wafer characterization to fabrication for research and development. Since the SPT-3G collaboration comprises around six different wafer characterization testing institutions, and far more wafers were tested in the process of finalizing the chosen set of ten in each year, testing data shown in this chapter is not necessarily from wafers that were deployed on SPT-3G and therefore is not necessarily representative of the deployed arrays. In Chapter 5 we present a characterization of the bolometer parameters for the detector wafers that were deployed in the first and second years, and include at that point some data and results from testing in northern cryostats prior to deployment for measurements that cannot easily be taken in situ in the SPT-3G receiver but that are important for characterizing the performance of the deployed array.
4.2 Transition Edge Sensor overview

4.2.1 Basic TES Operation

The use of TES bolometers for high-sensitivity measurements of anisotropies in the CMB has been well-established over several generations of previous instruments. Here we review the basic operating principles that drive design criteria for TES bolometers for the SPT-3G experiment in order to motivate the goals of detector wafer characterization both prior to and after deployment. A much more detailed treatment of TES detectors can be found in Irwin & Hilton (2005), and discussion of their usage for CMB experiments in Suzuki (2013), Lueker (2010), and Sayre (2014).

For their use in CMB experiments, where high frequency resolution is not needed, TES bolometers are typically employed as direct detectors, where their response is proportional to the total incident power. Sky power incident on the pixel is deposited on a thermally-isolated absorber with heat capacity $C \equiv \frac{dQ}{dT}$, which dissipates to the thermal bath of temperature $T_{\text{bath}}$ over a weak thermal link with thermal conductance $G \equiv \frac{dP}{dT}$. Without the presence of feedback, a change in power $\Delta P$, causes the island temperature to initially increase by $\Delta T = \Delta P / C$ and then approach a new steady-state temperature above the bath, $\Delta T = \Delta P / G$, with a characteristic thermal time constant of $\tau = C / G$. Changes in incident power causing changes in the island temperature can then be read out as changes in electrical resistance via a TES thermometer located on the island and biased in its superconducting transition so as to be extremely sensitive to small changes in temperature. For SPT-3G, the weak thermal link is formed by four thin SiN legs where the underlying silicon substrate has been etched away, thus physically suspending the absorber/TES island over the rest of the wafer substrate.

TES bolometers can be either current- or voltage-biased, but to take advantage of negative electrothermal feedback, which speeds up and linearizes the TES response, we choose to apply a constant voltage bias to the detectors. To do this, the TES is placed in parallel with a shunt resistor where $R_{\text{sh}} \ll R_{\text{TES}}$. The current from the TES circuit is then fed through the input coil of a SQUID amplifier, where small changes in the magnetic field from the input coil are converted into
changes in current around the SQUID’s superconducting loop and the current is then converted to
digital signals via room-temperature readout electronics, as described in Section 3.5. An overview of
a simplified thermal and electrical circuit of a single TES is shown in Fig. 4.1 where $R_L$ represents
the effective series combination of the shunt resistance and any stray resistance in the circuit and
$L$ here represents the SQUID coupling inductance. In our DfMUX readout scheme, each $R_{TES}$ is
connected in series with a capacitor $C_i$ and inductor $L_{MUX}$, forming a resonant RLC circuit where
the capacitance is varied per bolometer to change the resonant frequency, see Figure 3.11 for a more
complete drawing of the full DfMUX circuit for a single comb. For supplied voltage frequencies
away from the particular resonance frequency of a single detector, $\omega_i = 1/\sqrt{L_{MUX}C_i}$, the circuit
has high impedance, whereas for sinusoidal voltage applied at $\omega_i$, the circuit reduces to that shown
in Fig. 4.1. Since the sinusoidal carrier voltage applied to a single TES oscillates at frequencies
much faster than the TES response time, the bolometer sees an RMS voltage bias, $V_{bias}$, and as a
result experiences Joule heating $P_{elec} = \frac{V_{bias}^2}{R_{TES}} = I_{TES}^2R_{TES}$.

![Diagram of a simple TES circuit](image)

Figure 4.1: Diagram of a simple TES circuit, overviewing the electrical and thermal components
of the circuit and power inputs from applied external voltage and optical power from the sky.

The differential equation governing the thermal behavior of the TES circuit is given by:

$$C \frac{dT}{dt} = -P_{bath} + P_{elec} + P_{opt},$$

and for the electrical differential equation:
\[
\frac{dL}{dt} = V_{\text{bias}} - IR_L - IR_{\text{TES}}(T, I). \quad (4.2)
\]

The thermal power flowing to the bath can be described

\[
P_{\text{bath}} = k(T_{\text{TES}}^n - T_{\text{bath}}^n), \quad (4.3)
\]

where \( k = G/nT^{n-1} \). Here, \( n \) describes the mechanism of thermal transport, with \( n \approx 3 - 4 \) for insulators such as SiN used for the suspending legs of SPT-3G detectors, dominated by phonon transport (Irwin & Hilton 2005). For TES temperatures close to the bath temperature, \( P_{\text{bath}} \) becomes \( P_{\text{bath}} = \bar{G}(T_{\text{TES}} - T_{\text{bath}}) \), where \( \bar{G} \) is the average thermal conductance, different from the dynamic thermal conductance:

\[
G \equiv \frac{dP}{dT} = nkT^{n-1}, \quad (4.4)
\]

which is more useful for considering the response to small fluctuations around the TES operating point, i.e. temperatures \( T_{\text{TES}} \approx T_c \).

In the steady-state limit, we can write for the total power, \( P_{\text{tot}} \), using the thermal differential equation,

\[
P_{\text{tot}} = \text{constant} = P_{\text{opt}} + P_{\text{elec}} = \bar{G}(T_{\text{TES}} - T_{\text{bath}}), \quad (4.5)
\]

where the combination of applied electrical power and external (optical) power are balanced by the thermal power flowing through the legs to the bath.

For bath temperatures above \( T_c \), and/or for a combination of \( P_{\text{elec}} \) and \( P_{\text{opt}} \) sufficiently large, the TES will be driven out of its superconducting transition and behave like a normal metal resistor with resistance \( T_c \). For lower bath temperatures and lower total power applied to the bolometer, the TES will drop into its superconducting transition, and we choose a fixed \( V_{\text{bias}} \) so as to hold the TES at a particular depth in its steep superconducting \( R(T) \) transition.
4.2.2 Negative Electrothermal Feedback and TES Stability

By choosing a constant voltage bias, we take advantage of negative electrothermal feedback, which will linearize the bolometer’s response and increase dynamic range. For example, if the optical power on the bolometer increases, the temperature of the TES increases, causing the TES electrical resistance, $R_{\text{TES}}$, to increase, and the electrical power $P_{\text{elec}} = \frac{V^2_{\text{bias}}}{R_{\text{TES}}}$ correspondingly to decrease, holding the TES at a relatively fixed depth in the transition. The change in current through the TES in response to a change in optical power is then measured by the readout circuit.

To consider the response of the TES relative to a small change in optical power at its typical operating point, $R_L \simeq T_c$, we expand $R_{\text{TES}}$ in the limit of small changes in TES temperature and current:

$$R_{\text{TES}}(T, I) \approx R_0 + \frac{\partial R}{\partial T} \bigg|_{I_0} \delta T + \frac{\partial R}{\partial I} \bigg|_{T_0} \delta I$$

(4.6)

where $R_0$, $T_0$, and $I_0$ are the steady-state TES resistance, temperature, and current at the operating point. The steepness of the $R(T)$ transition is conventionally described using the logarithmic derivative of the transition profile, and similarly for the function of TES resistance with changes in current through the device:

$$\alpha = \frac{T_0}{R_0} \frac{\partial R}{\partial T} \bigg|_{I_0}, \quad \beta = \frac{I_0}{R_0} \frac{\partial R}{\partial I} \bigg|_{T_0},$$

(4.7)

though $\beta$ is generally considered to be small for SPT-3G detectors.

We characterize the strength of electrothermal feedback by defining a loop gain parameter

$$\mathcal{L} \equiv \frac{\alpha P_{\text{elec},0}}{GT_0}$$

(4.8)

which depends on the steepness of the $R(T)$ profile, $\alpha$, the supplied steady-state electrical power, $P_{\text{elec},0}$, the dynamic thermal conductance $G$, and the steady-state operating temperature $T_0 = T_c$.

For the thermal differential equation, 4.1, considering the response to small perturbations about the operating point,
\[
C \frac{d\delta T}{dt} = -\delta P_{\text{bath}} + \delta P_{\text{elec}} + \delta P_{\text{opt}} \tag{4.9}
\]

where \(\delta P_{\text{bath}} \approx G\delta T\), using the dynamic \(G\) relative to the operating point. We expand \(P_{\text{elec}}\) in the small perturbation limit:

\[
\delta P_{\text{elec}} \approx 2I_0R_0\delta I + I_0^2 \frac{\partial R}{\partial T}\delta T \tag{4.10}
\]

Substituting Eqns 4.6, 4.7, 4.8, and 4.10 into the thermal differential equation for small perturbations (Eqn. 4.9) and expanding the electrical differential equation similarly, we arrive at two linearized, coupled differential equations dictating the behavior of the TES circuit relative to small perturbations:

\[
C \frac{d\delta T}{dt} = (L - 1)G\delta T + 2I_0R_0\delta I + \delta P_{\text{opt}} \tag{4.11}
\]

\[
L \frac{d\delta I}{dt} = \delta V - (R_L + R_0)\delta I - \frac{L}{I_0} G \delta T, \tag{4.12}
\]

where we’ve here considered \(\beta\) to be negligibly small.

In the case of zero loop gain (i.e., operating the TES above transition, where its resistance is constant, \(R_{\text{TES}} = R_n\)), the first equation decouples and can be integrated independently to yield an exponentially decaying solution with a time constant describing the electrical behavior:

\[
\tau_{\text{elec}} = \frac{L}{R_L + R_0}. \tag{4.13}
\]

The electrical time constant describes the roll-off of the response of the TES circuit at high frequencies (Sayre 2014), or alternatively, the amount of time delay between a change in the bias voltage and the corresponding shift in current (Lucke et al. 2009).

In the case described in Figure 4.1 the inductance in the circuit is due to the SQUID input inductance. But in practice, reading out the bolometers using a DfMUX system, the inductance of the RLC MUX circuit, \(L_{\text{MUX}}\), will dominate the electrical bandwidth for the circuit, \(\tau_{\text{elec}} = \ldots\)
$2L_{\text{MUX}}/R_0$. In other words, the RLC circuit will roll-off the TES response at lower frequencies compared with the roll-off due to the SQUID input inductance.

For bolometer operation with non-zero electrothermal feedback, solving the coupled differential equations for the thermal and electrical behavior becomes more complicated. Negative electrothermal feedback, as quantified by the loop gain, serves to speed up the thermal time constant, and we can write, for $\tau_{\text{th, eff}}$, the thermal time constant as sped up by feedback,

$$
\tau_{\text{th, eff}} = \frac{\tau_{\text{th, 0}}}{(\mathcal{L} + 1)},
$$

(4.14)

where $\tau_{\text{th, 0}} = C/G$. Higher loop gain is beneficial in general, as it decreases the thermal decay time, linearizes the TES response, and provides higher dynamic range; however, if the loop gain is too high, or the natural thermal time constant is too short, relative to the electrical time constant, the TES circuit can become unstable. There is a general stability criterion, as calculated in Irwin et al. (1998):

$$
\tau_{\text{elec}} \leq \tau_{\text{th, eff}} / 5.8,
$$

(4.15)

which places restrictions on both the thermal and electrical parameters of the TES circuit architecture.

For sinusoidal perturbations in external power, $\delta P_{\text{ext}} = \Delta P_{\text{ext}} e^{i\omega t}$, the power-to-current responsivity, $s_I(\omega) = I(\omega)/\Delta P_{\text{ext}}$ for moderate loop gains $\mathcal{L} \ll \tau_{\text{th, eff}}/\tau_{\text{elec}}$ is given by

$$
s_I(\omega) = -\frac{1}{V_0} \left( \frac{\mathcal{L}}{\mathcal{L} + 1} \right) \left( \frac{1}{1 + i\omega\tau_{\text{th, eff}}} \right) \left( \frac{1}{1 + i\omega\tau_{\text{elec}}} \right).
$$

(4.16)

In the high-loop gain limit, and for frequencies below where the two time constants roll off, the power-to-current responsivity reduces to

$$
s_I(\omega) \sim -\frac{1}{V_0}
$$

(4.17)
4.2.3 Increasing bolometer heat capacity

Thin-film on-island heat capacities ($C$) are generally too small relative to the thermal conductivities ($G$) required by the loading conditions for instruments like SPT-3G, causing thermal time constants that are too short for stable operating conditions \cite{Lueker2009}, and therefore we seek to slow down the TES thermal time constant to allow for greater stability. Simply adding more TES material to increase $C$ is not necessarily a good solution because this will affect other TES parameters, such as $R_n$. Therefore, similar to a technique employed for SPT-SZ and SPTpol detectors \cite{Lueker2009,George2013}, we add a dedicated high-heat capacity material to the TES island in such a way that we increase the heat capacity of the island quickly relative to the amount of material added and don’t change other TES characteristics. This added material is referred to as “BLING” (“Bandwidth-Limiting Interface (Normally made of Gold)”). In the case of SPT-3G detectors, the added BLING material is made of palladium, which is non-superconducting.

The addition of the BLING material causes the thermal circuit to become potentially more complicated, where there is now a thermal link between the BLING material and the TES, in addition to the thermal connection between the TES and the bath. In the limit where the thermal connection between the BLING and TES is strong, the BLING and TES will act thermally united and the behavior of the TES is fundamentally unchanged; however, in reality, the BLING-TES thermal connection will not be infinitely strong and thermal decoupling between the BLING and TES may occur, resulting in the influence of two separate thermal time constants, one between the BLING and the TES and another between the TES and the bath. To characterize the thermal circuit for SPT-3G bolometers, we employ a technique developed by \cite{Lueker2009}, detailed further in Section 4.3.4.

A diagram similar to Fig. 4.1 but augmented for the TES with additional BLING is shown in Fig 4.2. The two thermal links are described by $G_0$ and $G_{\text{int}}$, setting up an additional thermal time constant, $\tau_{\text{int}} = C/G_{\text{int}}$. If $G_{\text{int}} \gg G_0$ even under electrothermal feedback, which causes the thermal time constant to speed up, the general bolometer behavior will be the same as Fig. 4.1.
Figure 4.2: Diagram of a TES circuit altered to include additional heat capacity in the form of added BLING.

For a sinusoidal power perturbation, $\delta P_{\text{opt}} = \Delta P_{\text{opt}} e^{i\omega t}$, the thermal conductance of the simple TES circuit can be expressed as

$$G(\omega) = G_0 + i\omega C = G_0(1 + i\omega \tau_0). \quad (4.18)$$

For the TES circuit with added BLING, we relate the BLING-TES thermal conductance to the TES island thermal conductance with $\gamma = G_{\text{int}}/G_0$ and the thermal conductance of the circuit as a whole is given by (Lueker, 2010)

$$G(\omega) = G_0 \frac{\gamma}{1 + \gamma} \left( \frac{1 + i\omega \tau_0}{1 + i\omega \frac{\tau_0}{1+\gamma}} \right). \quad (4.19)$$

If decoupling occurs, the BLING, which dominates the heat capacity, may be at a stable temperature
but the TES temperature, which is the temperature we measure through the readout circuit, can undergo oscillations ([Lueker et al., 2009]). Therefore, it’s important to quantify the strength and behavior of any potential decoupling.

4.2.4 Noise overview

There are several main sources of noise affecting the performance of SPT-3G bolometers, which provide constraints on TES design and operation. We overview those sources of noise here; for further detail and derivation, see [Lueker 2010]; [Sayre 2014]. When comparing the sensitivity of individual detectors, a useful metric is the noise equivalent power (NEP), defined as the equivalent size of a perturbation in power incident on the detector that would be measured with a signal-to-noise of one, over a 1 Hz bandwidth. For sources of noise that result in power fluctuations on the TES, the NEP is simply the square root of the power spectral density (PSD) of that power, $S_p$. For sources of noise arising from fluctuations in current, the PSD of current fluctuations must be referred back to fluctuations in power via the power-to-current responsivity, $s_I(\omega)$, see Eqn 4.16.

4.2.4.1 Photon noise

A fundamental constraint on the sensitivity of a TES detector is the inherent fluctuations in incident power due to arrival statistics of the photons being measured. Designing a CMB instrument that is “background-limited” is now considered a standard design criterion, meaning that the quadrature sum of all other sources of noise are subdominant to this fundamental photon power fluctuation power. Thermal sources of optical power, such as the CMB, atmosphere, and internal optics, are expected to follow a blackbody distribution, as described in Section 3.1.2. Assuming a single-moded and diffraction-limited etendue for the SPT optical system such that $A\Omega = \lambda^2$, we have from Eqn 3.1 for photons from a single optical element $i$ at temperature $T_i$, the number of photons with energy $h\nu$ incident on the detectors in one second of integration time is given by
\[ n = \eta \tau_i \epsilon_i \frac{1}{e^{h\nu/kT} - 1} \]  \hspace{1cm} (4.20)

Photons are expected to follow Poisson statistics, but their behavior can be complicated by photon bunching, causing the expected arrival rate to have larger fluctuations than as expected from Poisson statistics. For an arrival rate of \( n \) photons per second of integration time, the variance in \( n \) is given by \( \langle \Delta n^2 \rangle = n(1 + \varepsilon n) \), where \( \varepsilon \) accounts for photon bunching. For observations in the Wien limit of the Planck spectrum, where \( h\nu \gg k_B T \), \( \varepsilon \to 0 \), the variance becomes the typical Poisson variance, \( \langle \Delta n^2 \rangle = n \). For observations in the Rayleigh-Jeans side of the spectrum, for \( h\nu \ll k_B T \), \( \varepsilon \to 1 \), and the variance is larger, approaching \( \langle \Delta n^2 \rangle = n^2 \). The NEP associated with this variance, then, is given by multiplying the variance by the energy, and integrating over the spectral response of the detector:

\[ \text{NEP}_\gamma^2 = \int \nu (h\nu)^2 \langle \Delta n^2 \rangle d\nu \]  \hspace{1cm} (4.21)

Looking at Table 3.1, the dominant sources of loading for SPT-3G are the atmosphere and ambient-temperature optics, which will be observed closer to the Rayleigh-Jeans side of the spectrum and we therefore expect a bunching factor closer to 1. The expected NEP\( \gamma \) for SPT-3G detectors is 42, 72.5, 79 aW/rt(\text{Hz}) for 95, 150, 220 GHz, respectively.

### 4.2.4.2 Readout current noise

Statistical noise arises in the readout electronics, including the SQUID amplifier and room-temperature electronics, is the most-dominant source of noise after the photon background. Since these fluctuations are in current, they will be measured as a noise-equivalent current, NEI, which can be referred to equivalent fluctuations in power (NEP) on the TES in order to make a direct comparison with other sources of noise in the TES. The NEP can therefore be calculated by converting the power spectral density of fluctuations in current \( (S_I(\omega)) \) to fluctuations in power on the TES using the power-to-current responsivity. In the limit of relatively high loop gain, the
power-to-current responsivity becomes $s_I(\omega) \leq -1/V_0$:

$$\text{NEP}^2_{RO} = \frac{S_I(\omega)}{s_I^2(\omega)} = \frac{\text{NEI}^2_{RO}}{s_I^2(\omega)} \geq s_I(\omega)V_0^2$$  \hspace{1cm} (4.22)

Measurements and optimization of readout noise from the SPT-3G readout chain were ongoing in the years prior to and during deployment. As mentioned in Chapter 3 it was discovered in the first year of deployment that using SQUID amplifiers with high input inductance caused excess current noise due to current and therefore noise leakage through the TES circuit. This current leakage was mitigated in the second-year deployment by replacement of all the SQUID amplifiers with lower-input-inductance SQUIDs. For the final deployed focal plane (in year 3), measurements of readout current noise were taken by taking timestreams with the telescope pointed at the horizon, which will saturate all bolometers on the array with optical power and therefore make the detectors insensitive to photon and thermal fluctuation noise. Measurements of NEI in this configuration yield achieved RO noise of 13, 15, 18 pA/rt(Hz) at 95, 150, 220 GHz, respectively, which yield NEP\textsubscript{RO} of 47, 46, 56 aW/rt(Hz) for typical $V_0$ per band.

### 4.2.4.3 Thermal fluctuation noise

The next-largest contribution to the noise for SPT-3G is from statistical fluctuations in thermal energy due connecting a heat capacity $C$ at temperature $T_0$ to a thermal bath via a thermal connection with conductivity $G$. According to Kittel & Kroemer [1980], such a system will undergo energy fluctuations with a white spectrum with a variance of $\langle \Delta E^2 \rangle = k_B T_0^2 C$. These energy fluctuations are directly related to fluctuations in temperature in the TES island which have a thermal time constant of $\tau = C/G$. Therefore, to consider the fluctuations in power over a 1 Hz bandwidth from these thermal fluctuations, we can distribute the energy fluctuations over the thermal time constant of the detector and yield an NEP of

$$\text{NEP}^2_{G} = 4k_B T_0^2 G \times F(T_0, T_{\text{bath}}),$$  \hspace{1cm} (4.23)
where \( F(T_0, T_{\text{bath}}) \) ranges between 0.5 - 1, describing the nature of the thermal link and its non-equilibrium state during observations (Lueker, 2010). For typical detector \( T_0 = T_c \) and \( G \) for the final deployed focal plane, we expect \( \text{NEP}_G \) for SPT-3G of 27, 30, 31 aW/rt(Hz) for 95, 150, 220 GHz, respectively.

4.2.4.4 Johnson noise

The final, and least-dominant source of noise for SPT-3G is due to Johnson noise, arising as thermal fluctuations in any resistor at non-zero temperature. The fluctuations depend on the temperature of the resistive element in question and the expected power spectral density of voltage fluctuations is expected to follow \( S_V^2(\omega) = 4k_BTR \) over the electrical bandwidth of the circuit, with time constant \( \tau_{\text{th},0} \). Fluctuations will arise in the TES itself but also in other resistive elements in the TES circuit, namely the bias resistor, \( R_L \). Fluctuations in voltage will be converted to fluctuations in power on the TES via the impedance of the TES, \( Z_{\text{TES}}(\omega) \), and can then be converted into fluctuations in power by dividing by the power-to-current responsivity. However, the source of the voltage fluctuations will change the resulting noise current in the TES, depending on whether the source is external to the TES island. In this case, the voltage fluctuations will cause fluctuations in the bias voltage applied to the TES, whereas if the source is on the TES island, voltage fluctuations will cause direct power fluctuations and changes in the thermodynamic state of the TES itself (Sayre, 2014). Two different TES impedances are therefore useful for converting voltage fluctuations to NEP. From Irwin & Hilton (2005), the impedance of the TES relative to external voltage fluctuations is

\[
Z_{\text{TES,ext}}(\omega) = \frac{\mathcal{L}}{\mathcal{L} - \frac{1}{s_I(\omega)I_0(1 + i\omega\tau_{\text{th},0})}}
\]

resulting in NEP due to voltage fluctuations from the bias resistor of, under the assumption of relatively high loop gain:

\[
\text{NEP}_{J,R_L}^2 = 4k_BTR_LI_0^2.
\]
The impedance of the TES relative to voltage fluctuations internal on the TES island is given by (Irwin & Hilton, 2005)

$$Z_{\text{TES, int}}(\omega) = \mathcal{L} \frac{1}{-s I_{0} I(1 + i\omega\tau)}$$  \hspace{1cm} (4.26)

yielding an NEP due to voltage fluctuations in the TES of

$$\text{NEP}^{2}_{J_{\text{TES}}} = \frac{4k_{B}T_{0}P_{\text{elec}}}{\mathcal{L}^{2}}(1 + \omega^{2}\tau^{2})$$  \hspace{1cm} (4.27)

For SPT-3G, using typical deployment values for $R_{L}$, $T_{RL}$, $T_{0} = T_{c}$, $R_{\text{TES}}$, and $\mathcal{L}$, we expect the Johnson noise from both the TES and bias resistor to be subdominant to the other sources of noise, $\lesssim 10$ aW/rt(Hz).

4.3 Dark property characterization

4.3.1 Saturation power

The expected optical loading on the detectors, which depends on loading conditions from the atmosphere as well as loading and efficiencies from internal optics in the SPT-3G receiver, detector frequency response and optical efficiency (as shown in Table 3.1), provides a primary constraint on bolometer design. We choose $P_{\text{tot}} \gtrsim 2P_{\text{opt}}$, which, from Eq. 4.3, results in $P_{\text{elec}} \sim P_{\text{elec}}$. If $P_{\text{elec}}$ is too small relative to external optical power, in the worst case, changes in optical power may drive the bolometer out of its superconducting transition, and in general, the low electrical power will result in a limit on the maximum strength of the negative electrothermal feedback. Higher $P_{\text{elec}}$ provides strong negative electrothermal feedback, but unnecessarily high electrical power will result in higher bias voltage, and therefore larger currents and excessive readout noise.

We characterize the $P_{\text{elec}}$ for our detectors as a bolometer performance metric by measuring the amount of electrical power needed to barely hold the bolometer in its normal state, typically quantified as the amount of electrical power needed to hold the bolometer at a fixed depth in the transition, close to the normal state, referred to as the saturation power, $P_{\text{sat}}$. Note that the
Figure 4.3: Qualitative example IV curve showing relevant components of the superconducting transition.

measured $P_{\text{sat}}$ will depend on the amount of optical power present on the bolometer during the measurement, and therefore it’s important to measure $P_{\text{sat}}$ under well-quantified optical loading conditions. In the limit of no optical loading, the bolometer will operate under the condition $P_{\text{opt}} \sim P_{\text{elec}}$, and the $P_{\text{sat}}$ will measure the intrinsic saturation power of the bolometer, which is a result of the design and fabrication of the bolometer. While it’s possible to correct optically-loaded $P_{\text{sat}}$ measurements to ascertain the intrinsic dark saturation power, in practice it’s easier to take $P_{\text{sat}}$ measurements directly in a dark (4 K or 300 mK loading) testing configuration. $P_{\text{sat}}$ is measured in practice by taking “IV-curves.” To do this, each TES is given excessive electrical power to hold it normal (“overbiased”), while the stage temperature is above $T_c$. The stage temperature is then dropped to hold steady at $T_{\text{bath}}$, and then the applied voltage bias on the detector is reduced while monitoring the current (and therefore resistance) through the TES, watching the TES drop into the superconducting transition. An example IV curve for a single TES is shown in Figure 4.3 noting important components of the TES transition: the “normal branch,” where the TES is above the transition and behaves like a normal metal resistor such that $V/I = R = \text{constant}$, the “turnaround,” where the bolometer enters the transition, its resistance begins to
drop rapidly and therefore the current reaches a local minimum and begins to increase, and the “superconducting branch,” where the TES is fully superconducting and the remaining resistance in the circuit is due only to parasitics and $V/I = R_L \sim \text{constant}$. For typical operation when taking sky observations, we take an IV curve, lowering the bolometer past the turnaround to a chosen depth in the superconducting transition, described by the fractional resistance relative to the normal resistance, $f_R \equiv R_0/R_n$.

Sample IV curves for a single pixel from one test SPT-3G wafer are shown in Fig. 4.4, which are shown for both dark and optical configurations. Note that the saturation powers for the bolometers shift down as expected for the optical configuration relative to the dark configuration, due to the addition of optical power on the wafer through the cryostat window. To suppress the amount of optical power from 300 K into the cryostat, we employ a “neutral density filter” (NDF) made of machinable Eccosorb MF-110 with a anti-reflection coating of 15 mil PTFE attached with a glue layer of 2 mil HDPE, optimized for transmission at 150 GHz. Although the filter is intended to attenuate optical power equally across all frequencies as the name would imply, the transmission is a function of frequency with less power is transmitted with increasing frequency. Correspondingly, the 95 GHz $P_{\text{sat}}$ values in Fig. 4.4 shift considerably more between the dark and optical run relative to 220 GHz.

The thickness of NDF chosen for a given cooldown at CU depends on the expected dark $P_{\text{sat}}$ of the wafer: ideally to test how the bolometers will function when installed on the telescope, we’d like to supply the wafer with the same optical power and $T_{\text{bath}}$ that we expect in situ on SPT. $T_{\text{bath}}$ is easily tunable with an ADR; however, using an NDF, supplying the correct optical load is at best only possible to achieve for one of the three bands. In general, we choose an NDF thick enough that the 95 GHz bolometers won’t be saturated, given their lower $P_{\text{sat}}$ and additional transmission through the MF-110. In principle, we can then correct the optically-loaded $P_{\text{sat}}$ we measure in the lab to the dark value, using the expected loading in the cryostat. The primary contributions to this correction are: transmission through the NDF, loading from the inner walls of the cryostat at roughly 4 K, and thermal loading from the NDF itself, which has been measured to float somewhat
hotter than the rest of the 4 K enclosure, around 7 K. The transmission through the NDF is typically modeled with the function $\alpha = a \nu^b$, where $\alpha$ is the absorption coefficient. Published values for MF-110 at 5 K in Halpern et al. (1986) are $a = 0.3$ and $b = 1.2$, but empirical measurements from the CU cryostat indicate that these values may underestimate the amount of loading we observe, and therefore when applying corrections for measurements in the CU cryostat, we generally use an empirical value of $a = 0.197$. For most of the SPT-3G wafers tested for potential deployment, we used a 3.6-cm thick NDF, resulting in expected loading via transmission through the NDF of 6.3, 1.3, and 0.1 pW for 95, 150, and 220 GHz bands, respectively. This assumes 0.95-0.99% efficiency for several filters in the optical path between 4 K and room temperature: 50 K shader, and low-pass filters at 50 K and 4 K, and 95% transmission through the lenslet AR coatings on the wafer. Optical loading from the 4 K cryostat interior is expected to yield an additional 0.8, 0.8, 0.6 pW at 95, 150, 220 GHz, respectively. Measurements of the temperature of the NDF during cooldowns shows that the NDF runs somewhat hotter than the 4 K enclosure, roughly 7 K, which is expected to yield an additional 1.2, 2.3, and 2.1 pW at 95, 150, 220 GHz, respectively. All together, therefore, we expect optical loading during optical cooldowns in the CU cryostat with the 3.6 cm NDF to be 9, 4.4, 2.8 pW. This is relatively consistent with comparisons of measured $P_{\text{sat}}$ values both between separate optical and dark cooldowns with the same wafer and between dark and optical pixels on a single wafer during an optical cooldown.

The transition in detector fabrication from SPTpol to SPT-3G involved a large scale-up in detector count, and in order to make focal plane assembly reliable, feasible, and optimize close-packing of detectors on the focal plane, it was necessary to upgrade the fabrication capability at Argonne National Lab from single-pixels for SPTpol to six-inch wafer processing with 270 pixels per wafer. It therefore became important to characterize not only general bolometer properties but also yield and distribution of properties across each wafer. Because testing at CU relied heavily on SPTpol readout, our efforts to fully characterize yield and uniformity were relatively limited to reading out at most 1/12th of a wafer, but it was still possible to test in broad strokes for yield issues and potential fabrication problems that would result in gradients across a wafer. Figure 4.5
shows $P_{\text{sat}}$ characterization for a single wafer tested in anticipation for first-year deployment.
Figure 4.4: IV and RP load curves as well as $R(T)$ profiles for the six bolometers from a single pixel on a SPT-3G wafer characterized for wafer development prior to deployment. IV and RP curves are shown for both dark (wafer capped at $\sim 300$ mK) and optical (where the cryostat window has be capped at 300 K with an Eccosorb panel).
Figure 4.5: \( P_{\text{sat}} \) measured for a single wafer prior to first-year deployment.
4.3.2 Thermal conductivity and transition temperature

Once $P_{\text{tot}}$ and therefore $P_{\text{elec}}$ are constrained, this places design criteria on $\bar{G}$ and $T_c$, via Eq. 4.5. Because $\bar{G}$ is set by the geometry of the four SiN legs suspending the TES island, we have considerable freedom to select $\bar{G}$ within the confines of fitting six TES islands into the area of each pixel. For the first- and second-year SPT-3G focal planes, Ti-Au was chosen for the TES material. The $T_c$ of the Ti-Au TES is tunable by changing the relative thicknesses of the Ti and Au layers in the quad-layer TES design (Carter et al., 2018), heat treatment of the wafers during fabrication, and proximity effects from the Pd BLING. At a minimum, $T_c$ must be above the operating bath temperature of the SPT-3G receiver, which is expected to be $T_{\text{bath}} = 270 - 300$ mK. Larger values of $\bar{G}$ are beneficial by allowing for higher dynamic range in bolometer operation; however, higher $T_c$ and $\bar{G}$ both factor into high phonon noise and therefore both are constrained by the desire for noise performance limited by the photon background.

To measure $T_c$, we apply a small voltage bias to the bolometers and measure the current while sweeping the mK stage temperature across the $T_c$ transition. We apply a small voltage so as to not affect the $T_c$ of the device but still measure the current at relatively high signal-to-noise. $R(T)$ profiles for a single pixel from a SPT-3G wafer tested in the dark configuration are shown in Fig. 4.4, where the stage temperature has been swept at a rate of 1 mK/min from both above $T_c$ to below and back. We note a small but nearly negligible hysteresis between upward and downward sweeps, expected to be due to temperature lag of the TES, isolated from the ADR heat strap by the invar and silicon of the module assembly, relative to the temperature of the thermometer used for the PID of the stage temperature, located on the millikelvin stage assembly but connected to the ADR heat strap via copper.

To measure $G$ (and therefore $\bar{G}$), we take repeated IV curves at stage temperatures below $T_c$, and then fit Eq. 4.4 to the curve of $P_{\text{sat}}(T_{\text{bath}})$. Results for a selection of bolometers from a test wafer tested in a dark configuration are shown in Fig. 4.6. Errors in the fit parameters in Figure 4.6 result from uncertainty in the fit, but we also constrain the influence of possible detector
temperature uncertainty by comparing fits using stage temperatures measured in two locations on the detector module. There is no easy way to directly measure the temperature of the detector wafer itself, which is a 6-in silicon wafer and which is thermally buffered from the ADR heatsink strap by the detector module support structure made mostly of invar. To try to constrain any possible thermal gradients or drifts of the wafer temperature, we measure the temperature of the detectors using one thermometer (Ch 6) located on the copper mounting ring of the detector module with a direct copper connection to the ADR cold head (Ch 6), and another thermometer (Ch 5) located on the copper backplate on the back of the detector module, where the cold readout LC boards are mounted (see Figure 3.9). This thermometer has an indirect thermal connection to the ADR cold head via the invar of the detector module and therefore will measure any potential heating due to thermal conductivity through the striplines of the cold readout from 4 K. It therefore may be more sensitive than Ch 6 to drifts in the detector wafer temperature. We note that while fit values using temperatures from Ch 5 and Ch 6 are relatively consistent, and for $T_c$, the shifts are within the error bars from the fit, fit values for $n$ tend to shift by a few percent, and fit values for $k$ shift by upwards of 10%. Measurements of $G$ also provide better constraints on $P_{\text{sat}}$, since the $P_{\text{sat}}$ at a given bath temperature is constrained by measured $P_{\text{elec}}$ values at the full range of the fit, rather than just at a single bath temperature for single IV curves.

4.3.3 Normal resistance and Readout characteristics

Once $P_{\text{sat}}$, $T_c$, and $G$ have been constrained, the choice of heat capacity, $C$, and operating resistance, $R_0$, can be chosen under the influence of the expected loop gain (dependent on the steepness of the $R(T)$ transition), such that the expected time constants from the electrical readout circuit and thermal circuit will interact stably. These considerations are also constrained by characteristics of the DfMUX readout circuit: the choice of $L_{\text{mux}}$, range and width of bias resonances, $f_i$ and $\Delta f$, and capacitance in the DfMUX LRC circuit, $C_i$ [Suzuki 2013]. To accommodate the much-larger mux factor for SPT-3G (66x compared with 12x for SPTpol), we necessarily must use a much larger range of bias frequencies. While the mux factor for SPTpol was low enough that it
Figure 4.6: Top: Overplotting resistance as a function of electrical power from repeated IV curves taken at a variety of $T_{\text{bath}}$ for $T_{\text{bath}} < T_c$. As the bath temperature is increased, the needed electrical power to reach the same depth in the transition decreases. Here we quantify $P_{\text{sat}}$ as the amount of electrical power needed for the bolometer to reach a depth of $R_0 = 0.95 R_n$ in the transition, as shown by stars on the $R(P)$ curves. Bottom: Plotting measured $P_{\text{sat}}$ from the top plots as a function of $T_{\text{bath}}$ (points) and fitting Eqn 4.3 (lines). The separate green and blue points and curve fits are for stage temperatures measured in two different locations on the detector module, to help constrain any thermal gradients on the detector module.
was manageable for the components on the LC boards to be hand-mounted and soldered, for SPT-3G we use microfabricated chips where the inductor and interdigitated capacitor components for all the channels on each 66x comb have been optically-lithographed on a monolithic silicon wafer. High readout bias frequencies allow these lithographed components to be smaller; however, stray inductance and dielectric loss in the capacitor become more problematic (Suzuki, 2013). For SPT-3G we use a DfMUX frequency range from 1.6 – 5.3 MHz with logarithmically-spaced resonances, and inductance $L_{\text{mux}} = 60 \, \mu\text{m}$. The resonance width is dependent on the operating resistance and inductance, $\Delta f \sim R_0/L_{\text{mux}}$, and therefore the cross-talk ratio between adjacent channels due to leakage of bias current also increases with increasing operating resistance, $X\text{-talk} = R_0^2/4\pi\Delta f L_{\text{mux}}$. Increasing the operating resistance will also result in additional readout noise, NEP$_{\text{RO}}$, which also then places a limit on $R_0$, relative to the background limit of NEP$_{\gamma}$. However, $R_0$ is also constrained on the low side by the time constant stability requirement as well as the influence of stray resistance in the circuit, which will take a stronger effect as the fraction of $R_L/R_0$ increases. In principle it’s possible to choose any arbitrary operating resistance $R_L < R_0 < R_n$ by simply biasing the detector deeper into its superconducting transition; however, in practice it has proven difficult to operate full wafers of SPT-3G bolometers at depths $\lesssim 0.6 R_n$, and therefore tuning $R_n$ to provide a suitable $R_0$ is important.

Given the selected $L_{\text{mux}}$ for SPT-3G of 60 $\mu\text{H}$, and target $R_n$ of roughly 2 $\Omega$, the expected width of each LRC resonance for the DfMUX readout is $\delta f \sim R_0/L_{\text{mux}} \sim 5 \, \text{kHz}$. At the lowest DfMUX bias frequency, where the resonances are most-closely-spaced, the separation between frequency peaks is $\Delta f \sim 27500 \, \text{kHz}$.

Measuring $R_n$ can be done either using the normal branch of of an IV curve or the normal branch of a $R(T)$ profile. While in general these two methods yield consistent values, in practice the two methods don’t always exactly agree for individual detectors, as shown in comparing the $R(P)$ curves with $R(T)$ curves in Fig. 4.4. This is likely due to the different electrical and thermal conditions of taking the measurements. The $R(T)$ measurement is taken with a very small voltage applied to the bolometers, and the bolometers are driven normal by thermal power. The
total current in the comb will undergo large changes as bolometers individually drop to their superconducting branches, and therefore the $R(T)$ measurement may be more sensitive to cross-talk between channels on the same comb. We note generally that the LC resonances of the SPTpol readout were optimized for lower operating TES resistance (SPTpol $R_0 \sim 0.85 \, \Omega$) compared with SPT-3G bolometers, which will likely cause increased cross-talk due to wider LC resonances. Characterization of measured $R_n$ measured from IV curves for an SPT-3G wafer for first year deployment is shown in Figure 4.7.

![Graphs of $R_n$ measurements for different frequencies and TES resistance values](image)

Figure 4.7: $R_n$ as measured from the normal branch of IV curves for a single SPT-3G wafer prior to first-year deployment.

Constraining $R_n$ (and therefore $R_0$) sets the electrical time constant for the bolometer circuit, $	au_{\text{elec}} = 2L_{\text{max}}/R_0$, thus constraining $\tau_{\text{th,eff}}$ via the stability requirement, Eqn. 4.15, which is a combination of constraints on loop gain and $\tau_{\text{th,0}}$. We choose the heat capacity of the TES island, $C$, so as to provide a reasonable $\tau_{\text{th,0}} = C/G$. If the heat capacity is too low, $\tau_{\text{th,0}}$ will be too short relative to $\tau_{\text{elec}}$ for stable operation. If $C$ is too large, the bolometer may become excessively slow such that it would affect the appropriate scan strategy for sky observations. SPT observes the sky
by scanning a given patch at a constant speed. The scan speed is chosen to shift the measured sky signal, CMB polarization anisotropies, to sufficiently high frequencies in the bolometer timestreams so as to avoid $1/f$ noise. However, excessively slow bolometer time constants will limit the speed at which scans can be taken without heavy reliance on being able to accurately deconvolve the bolometer time constant. As noted above, we add BLING to the TES island to enhance and tune the heat capacity without affecting other parameters of the TES.

### 4.3.4 Time constants and thermal decoupling

Given a target $R_n$ of 2 $\Omega$, and a typical operating fractional depth of 0.8, we would expect an electrical time constant of 75 $\mu$s, placing a constraint on $\tau_{th, eff}$ of $\gtrsim 0.4$ ms. To characterize the effective thermal time constant of SPT-3G detectors as well as any possible decoupling between the TES and BLING, we employ a technique developed by Lueker (Lueker et al., 2009; Lueker, 2010; George et al., 2013) for SPT-SZ that utilizes the DfMUX readout system. The power-to-current responsivity of the TES (Eq.4.16) is a function of the loop gain, which in turn is a function of the thermal conductance, $\mathcal{L} = \frac{\alpha P_{elec}}{G(\omega)T_e}$, which we’re interested in characterizing for our TES+BLING circuit. Specifically, it can be shown (see Appendix A of Lueker (2010)) that the power-to-current responsivity can be written as

$$s_I(\omega) = -\frac{\mathcal{L}}{V_0} \left( \frac{G(\omega)(\gamma + 1)}{G_0 \gamma} (1 + i\omega \tau_{elec}) + \mathcal{L} (1 - i\omega \tau_{elec}) \right)^{-1}$$

(4.28)

To explore the thermal behavior of the circuit, we apply carrier voltage to two channels of the DfMUX circuit, one at the native resonance of the TES, $V_0 e^{i\omega t}$, and another with much smaller amplitude at a slightly shifted bias frequency $\omega + \delta \omega$, $V_t e^{i(\omega + \delta \omega) t}$, the so-called “tickle” voltage. The total electrical power seen by the detector, dropping higher-order terms, is given by

$$P_{elec} = \frac{V_{tot}^2}{R_0} \simeq \frac{V_0^2}{R_0} + \frac{2V_0V_t}{R_0 \sqrt{1 + \omega^2 \tau_{elec}^2}} \cos(\delta \omega t)$$

(4.29)

where the factor of $\sqrt{1 + \omega^2 \tau_{elec}^2}$ takes into account the suppression by the LC circuit of the voltage
applied off resonance, as seen by the TES. The TES sees a power fluctuation at frequency $\omega + \delta \omega$ of
\[ \delta P_{\text{elec}} = \frac{2V_0V_t}{R_0\sqrt{1 + \omega^2\tau_{\text{elec}}^2}} \]
which will be converted to a current in the side band via the power-to-current responsivity: $s_I(\omega) = \delta I/\delta P$ so
\[ I(\omega \pm \delta \omega) = |s_I(\omega)| \delta P_{\text{elec}} = \frac{2V_0V_t}{R_0\sqrt{1 + \omega^2\tau_{\text{elec}}^2}} |s_I(\omega)|. \tag{4.30} \]

This current will present in both symmetric sidebands relative to $\omega$, $\omega \pm \delta \omega$, and therefore we tune a demodulator frequency to the parallel side band, $\omega - \delta \omega$ where there is no externally-applied voltage and the measured current will give a direct measurement of the power-to-current responsivity, and therefore $G(\omega)$. In principle this sinusoidal perturbation could be applied directly to the voltage of the TES at its bias frequency, but for low loop gains, where the TES behaves almost like a resistor, a small perturbation on a large bias voltage will be difficult to measure. Deeper in the transition, at higher loop gains, the detector will be more responsive, but the bolometer’s change in response due to electro-thermal feedback would need to be disentangled in order to measure the thermal behavior \cite{Lueker2010}. Expanding Eqn. 4.30 yields \cite{George2013}:
\[ I(\omega \pm \delta \omega) = \frac{2L'V_t}{R_0\sqrt{1 + \omega^2\tau_{\text{elec}}^2}} \left( \frac{G(\omega)(\gamma + 1)}{G_0\gamma} (1 + i\omega\tau_{\text{elec}}) + L'(1 - i\omega\tau_{\text{elec}}) \right)^{-1}, \tag{4.31} \]
where $G(\omega)$ for the BLING+TES circuit is expected to follow Eqn. 4.19.

This measurement technique can be used to probe both the inherent thermal time constant, $\tau_{\text{th},0}$, as well as the speed-up of the thermal time constant as the bolometer is biased deeper in the transition, which provides a measurement of the effective thermal time constant of the bolometer under the influence of chosen conditions of optical loading and electro-thermal feedback. The comparison of $\tau_{\text{th},0}$ with $\tau_{\text{th},\text{eff}}$ therefore also provides a measurement of the loop gain, which can be compared to measurements of loop gain as calculated using $\alpha$, $P_{\text{elec}}$, $G$, and $T_c$. Additionally, the technique can be used to probe the tickle frequency at which any thermal decoupling between the TES and the BLING occurs and provide a measurement of $\gamma = G_\text{int}/G_0$. 
To measure $\tau_{th,0}$, there are two primary techniques. First, we can probe the response of the detector when the loop gain is effectively zero, i.e. when the detector is very high in its superconducting transition such that it behaves like a resistor with no electrothermal feedback, and therefore the measured time constant will be the inherent thermal time constant. However, the tickle signal will be very difficult to measure when the bolometer has no electrothermal feedback, and generally this method is too low-signal-to-noise to yield a reasonable measurement. In the second method, we bias the bolometer with the necessary amount of bias such that the bolometer sits at the turnaround point in the transition, as shown by Figure 4.3. This is the place in the TES transition where the current through the TES is at a local minimum and therefore $dI/dV = 0$. Substituting this into $G = \Delta P/\Delta T$ where $P = V^2/R$ yields that at $P_{elec} = P_{turnaround}$, the loop gain of the device is 1. Therefore, the inherent time constant can be calculated from the measured time constant at this bias position via $\tau_{th,0} = (\mathcal{L} + 1)\tau_{th,eff} = 2\tau_{th,eff}$.

Figure 4.8 shows an example of this measurement for a single bolometer. We plot the measured signal in the $\omega - \delta \omega$ sideband, normalized to the response a range of lowest tickle frequencies, below where any time constants will begin to roll-off or decoupling may occur. We expect our devices to have inherent thermal time constants of order 25 ms, that will speed up with with increased loop gain deeper in the transition to of order 1 ms. Therefore, we expect to see a 3 db roll-off of the response of our bolometer between 10–150 Hz. In contrast, the electrical time constant, should not begin to roll-off the bolometer response until frequencies of order 5 kHz and above. We take IV curves to a range of depths in the transition, and probe the response by applying the tickle at a range of $\delta \omega = 1 – 40,000$ Hz. Considering tickle frequencies less than of order 200 Hz, we can measure the roll-off due to the thermal time constant by fitting a single-pole model $\propto 1/|1 + i\delta \omega \tau_{th,eff}|$, which is a one-parameter fit for $\tau_{th,eff}$. For the example bolometer shown in Fig. 4.8 where we’re most interested in measuring $\tau_{th,0}$ using the second technique mentioned above, we note that bolometers on this wafer showed $P_{elec} = P_{turnaround}$ occurring at a fractional resistance (i.e. depth in the transition) of $f_R = 0.992 \pm 0.002$, and therefore we take tickle measurements at a range of fractional resistances in these values. The measured frequency of the roll-off at these fractional resistances
will then yield a direct measurement of $\tau_{\text{th,eff}}$ at a known loop gain, from which $\tau_{\text{th,0}}$ can be calculated. The measurements on this test wafer were done in the optical configuration, meaning that optical power through the cryostat window would be present on the wafer, which will affect the bolometer behavior. Because the MF 110 NDF used to suppress the optical power in the cryostat has transmission that is a function of frequency, we choose a 220 GHz detector in this case because the NDF is expected to effectively suppress transmission in the 220 GHz band to significantly less than a pW and therefore the bolometer is as close to dark as possible in this configuration, with the only optical power due to loading from inside the 4 K cryostat and from the NDF itself. Repeating this measurement for all biased 220 GHz detectors on the wafer with results shown in Figure 4.8 and selecting the $\tau_{\text{th,eff}}$ measurement from the closest $f_R$ to $P_{\text{elec}} = P_{\text{turnaround}}$ for each bolometer, we find $\tau_{\text{th,0}} \sim 20 - 40$ ms, as determined by the histograms in the right panel of Figure 4.8.

Similar to measurements of $\tau_{\text{th,0}}$, to measure the speed-up of $\tau_{\text{th,eff}}$ as we bias the detector lower in the transition where it will experience increasing electrothermal feedback, we similarly fit a single-pole model to only the tickle response data below $\sim 200$ Hz, as shown in the left panel of Figure 4.9. Effectively, the measurement of $\tau_{\text{th,eff}}$ is probing the tickle frequency at which the response has fallen by a factor of 3 db (or equivalently the power has reduced by a factor of two), indicated by where each response curve crosses the horizontal dashed line. We note that as the bolometer drops deeper into the transition, i.e., biasing at smaller fractions of $f_R = R_0/R_n$, the measured 3 db roll-off moves to higher tickle frequencies, corresponding to faster time constants, and for $f_R \lesssim 0.8$, the thermal time constant speeds up to $\sim 1$ ms. Given a measured $\tau_{\text{th,0}} = 20 - 40$ ms, and the relation of $\tau_{\text{th,eff}} = \tau_{\text{th,0}}/(L^2+1)$, we note that for these depths in the transition, assumptions of operating the bolometers in the high-loop gain limit are reasonable.

To characterize the thermal decoupling between the TES and BLING, we fit a two-pole model to the bolometer response data for the full range of tickle frequencies, as shown in the right panel of Figure 4.9 for a single bolometer. This model includes a roll-off for the effective thermal time constant, $\tau_{\text{th,eff}}$, which is expected at relatively low tickle frequencies, same as for the single-body model, a second roll-off for the electrical time constant at higher tickle frequencies,
Figure 4.8: Left: Lueker tickle measurements for a single 220 GHz detector, plotting measured current response in the sideband normalized to response at low tickle frequencies as a function of tickle frequency. Colored vertical lines indicate the highest frequency included in the single-pole model fit. The tickle measurements in this plot emphasized measuring $\tau_{th,0}$ by biasing the detector at a depth in the transition such that $P_{elec} = P_{turnaround}$ where the loop gain is known to be one. Right: Histogram of $\tau_{th,eff}$ for a single wafer for $f_R$ chosen per-bolometer to be closest to where the supplied $P_{elec}$ is equal to $P_{turnaround}$, and therefore $L = 1$ and $\tau_{th,0}$ can be determined as $\tau_{th,0} = 2\tau_{th,eff}$. In this set of tests, the wafer was tested in an optical configuration, and therefore we include only 220 GHz bolometers in this plot, since they are expected to see minimal optical loading transmitted through the NDF.

and the possibility of thermal decoupling of the BLING and TES, which manifests in the plots as the bolometer response flattening despite increasing tickle frequency. At low tickle frequencies, the TES and BLING will behave as a single unit; however, as the tickle frequency is increased, eventually the TES will stop behaving in a coordinated way with the BLING, and the frequency at which this decoupling occurs will depend on the strength of the internal thermal link.

We note that comparing the single-body fits for $\tau_{th,eff}$ from the left panel with the fits for $\tau_{th,eff}$ from the full two-body model yield very similar results as expected. For the two-body model fit shown in Figure 4.9, $\tau_{th,0}$ has been fixed to the range $15 - 20$ ms based on measurements of $\tau_{th,0}$ for this wafer, but we note that the two-body fit is not extremely sensitive to the chosen range. For the bolometer in Figure 4.9, the returned fits for $\gamma$ span from $\sim 100 - 200$. For the physical
bolometer behavior, $\gamma$ should be the same value regardless of depth in the transition, however we note that the bolometer may behave differently under differing levels of electrothermal feedback. Most importantly, measuring $\gamma \gtrsim 100$ indicates that the internal thermal coupling is much stronger than the coupling from the island to the bath, and therefore, thermal decoupling is unlikely to be problematic for bolometer performance for SPT-3G.

To consider the aggregate time constant behavior of multiple detectors across a wafer, the top left plot of Figure 4.10 shows histograms of $\tau_{\text{th,eff}}$ as a function of depth in the transition, showing the speed up of the thermal time constant with increasing loop gain deeper in the transition. We note that for $f_R \lesssim 0.75$, $\tau_{\text{th,eff}}$ plateaus at roughly 2.5 ms and does not continue to get shorter, consistent with the results for the single bolometer shown in Figure 4.9. The time constant measurements in the top left plot of Figure 4.10 were taken with the detectors at typical operating bath temperature of 280 mK, in a dark configuration with no optical power on the detectors. Since $P_{\text{elec}} = P_{\text{tot}}$ in the dark configuration, for a fixed depth in the transition, the bolometers will have higher loop gain in...
a dark configuration relative to the optical conditions expected in situ in the SPT-3G receiver. To characterize a detector wafer’s time constant that might be expected after deployment in the SPT-3G cryostat, we also take time constant measurements with the mK stage temperature elevated (but still in a dark configuration) so as to reduce the amount of electrical power to the level expected in the SPT-3G receiver where the bolometers will also receive optical power. Repeating the same measurements but with the mK stage now at 400 mK, which should reduce the $P_{\text{elec}}$ on the wafer from roughly 15 pW dark to roughly $8 - 9$ pW, as calculated using measured $P_{\text{sat}}(T_{\text{bath}})$ for this wafer, similar to those shown in Figure 4.6. Correspondingly, cutting the $P_{\text{elec}}$ almost a factor of two should decrease the loop gain by the same amount for the same depth in the transition, using typical loop gain values for this wafer, should increase $\tau_{\text{th,eff}}$ by slightly under a factor of two, consistent with what we see. As will be discussed further in the Chapter that follows, we note that we measure relatively consistent time constants in situ in the SPT-3G receiver as those measured in the lab with elevated stage temperature. The lower left panel of Figure 4.10 shows the characterization for a different pre-deployment SPT-3G wafer, here plotting $\tau_{\text{th,eff}}$ as a function of $f_R$ and overplotting multiple detectors. For this wafer, the characterization was done in an optical configuration and hence we only show results for the 150 GHz bolometers, since the other two bands have significantly different optical loading through the NDF and therefore different expected loop gain as a function of depth in the transition. The lower right panel of Figure 4.10 shows $\gamma$ as a function of $f_R$ for the same wafer and set of bolometers as the lower left plot, showing that $\gamma$ is relatively flat across all depths in the transition, which is expected since the BLING - TES coupling should not be a very strong function of the TES bias conditions.

4.4 Optical property characterization

4.4.1 Spectral response

SPT-3G employs multichroic pixels with a broad-band-sensitive antenna to facilitate close-packing of detectors on the focal plane. The central frequency and bandwidth of the spectral
Figure 4.10: Top left: Histograms of \( \tau_{\text{th,eff}} \) for a range of depths in the transition for a full wafer under testing, measured in a dark configuration with \( T_{\text{bath}} = 280 \text{ mK} \). Top Right: Similar histograms for the same set of bolometers as the left plot and in a dark configuration in the lab but with elevated \( T_{\text{bath}} = 400 \text{ mK} \) in order to emulate the conditions of electrothermal feedback expected in situ in the SPT-3G receiver. Lower left: Plotting \( \tau_{\text{th,eff}} \) as a function of depth in the transition for a different wafer, where we overplot multiple detectors with different colors. These measurements were taken on a wafer in an optical configuration and hence we show only the 150 GHz bolometers, since the other two bands will have different optical loading through the NDF and therefore different expected loop gain. Bottom right: Plotting \( \gamma \) as a function of \( f_R \), for the wafer and set of bolometers as in the lower left panel.

The response of each bolometer in a pixel is determined by quasi-lumped-element triplexer filters fabricated in-line in the transmission lines from the antenna to the TES islands, with similar filter design as developed for the PolarBear instrument (Suzuki et al., 2016). It’s important to measure the spectral bands of the detectors prior to deployment to ensure that the bands don’t suffer
from significant out-of-band leakage and have band edges that match our expectations, which are
designed to avoid spectral lines of water vapor absorption and reemission in the Earth’s atmo-
sphere. We use a Fourier Transform Spectrometer which employs a $\sim$1000 C hot source. A mylar
beam splitter divides the beam, the two components travel different path lengths, controllable by a
moveable mirror, and then are recombined to constructively or destructively interfere before shin-
ing onto the detectors through the cryostat window. The hot source has a broadband blackbody
thermal spectrum and therefore sweeping the moveable mirror over a range of possible path-length
differences traces out an interferogram of the bolometers’ spectral response. Taking the Fourier
transform then yields the bolometers’ sensitivity as a function of frequency. Sweeping over a longer
distance with the moveable mirror results in higher frequency resolution in the measured band,
and sweeping the mirror more slowly allows for higher signal-to-noise. Because our bolometers are
sensitive in mm-wavelengths, the distances of travel for the mirror are of order tens of cm, and
keeping track of phase and scattering so that the two beams will interfere when recombined is
relatively straightforward without extremely expensive optical elements.

Figure 4.11 shows example FTS spectra for a single SPT-3G test wafer, taken with 2 GHz
resolution. Grey dashed lines show expected band edges from simulations based on dielectric thick-
ness of this test wafer, and dot-dashed lines in blue show the locations of atmospheric water lines,
based on measurements at ALMA. Two frequency-dependent corrections have been applied: the
transmission through the NDF, using empirical values as discussed in Section 4.3.1 and correction
for the mylar beam splitter in the FTS, which has transmission that peaks around 150 GHz, and
drops to zero at 0 GHz and 300 GHz. For reference, Figure 4.12 shows the same spectra but with-
out either correction applied. Because the NDF suppresses optical more strongly with increasing
frequency and the transmission of the mylar also decreases to zero at both 0 and 300 GHz, dividing
out the two transmission corrections causes an amplification of noise at higher frequencies, as well
as at 0 GHz. We also note that we see some uneven response within each band, which may be due
to channel spectra, interference of the beam from reflections on optical elements along the optical
path, and note that this may cause some additional uncertainty in the measurements of the band
edges. The amplitude of the measured spectral response will depend on the signal-to-noise of individual FTS sweeps, which may vary scan-to-scan, and the overall magnitude of each bolometer’s measured response may vary between pixels depending on their antenna polarization orientation relative to the FTS, as the FTS supplied beam may be somewhat polarized from reflections off the beam splitter and optical surfaces. We therefore normalize the measured FTS response for each scan by the peak of the response within the a particular bolometer’s expected band, but note that uneven response within the band causes this normalization to be somewhat uncertain and can affect the measured band edges. For example, in the 150 GHz spectra in Figure 4.11 we note that uneven response across the band makes quantifying the upper edge of the band somewhat uncertain and the band edges quoted in the plot likely underestimate the upper band edge.

When the moveable mirror is at the location of zero path-length-difference, the two split beams will interfere constructively for all wavelengths, and therefore in the ideal case, the interferogram will be a purely cosine function. However, non-idealities due to discrete sampling and possible dispersion in the mylar beam splitter may cause phase errors resulting in some antisymmetry in the interferogram and a sine component (Rogers 2011). We therefore apply a measured phase correction that should shift signal back into the cosine component as best as possible. Any signal remaining in the imaginary, sine, component therefore provides a measurement of the noise, as shown in Figures 4.11 4.12.

Due to the unequal optical loading through the NDF, taking non-saturated and high signal-to-noise spectra in all three bands is challenging. For many of the 95 GHz bolometers shown in Fig. 4.11 which receive the most optical power through the NDF, the bolometers were near saturation, where the applied optical loading is high enough to drive them out of the transition, and causing reduced and non-linear response. Saturation will cause clipping of the peaks of the interferogram, which will manifest as response at the $2f$ harmonic of the band center, which can be seen in the response near $\sim$180 GHz in the uncorrected FTS spectra for 95 GHz bolometers in Fig. 4.12. In the opposite case, the 220 GHz bolometers are receiving minimal optical power and therefore the FTS measurement is quite low signal-to-noise. Because of the differential optical
loading between bands, the measured spectra can also be contaminated with cross-talk, particularly from 95 GHz to 220 GHz. To avoid this, when taking spectra on bolometers of a particular band, we only drop bolometers of that band into the transition and apply excess electrical power to bolometers in the other two bands so as to hold them in their normal branch, where their responsivity to both optical and electrical signals will be very low.

Figure 4.11: Spectral response FTS measurements taken for a single SPT-3G wafer, corrected for NDF and mylar beam-splitter transmission. Grey dashed lines show Sonnet simulations based on design criteria and Silicon Oxide dielectric thickness. Blue dot-dashed lines show expected atmospheric transmission using a model developed for ALMA (Pardo et al., 2001) assuming 0.5 mm of precipitable water vapor (PWV), which slightly overestimates typical atmospheric conditions at the South Pole.

It was discovered in the process of characterizing wafers for potential SPT-3G deployment that some of the 95 GHz bolometers in SPT-3G wafers had contamination with response at 50 GHz,
either response solely at 50 GHz, as shown in the top left plot of Figure 4.13 as compared with a non-contaminated 95 GHz bolometer from the same wafer, shown in the top right plot. The colored curves show repeated FTS scans for a single bolometer, showing that the response at 50 GHz is repeatable albeit noisy. Close examination of the triplexer filter components revealed that niobium on the capacitors of the in-line filters was being incompletely removed by etching during fabrication and the residual was causing shorting, resulting in the out-of-band leakage (Posada et al., 2018). An additional etching step was added to the fabrication chain that prevented this residual niobium for future wafers, and greatly improving the robustness of the measured bands for SPT-3G wafers. The lower two panels of Figure 4.13 show SEM images from Posada et al. (2018) showing an example
from a wafer with residual niobium and a wafer fabricated after the additional etch step was added.

Figure 4.13: Top: Left: 95 GHz bolometer with contamination from 50 GHz out-of-band leakage. Right: 95 GHz bolometer from the same wafer with a nominal response at 95 GHz. Bottom: SEM images from Posada et al. (2018) showing an example of residual niobium (left), which was found to be the cause of the 50 GHz response, and (right) an example from a wafer fabricated after an additional etch step was added to the fabrication chain to prevent the 50 GHz leakage.

Given that the NDF correction is a function of frequency, applying the correction will cause some shifting in the measured band edges. We apply the correction using the empirical values for the NDF absorption that we believe should characterize the loading in the CU cryostat most accurately, but there is some remaining uncertainty in the NDF correction. As a check, we can compare FTS taken at CU Boulder with spectra measured from the same wafer after installation in the SPT-3G receiver, which will be measured under significantly different loading conditions. FTS spectra taken in situ on the SPT-3G receiver are measured from the point in the optics chain just outside the optics cryostat but before the tertiary mirror. As a result, we expect that the response
of the detectors will be subject to a $\nu^2$ attenuation of the bolometer etendue when passing through the Lyot stop. Comparison of the measured 150 GHz band for one wafer deployed in the first-year focal plane of SPT-3G is shown in Figure 4.14, showing FTS measurements from the cryostat at CU Boulder, with empirical NDF and mylar beam-splitter corrections applied, with corrected and uncorrected FTS measurements from Pole. The corrected spectrum as measured at CU Boulder agrees well with the corrected Pole spectrum.

![Figure 4.14: Comparison of 150 GHz FTS spectra measured at CU Boulder with empirical NDF and mylar beam-splitter corrections applied with spectra measured for the same wafer in situ in the SPT-3G receiver after installation for first-year deployment. FTS spectra measured at Pole are measured through the optics chain in the optics cryostat, and we expect the bolometer’s etendue will undergo an attenuation at the Lyot stop with a $\nu^2$ dependence. Dividing out this $\nu^2$ dependence yields the “corrected” version of the Pole FTS spectrum.](image)

4.5 Niobium microstrip loss characterization

One final element of state-side testing that was pursued early in the fabrication developments of detector wafers for SPT-3G was characterization of the expected loss in the niobium microstrip that is used to feed signals between the antenna and the TESs as well as from the TESs to the edge of the wafer. Loss may be due to impurities in the superconductor, lacking film quality, and loss into the dielectric layer (Zhu et al., 2009), and since the microstrip for a single bolometer in a detector wafer for SPT-3G may span of order 20 cm, it’s essential to ensure that the potential loss
in the microstrip is low. The expected attenuation in a transmission line is $P/P_0 = \exp(-2\pi\delta L/\lambda)$ where $P_0$ is the input power, $P$ is the power after attenuation, $L$ is the transmission line length, $\lambda$ is the wavelength of the signal in the line, and $\delta$ is the loss tangent of the microstrip (Chang et al., 2015). Under the assumption of low ohmic losses in the microstrip, the loss tangent is given by the ratio of the imaginary and real coefficients of the complex dielectric constant, $\epsilon = \epsilon' + i\epsilon''$ and $\tan\delta = \epsilon''/\epsilon'$, in other words, the amount of the signal that has shifted from the real domain into the imaginary. The design criterion for SPT-3G detector wafers is to achieve loss tangents of $5 \times 10^{-3}$ or smaller (Chang et al., 2015).

The dielectric loss can be measured at radio frequencies using microstrip half-wavelength resonators with resonant frequencies in the range 6–10 GHz that are capacitively coupled to coplanar waveguide (Li et al., 2013). Although ultimately measurements of the loss tangent must be characterized at mm-wavelengths, measurements at radio frequencies are more straightforward and resonator fabrication is simple, and measurements at radio frequencies provide a lower limit on the loss at shorter wavelengths (Chang et al., 2015). Resonators for these tests were fabricated at Argonne National Laboratories and tested at National Institute of Standards and Technology (NIST), where they were cooled with an ADR and supplied GHz signals along superconducting coaxial cable from a VNA, and the output measured via a HEMT amplifier at 4 K. Figure 4.15 shows a photograph of a resonator chip with four lithographed resonators and shows transmission through the resonator, measured by the VNA, showing the locations of the four resonances. Loss is parametrized by the shift in each resonator’s resonant frequency as a function of temperature and measurements of radio frequency resonators can be used to probe two distinct sources of loss. First, loss in the SiO$_x$ dielectric due to the presence of a two-level system (TLS), and second, potential loss due kinetic inductance in the niobium superconductor. Briefly, TLS loss is due to the electrons tunneling between local minima within the amorphous dielectric material; for more detail see Gao (2008). Kinetic inductance loss in the superconductor is due to the fact that although superconductors have zero DC resistance, they have non-zero AC impedance due to the inertia of Cooper pairs. According to the BCS theory of superconductivity, electrons in a superconductor are paired
into Cooper pairs, bound by an energy gap \( 2\Delta \approx 3.5k_B T_c \). According to Mattis-Bardeen theory, excess thermal energy or photons with energy above the band gap can break Cooper pairs into so-called quasi-particles, and changes in the number of quasi-particles causes changes in the kinetic inductance and therefore surface impedance which can also be parametrized by the temperature dependence of the resonant frequency [Gao (2008)]. Figure 4.16 shows the measured shift in resonant frequency as a function of temperature for one resonator. The low-temperature portion, in red, is fit with a pure TLS-loss model, shown in the dashed line, as developed by [Gao (2008)]. This model is a two-parameter fit for \( f_r \), the resonant frequency, and \( F\delta \), where \( F \) is the filling factor, which is close to unity for these resonators. We measure that the dielectric loss tangent is roughly \( 1.7 \times 10^{-3} \), which is within our design criteria. The data diverges from the TLS model at higher temperatures (data in blue squares), and the working theory for this is the influence of loss due to the breaking of Cooper pairs. A simplistic combined TLS + Mattis-Bardeen model is fit the full range of frequencies, while holding the parameters of the TLS model fixed. This combined model then has two additional free parameters: \( \Delta \), the band-gap energy of the Nb superconductor, and \( \alpha \), the fraction of the kinetic inductance relative to the total inductance. Although we recognize that this combined model may be overly simplistic in modeling the true behavior of the niobium superconductor [Chang et al. (2015)], the model fits the data quite well with a value for the band gap similar to that expected for superconducting niobium. The fact that the band gap we measure gives relatively good agreement to pure niobium indicates that the niobium microstrip does not suffer substantially from impurities or other issues arising from fabrication [Chang et al. (2015)].

Millimeter wavelength loss measurements were also carried out considering the differential optical efficiency of two bolometers with differing lengths of microstrip, yielding upper limits for the microstrip loss of \( \tan \delta < 2 \times 10^{-3} \), which agree with the radio frequency loss measurements [Chang et al. (2015)].
Figure 4.15: Left: Photograph of a fabricated resonator chip with four half-wavelength resonators capacitively coupled to CPW feedlines. Photo from Chang et al. (2015). Right: Measured resonances at base ADR temperature as measured by a VNA.

Figure 4.16: Measured dependence of resonant frequency on temperature with fits of the low-temperature-only portion (red stars) to a model of dielectric loss due to the presence of a two-level system (TLS; dashed line), and a simple combined model fit across the full range of temperatures including components for TLS loss as well as breaking of Cooper pairs in the Nb superconductor according to Mattis-Bardeen theory. See text for references.
4.6 Bolometer characterization summary

To summarize, we have undertaken detector wafer testing efforts at CU Boulder to aid in characterization of SPT-3G bolometer properties prior to the first year of deployment and second year of operation of SPT-3G. Testing efforts focused on characterization of $P_{\text{sat}}$, $T_c$, $R_n$, $G$ and other parameters related to thermal conductivity, thermal time constants, loop gain, spectral bands, and microstrip loss. Wafer testing efforts were undertaken at numerous institutions within the SPT-3G collaboration in order to characterize and select the final set of ten wafers deployed in both the first and second years of SPT-3G. In this chapter, we have focused more on the methods employed for bolometer characterization and less on the results of those specific measurements for specific wafers. Bolometer characterization specifically for the ten wafers deployed each year in their relation to the performance of the deployed array are the focus of the following chapter, and a summary of bolometer characterization parameters can be found in Table 5.1 which includes results from measurements in situ in the SPT-3G receiver and from testing in northern cryostats prior to deployment.
Chapter 5

Characterization of the first- and second-year focal planes for SPT-3G

5.1 Introduction

During the austral summer of 2016-2017, SPT-3G was installed on the South Pole Telescope, which involved installation of a new optics bench, secondary and tertiary mirrors, two new cryostats weighing a combined \( \sim 1300 \text{ lbs} \), containing cooled refracting optics and a focal plane with accompanying new cold and warm readout electronics. The new SPT-3G camera commenced extensive characterization as well as sky observations during the austral winter of 2017; however, gathering science-quality data was hampered by unforeseen excess readout noise, inefficiencies in the optics chain, as well as array instability when operating the full focal plane for sky observations.

As mentioned in Chapter 3, it was discovered during the first year of deployment that although the deployed SQUID amplifiers had > 99% yield with excellent performance, in the context of the DfMUX readout circuit (shown in Fig. 3.11), their high input coil inductance caused leakage of noise from downstream of the SQUID into the TES via the LRC circuit and bias resistor circuit via the active nulling injection (Bender et al., 2018). SQUIDs with significantly lower inductance were developed and installed for the second year of SPT-3G, greatly improving the noise performance (Bender et al., 2018). Also as mentioned in Chapter 3, the large, refracting, alumina lenses in the optics cryostat deployed during the first year with a non-optimal two-layer anti-reflection (AR) coating, were replaced in the second year with a better-optimized three-layer coating, improving optical throughput. Bolometer \( P_{\text{sat}} \)s for the first-year deployed focal plane were developed using calculated expectations for optical loading through the optics of the receiver, but the true values
were not measured until the array went into operation after deployment. Quantifying the true optical power incident on the focal plane during the first year of observations allowed for fine-tuning of the target $P_{\text{sat}}$ for detector fabrication. A full set of ten new detector wafers were deployed in the second year with somewhat lower $P_{\text{sat}}$, adjusted to the true loading modulo the expected increase in loading from improved AR coatings. In this chapter, we discuss the characterization of the first-year focal plane post-deployment, and highlight the results of changes and improvements made for the second year.

5.2 Yield

5.2.1 Warm to cold detector yield

Many factors contribute to yield degradation between the maximum number of bolometers per detector wafer to the number of high-optical-response detectors in operation in the full focal plane array on a typical observing day. Prior to cooling down the detectors, hits in warm yield result from warm shorts, either between TESs or between a TES and ground, or opens resulting from imperfect fabrication yield or any issues arising in the automatic wirebonding. Once the detectors are cold, the yield will depend on the rate of successful SQUID tuning and the yield of LC resonances per comb and the ability to match LC resonances with bolometers.
Figure 5.1: Example plots showing numbers of successfully-tuned bolometers per wafer and per band for repeated full-array tunings from a roughly ten day period in July, 2017, during the first year of SPT-3G.
Each detector wafer has 269 fabricated pixels, each with 6 bolometers, for a total maximum of 1614 bolometers per wafer. Each detector wafer is read out by 24 LC combs, and during the first year of SPT-3G deployment, we employed a 64x DfMUX multiplexing factor, for a maximum of 1536 bolometers capable of being read out per wafer, and therefore 15360 bolometers maximum across the full array. In the second year, the multiplexing factor was upgraded to 68x, where 66 channels per comb were devoted to bolometers and two to calibration resistors, for a total maximum of 15840 bolometers read out. After wirebonding and plucking bolometers with warm shorts to ground, the average warm yield for wafers in the first year focal plane was 88% (Everett et al., 2018), which increased slightly to 90% for the second year focal plane (Dutcher et al., 2018). The SQUID tuning yield on the 240 SQUIDs is essentially 100% over repeated daily tunings. One wafer in the first-year focal plane, W136, was deployed without 1/3rd of its SPT-3G cold readout in order to install a set of SPTpol LC boards to read out a portion of the wafer. Although this resulted in a significant yield hit for that wafer (which had a cold yield of 54%), the SPTpol readout was useful for debugging and noise characterization of the first-year array. The rest of the wafers in the first-year focal plane had an average cold yield of 78%, calculated as the number of identified LC resonances matched to bolometers divided by the maximum permitted by 64x multiplexing. Thus the total number of bolometers with LC resonance mappings in in the first-year focal plane was 11910. The SPTpol readout was removed for the second year of deployment. The total cold yield of identified LC peaks in the second year focal plane increased to 85% (Dutcher et al., 2018). Diagrams for the first and second year deployed arrays showing the layout of the LC readout combs on the focal plane, and showing pixels with bolometers successfully matched to LC channels in the cold hardware map can be found in the Appendix.

Additional hits in yield can arise when preparing the array for daily observations, both from bolometers that fail to drop stably into their superconducting transitions (“tuning”) and from bolometers that lack strong optical response. Achieving repeatable high-yield, full-array tunings with good optical response and stability during sky observations was an ongoing focus of work during the first year of deployment. Implementing changes to the grounding configuration of the
warm read out electronics made large improvements in both noise reduction and full-array stability. To monitor the daily yield during sky observations, we check the number of successfully-tuned bolometers per full-array tuning, an example of which is shown in Figure 5.1 for repeated full-array tunings taken over roughly 10 days in July, 2018. To characterize the bolometers’ sensitivity to optical signals, independent of sky observations, we use a thermal, chopped calibration source installed behind a shutterable hole in the middle of the secondary mirror, such that the bolometers still receive a majority of their optical loading from the sky, and therefore will be in the same state as for sky observations, but with an augmentation of their received optical power from the chopped calibrator source. The highest tuning yield in the first year of SPT-3G operation was roughly 10000 bolometers in the transition; but on average, typical tunings during the first year of deployment achieved 8000 bolometers tuned in the transition with good response to the calibrator. In the second year of SPT-3G, operational yield numbers were bumped up to 76% tuned into the transition, of which 72% had high signal-to-noise response to the calibrator, for a total of roughly 10,500 high-response bolometers operational during typical sky observations (Dutcher et al., 2018).

5.3 Bolometer characterization

5.3.1 First-year focal plane characterization: $T_c$, $R_n$, $R_p$, $P_{\text{sat}}$

Although every detector wafer deployed in the first year of SPT-3G was tested in a northern cryostat prior to deployment, not every wafer was tested in both a dark and optical run, and most northern cryostats have relatively limited readout capacity, generally allowing for testing a maximum of 1/6th of a wafer. Optical runs in northern cryostats will necessarily have different optical loading conditions than the receiver at Pole, and quantifying optical loading in northern cryostats is complicated by uncertainties in NDF corrections. Therefore full characterization after installation in the SPT-3G receiver of the ten wafers deployed in the first year was important both for characterizing expected performance in the first year and for feeding back information to fabrication if necessary.
To aid with bolometer characterization post first-year deployment, a set of $R(T)$ measurements was taken in-situ in the SPT-3G receiver, allowing for quantifying normal resistance, parasitic resistance, transition temperature as well as characterizing uniformity and yield across the full array and identifying any strangely-behaving or non-transitioning bolometers. The temperature of the millikelvin stage was swept from above the $T_c$ of the bolometers to below $T_c$ and back, while applying a small voltage to the bolometers and monitoring the current, in the same method as used in northern testbeds. Figure 5.2 shows the results of the downward and upward sweeps for a single wafer. We observe a roughly 20 mK hysteresis between upward and downward sweeps, which is expected due to the thermal mass of the stage. $T_c$ is defined as the temperature at which each detector reaches a depth of 0.95$R_n$ in the transition and each TES’s reported $T_c$ is taken as the average from upward and downward sweeps. Figure 5.3 shows histograms of $T_c$ for the same wafer as Fig. 5.2 separating by dark and optically-coupled bolometers. Figure 5.4 shows stacked histograms of measured $T_c$ for all ten wafers deployed in the first year of SPT-3G, colored by wafer and showing separate plots for optically-coupled and dark bolometers. Optical power on the focal plane will suppress the measured $T_c$ of the devices relative to the intrinsic $T_c$ of the films. We find of order a 30 mK offset between dark and optical bolometers, varying by band and wafer. Most wafers deployed in the first-year focal plane have measured $T_c$ of 525–530 mK for optically-coupled bolometers and 550–555 mK for dark bolometers, except for wafers W136, W139, and W142, which have $T_c$ shifted somewhat lower.

From sweeps of $R(T)$, we can also extract the per-bolometer normal and parasitic resistances, $R_n$ and $R_p$, taken from the normal and superconducting branches of each bolometer’s transition. The parasitic impedance in the bolometer circuit will result from any non-superconducting elements in the circuit and may be located on the bolometer island or elsewhere in the circuit, such as in the readout electronics. The parasitic may include resistive and reactive components. Using the assumption that the measured $R_p$ is purely resistive and therefore will act like a voltage divider, we use the $R_p$ to correct the measured $R_n$ to yield the expected $R_n$ due only to the TES. Figure 5.3 shows histograms of $R_n$ and $R_p$ for a single wafer deployed in the first year. We separate by
optical and dark bolometers as a cross-check, since dark and optical bolometers should show no significant difference in measured $R_n$ or $R_p$, which agrees with our findings. Figure 5.5 shows stacked histograms of $R_n$ and $R_p$ colored by wafer and band for all first-year deployed wafers. Measured $R_p$ is relatively consistent between each wafer, and measured $R_n$ are generally in the range $2 - 2.5 \, \Omega$ for most wafers except wafers W136, W139, and W142, which have measured $R_n \sim 1 - 1.5 \, \Omega$ due to differences in TES design in fabrication.

The bias frequencies used for SPT-3G LC resonances span a much higher and wider range ($1.6 - 5.3 \, \text{GHz}$) relative to SPTpol, and we find that for the most part, the measured $R_p$ are relatively flat across the range of bias frequencies, with a median value of $R_p = 0.28 \, \Omega$. The resonances are arranged within each LC comb such that the 95 GHz bolometers span the lowest bias frequencies ($\sim 1.6 - 2.5 \, \text{GHz}$), 150 GHz bolometers the middle range ($\sim 2.5 - 3.7 \, \text{GHz}$), and 220 GHz bolometers the highest range ($\sim 3.7 - 5.3 \, \text{GHz}$). As shown in Figure 5.5, we see that the measured $R_p$ is relatively flat between all three bands. Although characterization of the source of parasitics in the bolometer circuit are on-going, a variety of sources are expected to contribute, including inductance in the NbTi striplines and stray impedance in the LC readout. We note that since these $R(T)$ measurements were performed relatively early in the first-year of deployment to aid in debugging and characterization of the array, some bolometers, specifically a set of 220 GHz bolometers that had measured $R_n$ values considerably higher than the bulk of the array, had been left unbiased during the $R(T)$ measurements and therefore are not included in the plots. It was discovered later that the measured high $R_n$ of these 220 GHz bolometers resulted from the need to apply a different transfer function for each channel based on the ordering of each channel’s inductor and capacitor in the LC chip. Inductors and capacitors are alternated in the LC chip design to mitigate cross-talk between bolometers due to mutual inductance (Hattori et al., 2014), but the result is that bolometers alternate in being biased in a LCR circuit compared with a CLR. The maximum correction factor using the correct transfer function per channel is of order 15% (Dutcher et al., 2018).

We measure $P_{\text{sat}}$ values for bolometers in the full first-year focal plane by looking at repeated
IV curves taken over a two-week period. We define $P_{\text{sat}}$ as $P_{\text{sat}} = P_{\text{elec}}(0.95R_n)$ and take the average per bolometer over repeated tunings. Measurements of $P_{\text{sat}}$ are shown in the top panels of Figure 5.6 for 95, 150, and 220 GHz, where stacked histograms show $P_{\text{sat}}$ for optically-coupled bolometers and vertical lines show median dark bolometer $P_{\text{sat}}$ values per wafer and band. $P_{\text{sat}}$ measurements have been corrected for $R_p$ on a per-bolometer basis for those bolometers with measured $R_p$ values from the $R(T)$ data, assuming the $R_p$ is purely resistive. For bolometers without a measured $R_p$, we correct using the median value of $R_p$ across the array of $R_p = 0.28 \, \Omega$.

The ideal design $P_{\text{sat}}$ for SPT-3G bolometers is chosen such that $P_{\text{sat}} \simeq 2P_{\text{opt}}$ under dark conditions and therefore $P_{\text{elec}} \simeq P_{\text{opt}}$ during bolometer operation. This will ensure that the bolometers have sufficient electrical power to operate under high electrothermal feedback and will not saturate under excess optical power relative to electrical power, but will also ensure that $P_{\text{elec}}$ is not excessively high, resulting in additional noise. Readout NEP scales with voltage bias and Johnson noise in the circuit scales with $P_{\text{elec}}$ (see Section 4.2.4). Since the actual optical power on the focal plane could not be quantified until the receiver was deployed at Pole, to ensure the detectors would not saturate in the case of unforeseen excess optical loading, the detectors deployed in the first-year were chosen erring on the side of higher $P_{\text{sat}}$. During the first year, the optical loading on
Figure 5.3: Stacked histograms of measured $T_c$, $R_n$, and $R_p$ for a single wafer in the first year focal plane. Histograms are split by band and by optically-coupled compared with dark bolometers. We expect that optical power on the focal plane will cause a reduction in the measured $T_c$ of optical compared with dark bolometers. We expect no significant difference between the normal and parasitic resistances of optical compared with dark bolometers.

The focal plane was quantified, as discussed in the following section, and it was noted that the the $P_{sat}$ values for wafers deployed in the first year were higher than the design criterion. Therefore, a new set of ten wafers with lower designed $P_{sat}$ were developed, fabricated, tested, and deployed for the second year of SPT-3G deployment. The design of these wafers was also adjusted to result in somewhat lower $T_c$ and lower $R_n$. Since higher $T_c$ results in higher thermal fluctuation noise ("G" noise) and higher Johnson noise, we adjust target $T_c$ downward, while still maintaining $T_{bath}$ sufficiently above $T_{bath}$. While in principle, the fabricated $R_n$ is not a critical design parameter,
since the TES resistance at the operating point, $R_0$, is adjustable by biasing to different depths in the transition (choosing different $f_R$ within the limits of relatively high loop gain via relatively steep $\alpha$). However, in practice it was found that tuning full combs of detectors deep in the transition caused array instability. Biasing at low $f_R$ risks individual bolometers “latching” (i.e. dropping out of the transition and into the superconducting branch), which can then overload the SQUID amplification circuit with too much current. Given the higher multiplexing factor, the likelihood of latching increases, increasing the risk that full combs will become unstable and overload the SQUID ADC. Characterizing the parasitic impedance in the bolometer circuit during the first year of deployment also supplied a better-quantified lower limit on the design specification for $R_0$, in conjunction with time constant stability constraints. Therefore, performance during the first year allowed for fine tuning of the design $R_n$ such that we can supply the proper $R_0$ during operation at a depth in the transition (typically $f_R \sim 0.7 - 0.9$) with high loop gain and good operating stability and therefore high yield.
Figure 5.5: Top left: Stacked histograms separating by wafer of measured normal resistance measured from $R(T)$ in-situ on the SPT-3G receiver during characterization of the first-year focal plane. Top right: Same as left but showing measured parasitic resistance. Bottom: Same as upper right but coloring by frequency band. All three plots are from Everett et al. (2018).

5.3.2 Second-year focal plane characterization: $P_{\text{sat}}$ and $R_n$

Figures 5.7, 5.8, 5.9, 5.10 show distributions of $P_{\text{sat}}$ and $R_n$ per band and per wafer for the ten wafers deployed in the second-year focal plane, showing the results of the design modifications in fabrication, as discussed in the previous section. Histograms are split by optically-coupled and dark bolometers, where, as expected, $R_n$ distributions are insensitive to optical vs dark classification, but optical $P_{\text{sat}}$ values are suppressed relative to dark, representing the optical power present on the
Figure 5.6: Top panels: Stacked histograms of measured $P_{\text{sat}}$ for optically-coupled bolometers for wafers deployed in the first year of SPT-3G, separated by wafer and band. Vertical lines show median dark $P_{\text{sat}}$ per wafer and band. From [Everett et al., 2018].

focal plane. We note that, in line with adjustments made in fabrication, average $P_{\text{sat}}$ values for the second year focal plane have shifted downward substantially. $R_n$ has also shifted downward slightly, but not considerably. At the time these measurements were made, direct $R_p$ measurements had not been made on the second-year focal plane, so the plots shown here have not been corrected for $R_p$.

We expect that $R_p$ for the second-year focal plane will be similar to that for the first-year, with a median similar to 0.28 $\Omega$, and applying the $T_c$ correction to the $P_{\text{sat}}$ measurements should shift the measured $P_{\text{sat}}$ down by roughly 15% or 1 – 2 pW. We also note that in the distributions in $R_n$, there is obvious bimodal behavior, particularly in the 220 GHz bolometers. The $R_n$ measurements shown in Figures 5.9 and 5.10 are shown without applying the correction for the appropriate transfer function per channel to account for the alternating order of the inductor and capacitor in the LC circuit. Including this correction tightens the distributions of $R_n$ and eliminates the
bimodality (Dutcher et al. 2018).
Figure 5.7: Histograms of measured $P_{\text{sat}}$ per band and per wafer for wafers W172, W174, W176, W177, and W180 deployed in the second year of SPT-3G. Separate histograms are plotted for optically-coupled bolometers compared with dark bolometers, where the difference in $P_{\text{sat}}$ provides a measurement of the optical power present on the focal plane. $P_{\text{sat}}$s are calculated in this plot with no correction for $R_p$. 
Figure 5.8: Histograms of measured $P_{\text{sat}}$ per band and per wafer for wafers W181, W187, W188, W201, and W203 deployed in the second year of SPT-3G, separating by optically-coupled compared with dark bolometers. $P_{\text{sat}}$s are calculated in this plot with no correction for $R_p$. 
Figure 5.9: Histograms of measured $R_n$ per band and per wafer for wafers W172, W174, W176, W177, and W180 deployed in the second year of SPT-3G. Separate histograms for optically-coupled bolometers are compared with dark bolometers as a cross-check, as we expect the two groups to show no significant difference in $R_n$. $R_n$s are shown in this plot with no correction for $R_p$ and no correction for the cold hardware transfer function, which has been shown to cause the bimodality in measured $R_n$ for 220 GHz bolometers due to differences in LCR compared with CLR ordering in the DiMUX circuit (Dutcher et al., 2018).
Figure 5.10: Histograms of measured $R_p$ per band and per wafer for wafers W181, W187, W188, W201, and W203 deployed in the second year of SPT-3G. $R_n$s are shown in this plot with no correction for $R_p$ and no correction for the cold hardware transfer function, which has been shown to cause the bimodality in measured $R_n$ for 220 GHz bolometers due to differences in LCR compared with CLR ordering in the DfMUX circuit (Dutcher et al., 2018).
5.4 Optical loading measurements

5.4.1 First-year optical loading

To quantify the optical power present on the bolometers and therefore compare it with theoretical expectations, as overviewed in Table 3.1, we employ two methods and compare the results: 1) We compare measured $P_{\text{sat}}$ values for optically-coupled and dark bolometers on the focal plane as installed in the receiver, and 2) we compare measured $P_{\text{sat}}$ for optically-coupled bolometers on the focal plane with measured $P_{\text{sat}}$ values for the same bolometers tested in a dark configuration in a northern testbed prior to deployment. As mentioned in Section 3.3, each detector wafer was fabricated with bolometers with intentional omissions of circuit elements such that the TES would receive no optical power from the sinuous antenna. For each wafer, there are of order 40 dark bolometers (about 2.5% of total), and therefore while the first method is relatively free of systematics since measurements are taken simultaneously using the same thermal environment and readout configuration, the measurements suffer from relatively small number statistics.

To improve the number statistics in measuring the optical loading, we use the second method, where we compare $P_{\text{sat}}$ as measured in the SPT-3G receiver at Pole with $P_{\text{sat}}$ measurements from dark tests in northern cryostats prior to deployment. This allows for measuring optical power by direct per-bolometer $P_{\text{sat}}$ comparison for any bolometer that overlapped between the stateside measurements and bolometers read out at Pole; however, the measurement may suffer from worse systematics, since the two sets of data are taken months apart in physically different cryostats with potentially different readout characteristics and specific thermal environments. Two wafers deployed in the first year of SPT-3G were tested in a dark configuration prior to deployment: W152 and W158, and each had $P_{\text{sat}}$ values measured via measuring $G$, as discussed in Section 4.3.2, which provides a better constraint on $P_{\text{sat}}$ compared with simply taking a single value from an IV curve taken at the operating $T_{\text{bath}}$. Here we focus on results from W158 which had higher fidelity data. Results for this wafer are shown in Figure 5.11, including histograms per band of dark, optical, and differenced $P_{\text{sat}}$, as well as $P_{\text{sat}}$ and $\Delta P_{\text{sat}}$ plotted as a function of bias frequency. Measured
optical $P_{\text{sat}}$ values have been corrected for $R_p$ on a per-bolometer basis using measured $R_p$ from the $R(T)$ taken at Pole, and the median of 0.28 $\Omega$ has been applied for bolometers with no $R(T)$ data. Measured dark $P_{\text{sat}}$ values have been corrected for $R_p$ on a per-bolometer basis using $R_p$ measured for each bolometer during testing at the stateside test cryostat, taking the $R_p$ from the superconducting branch of either an $R(T)$ measurement or IV curve. Errors for the dark $P_{\text{sat}}$s are drawn from uncertainties in fitting the $P_{\text{elec}}(T_{\text{bath}})$ function, and errors for the optical $P_{\text{sat}}$s are 16% and 84% percentiles of the distribution in $P_{\text{sat}}$ values for each bolometer from repeated tunings over a two week period.

The expected optical loading per band for the first year of deployment was 4.4, 7.1, 8.4 pW for 95, 150, 220 GHz, respectively, based on predicted loading from the sky and internal optics, including predicted efficiencies for the internal optics of the optics cryostat and bolometer optical efficiencies from stateside lab measurements (i.e. similar predictions to Table 3.1 but for predictions appropriate for first-year deployment). Optical power as measured by comparing median dark $P_{\text{sat}}$ minus median optical $P_{\text{sat}}$ per band and per wafer is shown in the bottom panels of Figure 5.6. Measured values of 2.4±0.3, 5.7±0.5, 3.4±0.8 pW at 95, 150, 220 GHz, respectively, are relatively consistent but somewhat lower than the expected values at 95 and 150 GHz and quite a bit lower than expected at 220 GHz.

Measured optical powers using this second method for this single wafer are 5.6±1.1, 7.2±1.5, and 5.9±3.1 pW for 95, 150, and 220 GHz, respectively. We note that the 220 GHz bolometers as measured using the second method also show reduced loading relative to expectations in comparison with the other two bands. The 220 GHz bolometers using the second method also show a larger spread and even potentially bimodality in their distribution in both optical and dark $P_{\text{sat}}$ compared with the other two bands, which does not necessarily correlate per bolometer (i.e. the distribution of measured optical powers taken by subtracting dark $P_{\text{sat}}$ minus optical $P_{\text{sat}}$ on a per-bolometer basis is wider than the individual dark and optical $P_{\text{sat}}$ distributions). Further investigation showed that this bimodality also did not correlate when grouping bolometers by inductor-capacitor ordering in the LC circuit. There is a chance that since the two $P_{\text{sat}}$ datasets were taken with different readout
hardware and separated by months in time that there were slight unaccounted mismatches in channel identification when creating the mapping from bolometer to $LC$ resonance. The measured optical power from the second method is somewhat higher than that measured from the first method, although it is within roughly one sigma at 150 and 220 GHz, and larger at 95 GHz.

We expect the lower measured optical loading, particularly at 220 GHz, was due to non-optimal AR performance of the large alumina lenses in the first year of deployment. The AR coating on the large alumina lenses was replaced for the second year of SPT-3G observations with a better-optimized three-layer AR coating, as discussed in [Nadolski et al. (2018)]. As a result, we expected an increase in optical loading in the second year deployed focal plane, as discussed in the following section.

We note that the detector design goal, as discussed in Section 4.2, is to achieve an intrinsic dark $P_{\text{sat}}$ for the bolometers such that the bolometers in operation experience $P_{\text{tot}} \gtrsim 2P_{\text{opt}}$ so that $P_{\text{elec}} \sim P_{\text{opt}}$ at the TES operating point under the optical loading conditions in the SPT-3G cryostat. Although wafers deployed in the first year had a wide range of $P_{\text{sat}}$, most had $P_{\text{sat}}$ generally in excess of $P_{\text{opt}}$, which contributed to excess noise. With the optical loading in the receiver now quantified during the first year of deployment, hitting the target of $P_{\text{elec}} \sim P_{\text{opt}}$ was a primary goal of detector fabrication for deployment in the second year. However, hitting the target exactly was complicated by the simultaneous expected increase in optical loading on the focal plane from improved AR coatings.
Figure 5.11: Optical loading measurements for a single wafer deployed in the first year of SPT-3G, from per-bolometers comparisons of optically-loaded $P_{\text{sat}}$ values measured in the SPT-3G receiver at Pole with dark $P_{\text{sat}}$ measurements taken in a dark configuration in a northern cryostat prior to deployment. Top left: plotting per-bolometer dark and optical measured $P_{\text{sat}}$ as well as $\Delta P_{\text{sat}} = P_{\text{sat, dark}} - P_{\text{sat, opt}}$ as a function of bias frequency in the LC comb. The other three panels show histograms for 95, 150, and 220 GHz of dark, optical, and delta $P_{\text{sat}}$. 
5.4.2 Second-year optical loading

To quantify the changes between the first- and second-year deployed focal planes, Figure 5.12 shows histograms per wafer using the first method outlined above, comparing measured $P_{\text{sat}}$ for dark bolometers minus median optical $P_{\text{sat}}$ per band and per wafer. Note that these measurements were made on $P_{\text{sat}}$s calculated without an $R_p$ correction applied; however, we expect this to have a small effect on the measured optical powers, since the $R_p$ correction will shift both optical and dark $P_{\text{sat}}$ values by relatively similar amounts. We find median optical loading across all wafers to be 4.3, 8.4, 6.3 ±1−2 pW for 95, 150, 220 GHz, respectively. We also employ method 2 mentioned above, and Figure 5.13 shows results for three wafers deployed in the second-year focal plane. We note that although there is some variation in dark $P_{\text{sat}}$ between wafers, due to changes in design and fabrication, the optical power per band between the three wafers is comparable and similar to the optical power measured using method 1. The second-year optical loading expectations, applying expected improvements from the new AR coatings are 5.09, 7.68 and 9.99 pW at 95, 150, and 220 GHz, respectively, as shown in Table 3.1. Our measured optical powers for the second-year focal plane from both methods match expectations relatively well, although we note that the optical power in 220 GHz has a quite wide distribution, similar to the first-year focal-plane wafer discussed above, and the overall optical loading at 220 GHz is somewhat lower than expectations. We expect this lower 220 GHz optical loading is still due to some remaining non-ideality in the revised AR coatings of the large alumina lenses (Nadolski et al., 2018).

We note that wafers deployed in the second year of SPT-3G are overall much closer to the desired design specification of $P_{\text{elec}} \sim P_{\text{opt}}$ compared with the first year. However, some wafers in some bands achieve this target more closely than others. For example, as shown in the left panels of Figure 5.13 W172 shows nearly ideal ratios of optically-loaded $P_{\text{sat}}$ compared with measured $P_{\text{opt}}$ in the 95 GHz band, but has an excess of optical power relative to electrical power in the other two bands. Conversely, W177 has close to an ideal ratio at 150 GHz and close at 220 GHz, but in the 95 GHz band has excess electrical power relative to optical power.
We can assess our measured optical loading per band relative to expectations as shown in Table 3.1 by considering measured optical efficiencies of our detectors relative to the expected efficiencies noted in the table, and by considering possible modifications to measured $P_{\text{sat}}$ by a more careful accounting of the cold transfer function of the DfMUX electronics. During the first and second year of SPT-3G, we routinely make sky observations of a galactic HII region, RCW38, which has well-studied mm-wavelength properties and is used as a temperature calibration sky source. Comparing the power measured by the bolometers relative to the expected true sky power from RCW38, observed in the Rayleigh-Jeans limit, we can measure the cumulative optical efficiency of our bolometers and compare both with expected efficiencies referenced in Table 3.1 and with optical efficiencies measured in northern cryostats prior to deployment (Pan et al., 2018). Measured per-bolometer RCW38 optical efficiencies for the second year focal plane are 0.26, 0.35, and 0.11 for 95, 150, and 220 GHz, respectively (from intra-collaboration communication), measured relative to the power expected from RCW38 in a single polarization. Expected cumulative optical efficiencies calculated from transmission along the optical path that are used in calculating the expected optical loading (shown in Table 3.1), are 0.14, 0.18, and 0.17 for 95, 150, 220 GHz, respectively, which are relative to a total sky power, and therefore should be a factor of two lower than the RCW38 efficiencies if the expectations perfectly matched the observed efficiencies. We note that we see relatively consistent agreement at 95 and 150 GHz, and therefore the measured optical loading should not need a large correction to account for differences in expected compared with actual optical efficiencies. We note that our measured optical efficiency at 220 GHz is substantially lower than the expectation, which is also consistent with our measured optical loading at 220 GHz being lower than the expectation.

Although we expect the conversion from bolometer timestream units to Watts of power in the DfMUX firmware will be quite accurate, it may be that the true transfer function is somewhat more complicated on a finer scale, and for example, may have some dependence on bias frequency, and therefore observing band for SPT-3G, which we are currently not accounting for. Therefore, it may be that we are missing a correction between Watts as measured in the native DfMUX firmware
with true Watts of sky power. From comparisons between SPT-3G and SPTpol readout applied to SPT-3G wafers, studies of the SPT-3G cold readout circuit, and comparisons of quantifiable sky loading modulations with resultant measured power on the bolometers (from intra-collaboration communication), we expect the possible correction to our measured to be relatively low, of order a 5 – 25% positive correction, that increases with increasing bias frequency. However, more studies are needed to better quantify the correction.

Figure 5.12: Histograms for all wafers in the second-year focal plane split per band of $\Delta P_{\text{sat}}$ taken from subtracting the median measured $P_{\text{sat}}$ for optically-coupled dark bolometers for a particular wafer and band from the $P_{\text{sat}}$ measured for each dark bolometer. Because each wafer-band combination will only have a maximum possible of roughly 10-15 dark bolometers, the number statistics for this measurement are low.
Figure 5.13: Continued on next page
Figure 5.13: Optical loading for three wafers deployed in the second year focal plane of SPT-3G calculated by comparisons of $P_{\text{sat}}$ for optically-coupled bolometers in situ in the SPT-3G receiver with measurements of dark $P_{\text{sat}}$ for the same bolometers taken during testing in a dark configuration in a northern cryostat prior to deployment. Left panels: plotting per-bolometer dark and optical measured $P_{\text{sat}}$ as well as $\Delta P_{\text{sat}} = P_{\text{sat,dark}} - P_{\text{sat,opt}}$ as a function of bias frequency in the LC comb. Right panels: histograms of median per-bolometer delta $P_{\text{sat}}$, separated by band. The optically-loaded $P_{\text{sat}}$ measurements were drawn from single full-array tuning of the SPT-3G array, and therefore the Pole $P_{\text{sat}}$ values are presented without a measured error bar. The errors on the dark $P_{\text{sat}}$ data are taken from uncertainty in fitting the $P_{\text{sat}}(T_{\text{bath}})$ function in the $G$ measurement.
5.5 Time constants and Loop gain

5.5.1 Characterizing loop gain for first-year deployment

To quantify the expected operating loop gain of the bolometers deployed in the first year focal plane, we use data taken in a dark cryostat configuration prior to deployment in order to measure the intrinsic, non-optically-loaded loop gain. As discussed in Chapter 4, the loop gain is given by $\mathcal{L} = \frac{\alpha P_{\text{elec}}}{G(T)}$ where $\alpha$ is the logarithmic derivative of the $R(T)$ profile. $G$ is measured as discussed in Chapter 4 where repeated IV curves are taken while changing the bath temperature for all accessible $T_{\text{bath}} < T_c$. Here, $\alpha$ is measured via $R(T)$ measurements in the dark configuration, and for calculating the loop gain in the range of transition depths we expect to use during operation, we use the median $\alpha$ between $f_R = 0.7 - 0.9$. Figure 5.14 shows histograms per band of loop gain calculated per bolometer for a single wafer deployed in the first-year focal plane. For reference, we also show distributions of all four measured quantities that enter the loop gain calculation. High loop gain, indicating strong electrothermal feedback, is beneficial for bolometer operation since it linearizes the bolometer response and optimizes the dynamic range but extremely high loop gain can result in instability because the resulting thermal time constant will be too short relative to the readout time constant (see Section 4.2.2). We note that bolometers for SPT-3G have higher loop gains than previous generation SPT instruments, mostly due to steep $R(T)$ profiles and high $P_{\text{sat}}$, especially for the first year of SPT-3G. However, we note that we don’t expect the loop gain to be too high, both from time constant measurements as discussed in Chapter 4 and from noting that the loop gain measured on wafers in the dark configuration provides an upper limit on the on-sky loop gain, where the actual $P_{\text{elec}}$ provided to the bolometers in the SPT-3G receiver will be less due to the presence of optical power, and loop gain is directly proportional to electrical power. In-operation, optically-loaded $P_{\text{elec}}$ will reduce by the amount of optical power on the focal plane, resulting in an expected reduction in loop gain for the first year focal plane by roughly 15% at 95 and 220 GHz and 24% at 150 GHz relative to the intrinsic loop gain shown in Figure 5.14. We also note that for the second year focal plane, since the architecture of the TES design is generally
similar to the first year, we expect relatively comparably steep $R(T)$ profiles as wafers in the first-year focal plane. Design $P_{\text{sat}}$ for the second year are considerably lower than the first year, but design $T_c$ is shifted downward somewhat as well as is $G$, and therefore we expect loop gains for the second year to shift down some but not hugely, and expect loop gains for the second year focal plane to be of order 30 with loop gain of order 12 under optical loading in situ in the SPT-3G receiver.

5.5.2 Second-year operating depth optimization

Given the unforeseen elevated noise and array operation instability during the first year of deployment, much of the first year of SPT-3G was devoted to understanding the operation of the array in order to maintain and optimize yield during sky observations as well as mitigate noise. Improvements made for the second year resulted in much greater array stability and enhanced noise performance, allowing for greater fine tuning of the specific operating point of the focal plane. Exploring array yield and performance as a function of operating depth in the bolometer transition allows for optimizing on-sky loop gain and response linearity. In general, biasing deeper in the transition should serve to speed up the thermal time constant, but biasing very deep in the transition can risk bolometers latching, as mentioned above in Section 5.3.1.

A hot, thermal calibration source with a variable-speed mechanical chopping wheel is mounted looking through a shutterable hole in the center of the secondary mirror, allowing for measurements of the bolometers’ optical response and effective time constants in the SPT-3G receiver under similar loading conditions as during sky observations. The detector response is measured as the frequency of the chop increases. For chopping frequencies far slower than the detector response time, the bolometers will trace out the chop signal completely, but as the chop frequency is increased, eventually the frequency will exceed the bolometer time constant and the bolometer response will attenuate. The bolometer response as a function of chop frequency is fit to a single-pole roll-off model, where $\tau_{\text{th,eff}}$ can be measured via the $3\,\text{dB}$ attenuation point in response as a function of chop frequency. During the deployment of the second-year focal plane, a set of time constant
Figure 5.14: Histograms of intrinsic TES loop gain measured from data taken in a dark testing configuration prior to first-year deployment and calculated using $\mathcal{L} = \frac{\alpha \rho_{\text{elec}}}{G T_c}$. For reference, histograms of each of the four quantities that enter the loop gain calculation are also shown, although the loop gain calculation is done on a per-bolometer basis.
measurements was repeated at a range of operating depths in the transition \((f_R = 0.5 - 0.9)\). To ensure the time constant measurements are being measured on relatively large numbers of bolometers with high optical response, Figure 5.15 show histograms of signal-to-noise per wafer and per depth. We note that the histograms per wafer and \(f_R\) are relatively wide because of grouping all three bands together: the 95 GHz bolometers have measured calibrator signal-to-noise of roughly a factor of a half that of the 150 GHz and 220 GHz detectors. This is as expected because in the frequency bands of our detectors, we expect to be observing the calibrator source (with a temperature of \(\sim 1000\) K) in the Rayleigh-Jeans limit and assuming a single-moded etendue such that \(A\Omega = \lambda^2\), the amount of optical power in a given band will scale directly with the width of the band (also under the assumption of flat response within the band edges). The 95 GHz bandwidth is roughly half that of the 150 GHz band. (We note that while the 220 GHz bandwidth is also wider than 150 GHz, measurements of the optical power on the bolometers, as discussed in Section 5.4, indicate that we see lower optical efficiency in the 220 GHz band relative to 150 and 95 GHz.) In the case of this current test, we use the calibrator signal-to-noise simply as a check to ensure that we have reasonable numbers of bolometers with good optical response at all depths in the transition. We note that several wafers, specifically W180, W187, W188, take on significant yield hits in the number of highly-responsive bolometers for depths in the transition deeper than \(f_R = 0.7\), due to significant numbers of combs becoming unstable and latching.

Figures 5.16 and 5.17 shows histograms of measured \(\tau_{th,\text{eff}}\) per band, wafer, and depth in the transition. These time constants and their modulation with \(f_R\) should measure the balance of the speed-up of the thermal time constant due to increasing electrothermal feedback with decreasing \(f_R\) and the slowing of the time constant due to the presence of optical power, which will reduce the loop gain compared with dark operation. Therefore, as expected, most wafers have time constants that decrease while tuning deeper in the transition from \(f_R = 0.9\) to 0.8, due to increasing electrothermal feedback (higher loop gain). But we note that the time constants for most wafers tend to plateau for depths \(f_R \lesssim 0.7\). Given that the time constants don’t continue to shorten with increasing depth, this indicates that we have likely reached relatively high-loop-gain operation by a depth of
\( f_R = 0.7 - 0.8 \). Since we do see yield loss from instability going deeper than \( f_R = 0.7 \), we choose to bias the detectors in the range \( f_R = 0.7 - 0.8 \), where bolometers see high electrothermal feedback and also high stability and yield. We note that there is some variation in time constant between wafers, most notably W203 has quite fast time constants for all depths in the transition, and W172 shows a wide and bimodal distribution, the origin of which is not clearly understood.

Median \( \tau_{\text{th,eff}} \) for the second year focal plane is around 3.5 ms for 95 and 150 GHz but with a relatively wide distribution between 2 – 8 ms, and somewhat shorter for 220 GHz, due to the low 220 GHz optical efficiency: because the 220 GHz see less optical power than expected, they have a larger share of electrical power compared with optical power and therefore increased electrothermal feedback. We note that the measured effective time constants as deployed on the focal plane agree relatively well with measured time constants from stateside testing in a dark configuration with elevated stage temperature to emulate optical loading conditions, as discussed in Section 4.3.4, and specifically as shown in Figure 4.10. The amount of by which the optical time constants increase relative to dark time constants at the same depth in the transition (and therefore same level of electrothermal feedback) is also consistent: for bolometers with \( P_{\text{sat}} \) in line with design the design criterion \( P_{\text{tot}} \sim 2P_{\text{opt}} \), and therefore \( P_{\text{elec}} \sim R_n \) in the transition, a decrease in \( P_{\text{elec}} \) by roughly a factor of two due to the addition of optical power, corresponds to a change in loop gain by a factor of two. Since \( f_R = \frac{\tau_{\text{th,eff}}}{(Z+1)} \) for typical changes in \( P_{\text{sat}} \) between dark and optically-loaded, we expect an increase in \( \tau_{\text{th,eff}} \) of slightly less than a factor of two.

### 5.6 Noise performance and monitoring

As noted in Section 3.5, current leakage due to high SQUID input inductance resulted in unforeseen excess noise that degraded the bolometer performance during the first year of SPT-3G deployment. This excess noise was mitigated in the second year of deployment by full replacement of the SQUID readout amplifiers with newly-fabricated low-inductance SQUIDs. Non-idealities in the grounding scheme of the warm-to-cold readout chain also injected additional noise into the TES circuit which was also reduced through hardware modifications during the first year and prior to
Figure 5.15: Histograms of signal-to-noise to the chopped, thermal calibrator source during measurements of $\tau_{\text{th,eff}}$ as a function of depth in the transition.

The second year (Bender et al., 2018). Figure 5.18 from Bender et al. (2018) shows the resultant reduction in operating noise level, where noise is measured for reference here with bolometers held normal (“overbiased”), which will greatly reduce the noise from the photon background, providing a direct comparison of readout noise reduction from hardware improvements. We monitor the noise performance over time, to ensure noise levels are repeatable, and test for non-uniformity in noise level between different wafers or LC combs. Figure 5.19 shows an example of the achieved overbiased noise for a set of repeated full-array tunings taken over the course of roughly 10 days in February, 2018. We note that most combs have repeatable and high-yield noise performance, but there are combs with excess noise relative to other combs from the same wafer and other wafers in the focal plane, and often these combs have repeatably abnormal noise performance. The
Figure 5.16: Measured effective thermal time constants for wafers W172, W174, W176, W177, W180 as a function of depth in the transition. Here time constants are measured via optical response to a chopped thermal source in situ in the SPT-3G receiver.

Noise measurements shown in Figure 5.19 were taken during deployment of the second year focal plane, while work was ongoing to optimize of the array tuning configuration, and therefore the data shown in this figure is not necessarily representative of the final operating state of the focal plane.
Figure 5.17: Measured effective thermal time constants for wafers W181, W187, W188, W201, W203 as a function of depth in the transition.

Continued fine-tuning of noise performance is on-going in the current (third) year of deployment, focusing primarily on fine-tuning per-bolometer tuning parameters to optimize noise performance and fine-tuning the effective bolometer $P_{\text{sat}}$ by adjusting the $mK$ stage temperature to reduce noise caused by excess $P_{\text{opt}}$. 
Figure 5.18: Improvement in median full-array overbiased noise level between first and second years of SPT-3G, with the primary improvement due to reduced current leakage from replacement of the high-input-inductance SQUIDs in the first year with newly-fabricated lower-input-inductance SQUIDs in the second year. Figure from (Bender et al., 2018).
Figure 5.19: Noise measured on the second-year focal plane in the overbiased state for a set of repeated full-array tunings taken over the course of roughly 10 days in February, 2018. Colors correspond to each wafer, which have been separated along the horizontal axis purely for visualization. Each point corresponds to a single LC readout comb, where the size of the point is scaled by the number of bolometers that were operational on that comb during a given full-array tuning.
5.7 Overview of focal plane performance parameters

Table 5.1 overviews bolometer characterization parameters for wafers deployed in the first and second years of SPT-3G. For measurements not made directly in the SPT-3G receiver (such as measurements of $P_{\text{sat}}(\tau_{\text{th},0})$ which yield $G$, $k$, and $n$), we draw values from data taken on multiple wafers at multiple northern cryostats using a dark configuration.
Table 5.1. Summary of bolometer characterization for year-1 and year-2 focal planes

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th></th>
<th>2018</th>
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<tr>
<td></td>
<td>95 GHz</td>
<td>150 GHz</td>
<td>220 GHz</td>
<td>95 GHz</td>
</tr>
<tr>
<td>$P_{\text{sat}}$ [pW]</td>
<td>10-25</td>
<td>12-30</td>
<td>12-30</td>
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<td>$P_{\text{opt}}$ [pW]</td>
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<td>4.5 ±0.7</td>
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<td>$P_{\text{elec}}$ * [pW]</td>
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<td>8-25</td>
<td>8-26</td>
<td>3.5-12</td>
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<tr>
<td>$T_{c}$ ** [mK]</td>
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<td>510-570</td>
<td>510-570</td>
<td>415-475</td>
</tr>
<tr>
<td>$G(T_{c})$ *** [pW/K]</td>
<td>140±15</td>
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<td>150±20</td>
<td>100±15</td>
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<tr>
<td>$r$ ***</td>
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<td>3.0±0.2</td>
<td>3.0±0.2</td>
<td>2.8±0.2</td>
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<tr>
<td>$R_{n}$ [Ω]</td>
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<td>60-125</td>
<td>60-75</td>
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<tr>
<td>$\tau_{\text{th,eff}}$ * [ms]</td>
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<td>1.9</td>
<td>1.5</td>
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<td>$\mathcal{L}$ **</td>
<td>20-60</td>
<td>20-60</td>
<td>20-60</td>
<td>30</td>
</tr>
<tr>
<td>band center [GHz]</td>
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<td>153.8±1.3</td>
<td>223.5±2.6</td>
<td>95.0±1.3</td>
</tr>
<tr>
<td>band width [GHz]</td>
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<td>37.7±1.2</td>
<td>47.4±1.8</td>
<td>24.8±2.6</td>
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<tr>
<td>$\eta$ ****</td>
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<td>0.086</td>
<td>0.26</td>
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<tr>
<td>NEP$_{\text{tot}}$ **** [aW/rt(Hz)]</td>
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<td>NET$_{\text{tot}}$ **** [µK-rt(s)]</td>
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<td>440</td>
<td>1800</td>
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<tr>
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<td>7</td>
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<td></td>
</tr>
<tr>
<td>mapping speed **** [1/nK-s]</td>
<td>9.6</td>
<td>20</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

Note. — *under Pole optical loading conditions  ** Measured under dark loading conditions or corrected using $T_{c}$ suppression measured between optical and dark bolometers in $R(T)$ taken during the first year of SPT-3G deployment. **from testing results from measurements in a northern cryostat in a dark configuration prior to deployment. ****Measured from on-sky observations post-deployment. Optical efficiencies are measured using observations of RCW38. (Values in this table are derived from measurements as detailed in this Chapter, from intra-collaboration communication, and referenced from [Pan et al., 2018; Dutcher et al., 2018; Bender et al., 2018].)
Chapter 6

Conclusions and future prospects

Embarking into the third year of SPT-3G deployment in 2019, a few small but important modifications were introduced relative to the second year. Two wafers, W187 and W201 were replaced with W204 and W206 and roughly one third of the SQUIDs were replaced with better-performing (higher-transimpedance) SQUIDs, which should reduce readout noise. It was discovered during the second year of deployment that the millikelvin stage was susceptible to microphonic heating resulting from telescope motion and environmental factors. Although the effect on bolometer performance is not fully understood and preliminary science analyses using data from the second year are underway, the millikelvin stage was redesigned and replaced prior to the third year of SPT-3G, strongly reducing the microphonic sensitivity and therefore greatly increasing the temperature stability of the focal plane during sky observations. Work to optimize the array performance is on-going, including further work to optimize tuning depth in the transition on a per-bolometer basis, to optimize response and reduce noise.

The primary SPT-3G observational goal focuses on observing a 1500-square-degree patch of sky, with the plan to complete a five-year survey in 2023. After the conclusion of the second year of SPT-3G (2018), map depths achieved were 19, 15, and 50 $\mu$K-arcmin in intensity at 95, 150, 220 GHz, respectively, and a factor of $\sqrt{2}$ higher in polarization (from intra-collaboration communication). The expected final noise depths at the end of five years of observations are 3, 2, 9 $\mu$K-arcmin in intensity at 95, 150, 220 GHz, respectively (Bender et al. 2018). Multi-frequency, arcmin-resolution maps of these depths will enable fine-scale measurements of lensing
tail of the CMB power spectrum, which in turn can help to constrain the sum of neutrino masses and the number of light relics \cite{Benson2014}. The SPT-3G survey features overlapping sky coverage in collaboration with other projects, amplifying the power of its results. SPT-3G and the BICEP2/Keck Array are currently observing the same patch of sky, which will enable the SPT-3G data to be used to “de-lens” the lensing B mode signal from the lower-angular-resolution BICEP2/Keck maps, or from the SPT-3G maps themselves, potentially aiding in a confirmed discovery of B modes caused by inflation. The deep SPT-3G maps will also be instrumental in advancing studies of cosmology via better understanding of the growth of structure from galaxy clusters out to higher redshifts than currently available, work further augmented via overlapping sky coverage with the optical Dark Energy Survey. Finally, the large-area and low-noise maps of SPT-3G will enable the discovery of potentially tens of thousands of compact emissive sources, and will probe the populations of these sources down to flux levels only accessed originally by very small-area surveys, such as SCUBA-2. Bridging the gap between small-area surveys of dim sources with large-area surveys of bright sources, selected preferentially by lensing, will enable greater understanding of the relationship between lensed and unlensed populations, and therefore greater understanding of star-forming dusty galaxies at high redshift.
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Appendix A

(1) Hardware map generation

After deployment of the SPT-3G array, cold hardware mappings were generated relating LC channels per comb in the readout to each physical bolometer on the array. Figures A.1 and A.2 show all the pixels in the focal plane with mapped bolometers for the first and second year focal planes, respectively. Colors indicate pixels that are read out in the same LC comb per wafer with successful hardware mappings. Gaps indicate yield hits in the cold hardware mapping, which are pixels with no successful hardware mappings. These may be single pixels on a comb due to failures in warm or cold yield, or may be full combs due to LC chip yield or comb tuning failures.
Figure A.1: Cold hardware readout mappings between LC channel and pixel for the focal plane deployed in the first-year for SPT-3G.
Figure A.2: Cold hardware readout mappings between LC channel and pixel for the focal plane deployed in the second-year for SPT-3G.