The Next Generation Balloon-Borne Large Aperture Submillimeter Telescope (blast-Tng)

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The Next Generation Balloon-Borne Large Aperture Submillimeter Telescope (blast-Tng)

Abstract
Large areas of astrophysics, such as precision cosmology, have benefited greatly from large maps and datasets, yielded by telescopes of ever-increasing number and ability. However, due to the unique challenges posed by submillimeter polarimetry, the study of molecular cloud dynamics and star formation remain stunted. Previously, polarimetry data was limited to a few vectors on only the brightest areas of molecular clouds. This made drawing statistically-driven conclusions a daunting task. However, the successful flight of the Balloon-borne Large Aperture Submillimeter Telescope for Polarimetry (BLASTPol) generated maps with thousands of independent polarization measurements of molecular clouds, and ushered in a new era of empirical modeling of molecular cloud dynamics. Now that the potential benefits from large-scale maps of magnetic fields in molecular clouds had been identified, a successor that would truly unlock the secrets must be born.

The Next Generation Balloon-borne Large Aperture Submillimeter Telescope (BLAST-TNG), the successor to BLASTPol, has the ability to make larger and more detailed maps of magnetic fields in molecular clouds. It will push the field of star formation into a statistics-driven, empirical realm. With these large, detailed datasets, astronomers will be able to find new relationships between the dust dynamics and the magnetic fields. The field will surge to a new level of understanding. One of the key enabling technologies of BLAST-TNG is its three arrays of polarization-sensitive Microwave Kinetic Inductance Detectors (MKIDs). MKIDs are superconducting RLC circuits with a resonant frequency that shifts proportionally to the amount of incident radiation. The key feature of MKIDs is that thousands of detectors, each with their own unique resonant frequency, can be coupled to the same readout line. This technology will be able to drive the production of large-scale monolithic arrays, containing tens or hundreds of thousands of detectors, resulting in an ever-increasing rate of scientific progress.

The current limiting factor that determines how many MKIDs can be placed on the same readout line is the bandwidth and processing limitations of the readout hardware. BLAST-TNG has pushed this technology forward by implementing the first Reconfigurable Open-Architecture Computing Hardware (ROACH2) based readout system. This has significantly raised the processing abilities of the MKID readout electronics, enabling over 1000 MKIDs to be read out on a single line. It is also the first ever ROACH (1 or 2) based system to ever be flown on a long duration balloon (LDB) payload.

This thesis documents the first-ever deployment of MKIDs on a balloon payload. This is a significant technological step towards an MKID-based satellite payload. This thesis overviews the balloon payload, details the underlying detector physics, catalogs the detector and full-scale array development, and ends with the room-temperature readout electronics.

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Doctor of Philosophy (PhD)

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THE NEXT GENERATION BALLOON-BORNE LARGE
APERTURE SUBMILLIMETER TELESCOPE
(BLAST-TNG)

Bradley Jerald Dober

A DISSERTATION

in

Physics and Astronomy

Presented to the Faculties of the University of Pennsylvania

in Partial Fulfillment of the Requirements for the degree of Doctor of Philosophy

2016

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Christopher Mauger, Associate Professor of Astronomy and Astrophysics

Robert Thornton, Associate Professor of Physics
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Finally, a great thanks to the BLASTPol and BLAST-TNG science team. Without you, there would be no need to build these telescopes.
ABSTRACT

THE NEXT GENERATION BALLOON-BORNE LARGE APERTURE SUBMILLIMETER TELESCOPE (BLAST-TNG)

Bradley Jerald Dober

Mark J. Devlin

Large areas of astrophysics, such as precision cosmology, have benefited greatly from large maps and datasets, yielded by telescopes of ever-increasing number and ability. However, due to the unique challenges posed by submillimeter polarimetry, the study of molecular cloud dynamics and star formation remain stunted. Previously, polarimetry data was limited to a few vectors on only the brightest areas of molecular clouds. This made drawing statistically-driven conclusions a daunting task. However, the successful flight of the Balloon-born Large Aperture Submillimeter Telescope for Polarimetry (BLASTPol) generated maps with thousands of independent polarization measurements of molecular clouds, and ushered in a new era of empirical modeling of molecular cloud dynamics. Now that the potential benefits from large-scale maps of magnetic fields in molecular clouds had been identified, a successor that would truly unlock the secrets must be born.

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magnetic fields. The field will surge to a new level of understanding. One of the key enabling technologies of BLAST-TNG is its three arrays of polarization-sensitive Microwave Kinetic Inductance Detectors (MKIDs). MKIDs are superconducting $RLC$ circuits with a resonant frequency that shifts proportionally to the amount of incident radiation. The key feature of MKIDs is that thousands of detectors, each with their own unique resonant frequency, can be coupled to the same readout line. This technology will be able to drive the production of large-scale monolithic arrays, containing tens or hundreds of thousands of detectors, resulting in an ever-increasing rate of scientific progress.

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Chapter 1

Introduction

1.1 Magnetic Fields and Star Formation

Despite decades of research, the physical processes regulating star formation still remain poorly understood. Large-scale observations of star forming regions provide counts of the number of dense clouds, each of which will eventually evolve into many thousands of stars. However, when simple models of gravitational collapse are applied to the clouds, they yield a Galactic star formation rate (SFR) that is many times larger than what is actually observed. Some process or combination of processes must be slowing the collapse of the clouds. The two prevailing theories involve turbulence, which prevents the effective dissipation of energy, and Galactic magnetic fields, which are captured and squeezed by the collapsing cloud providing a mechanism for mechanical support.

If magnetic fields are the dominant method for regulating star formation, the magnetic field lines throughout a molecular cloud should be smooth and not influenced by irregular structure. In addition, molecular cloud structures, from the spatial scales of the filamentary structure all the way down to individual prestellar cores, should
Figure 1.1: Molecular cloud structure 3D simulations generated under both turbulent (Left) and strong magnetic field (Right) regimes. The 3D simulations are compressed to a 2D image, where the color traces the number density along the line of sight, and the lines trace the magnetic field structure. The structure produce in the strong field simulation is much more correlated with the magnetic field lines.

be correlated with the magnetic field lines. However, if turbulence is the dominant star formation regulator, the magnetic field lines throughout a structure should be chaotic and uncorrelated [20]. Figure 1.1 shows numerical simulations of molecular cloud evolution in both cases of turbulence and strong magnetic fields [108].

In many numerical simulations, magnetic fields dramatically affect both the star formation efficiency and lifetime of molecular clouds [50, 68, 69, 108]. However observationally, the strength and morphology of magnetic fields in molecular clouds remain poorly constrained. By measuring the properties of the magnetic fields, such as their strength and morphology, we can gain a further understanding of their role in star formation.
1.2 Techniques for Observing Magnetic fields

There are multiple observational techniques employed for measuring both the strength and morphology of magnetic fields in molecular clouds. Each technique possesses its own relative strengths and weaknesses.

1.2.1 Zeeman Splitting

The Zeeman effect is the only available technique for directly measuring the strength of a magnetic field \[19\]. This is achieved by measuring the strength of the splitting of molecular line transitions. However, it is only able to measure the line-of-sight component of the strength and direction of the magnetic field. This limitation can be statistically corrected for by observing multiple lines of sight. However, Zeeman splitting can only be measured in very few molecules present in molecular clouds (HI, OH, and CN) \[20\]. In addition, measuring the Zeeman effect is only possible on extremely bright molecular cloud sightlines. This eliminates Zeeman splitting as a viable technique for many clouds of interest (including Vela C).

1.2.2 Faraday Rotation

Faraday rotation is a potential method for measuring the strength of the magnetic field along the line-of-sight. The position angle of linearly polarized light is rotated as it travels through an ionized gas by \( \theta \propto n_e B_{\text{LOS}} L \lambda^2 \), where \( n_e \) is the electron density, \( L \) is the distance through the gas, and \( \lambda \) is the wavelength of the light. It is difficult to measure Faraday rotation in molecular clouds due to their small size and low fraction of ionized gas. In addition, in order to set the zero angle of the light, Faraday rotation requires a background source that is visible both on and off the cloud. There have
been some measurements of Faraday rotation in molecular clouds with mixed results [127, 113, 101].

1.2.3 Comparison of Molecular Line Widths

In the presence of magnetic fields, [57] posited that ions would be constrained from moving across the magnetic field lines, while neutral gas would be free to move independently. For a strong magnetic field, the ion’s mean velocity perpendicular to the field would be negligibly small. Therefore, one can measure the relative strength of the magnetic field by measuring the relative line widths of neutral and ionized gas populations. However, this measurement requires a population of neutral and ionized gas that exists in the exact same place in the cloud. This technique has been applied to observations of HCN, HCO⁺, and N₂H⁺ lines [57] as well as H¹³CN and H¹³CO⁺ [58] with mixed results.

1.2.4 Polarized Dust Emission

A useful tracer of magnetic fields in star forming regions is polarization. By mapping polarization from dust grains that are aligned with respect to their local magnetic field [66, 18], the field orientation (projected on the sky) can be traced. Molecular clouds typically have temperatures of several tens of Kelvin with emission peaking in the submillimeter. Previous submillimeter polarimetry observations have generally been restricted to bright targets (> 1 Jy) and small map sizes (< 0.05 deg²) [29, 74].

The amount of dust polarization varies weakly with the magnetic field. However, it is possible to infer the strength of the magnetic field in the molecular cloud from the magnetic field morphology. The early Chandrasekhar-Fermi (CF) method [36] of
inferring the strength of the magnetic field suggests that the irregular component of the magnetic field will show up as a dispersion in the polarization position angles, or vectors:

\[ B_{\text{pos}} = Q \sqrt{\frac{4 \pi \rho}{\delta \phi}} \delta V \]  

(1.1)

where \( \rho \) is the gas density, \( \delta V \) is the velocity dispersion, \( \delta \phi \) is the polarization dispersion in degrees, and \( Q \) is a factor of order one. This suggests that stronger magnetic fields will have less polarization dispersion. Modern techniques that quantify the strength of the magnetic field compare 3D magnetohydrodynamic (MHD) simulations to observations [108].

1.3 Why Ballooning?

Due to the many water absorption lines present in the submillimeter, see Figure 1.2, observing submillimeter radiation is limited to wavelengths longer than 350 \( \mu \)m and only from extremely dry sights. The lower transmission, coupled with higher background radiation further limits ground-based submillimeter observations to only the brightest regions of molecular clouds. However, long-duration balloon payloads are able to float about \( > 99.5\% \) of the atmosphere with a month-long observing season at a fraction of the cost and time required to construct a satellite. By launching from McMurdo during the Antarctic summer, while the winds are typically circumpolar, it enables a scientific payload to be powered by solar panels, and to possible be retrieved and flown again.
Figure 1.2: Atmospheric transmission at various altitudes shown as percent transmitted as a function of wavenumber \[ \text{[112]} \]. The observational bands of interest in this thesis are highlighted in red, green, and blue. For balloon altitudes (35-40 km), there is negligible in-band absorption.
Chapter 2

Previous Results

2.1 History of BLAST and BLASTPol

The Balloon-Borne Submillimeter Telescope for Polarimetry (BLASTPol) arose by adapting the Balloon-Borne Submillimeter Telescope (BLAST) to operate as a polarimeter. BLAST, which flew in 2005 from Kiruna, Sweden and in 2006 from McMurdo, Antarctica, was a precursor to the Herschel satellite. BLAST’s primary science goal was to study the cosmic infrared background (CIB). BLAST produced a host of high-profile results, which include producing a 0.8 deg$^2$ confusion-limited map of the CIB in the GOODS South region at 250, 350, and 500 µm. In a series of papers, BLAST determined that over half of all far infrared light in the universe comes from galaxies at $z \geq 1.2$ [26, 72, 90]. BLAST also made the first determination of deep, extragalactic number counts [92], the detection of clustering in the CIB [119], and resolved submillimeter images of several nearby galaxies [125]. In addition, measurements conducted by BLAST confirmed previous results that showed that the galactic star formation rate (SFR) is significantly less than what was previously predicted [84]. The measured cold core lifetimes are longer than what is predicted.
by simple gravitational collapse, which implies some form of non-thermal support for cold cores. In essence, BLASTPol was conceived to help solve this discrepancy found by BLAST and other previous work.

By converting BLAST into a polarization-sensitive instrument, BLASTPol was able to map the magnetic fields in molecular clouds to determine their role in star formation. Polarization sensitivity was achieved by first covering the feedhorn arrays with polarizing grids that alternate orientations by 90° between pixels. Next, an rotatable achromatic half-wave plate (HWP) was installed inside the cold reimaging optics box. Both features are shown in Figure 2.1. BLASTPol was flown from McMurdo in both 2010 and 2012. During the 2010 flight, an IR-blocking filter that was mounted in front of the cryostat window melted and severely distorted the beams and instrumental polarization of the detectors. However, the 2012 was largely regarded as a success and produced thousands of polarization vectors, or B-vectors, on several giant molecular clouds (GMCs). The remaining sections of this chapter will summarize the data reduction and analysis pipeline, highlight two important published results from the BLASTPol 2012 flight \cite{37, 41}, and finally discuss some ongoing research on protostellar cores.

2.2 Results from BLASTPol 2012 Flight

BLASTPol launched from McMurdo on December 26th, 2012, and took data for 300 hours at which point the cryogens were depleted. BLASTPol observed several targets which are highlighted in table 2.2. These targets were chosen after considering constraints such as visibility from Antarctica at the time of launch, source brightness, and distance. The giant molecular cloud (GMC) Vela C was the highest priority target
due to its size and distance. There were two different types of observations performed on Vela C during this flight: An 11 hour scan was made over a large 12 deg$^2$ map, and a 43 hour deep 3.1 deg$^2$ map which covered four of the five cloud subregions defined by an $A_V = 7$ mag cutoff by [55]. The larger region was observed in order to perform the background subtraction on the smaller map. To reduce polarization systematics, the observations required complete scans to be made at each of the four HWP angles. In addition, to maximize cross-linking due to sky rotation, full sets of scans were also made at different times of the flight. The completed maps were smoothed to 2.5$'$ at 500 $\mu$m to account for a non-Gaussian beam structure encountered during the flight [38].
Figure 2.2: The 500 µm intensity map of Vela C and its surroundings. The cyan lines show the boundary of the two raster scans used to make the map. The total area in the solid cyan contour was observed for 11 hours, while the smaller region denoted by the dashed cyan lines was observed for 44 hours. The C, A1, and A2 regions are the regions used for diffuse emission background subtraction. The dark blue area is the region which passed all validity tests. The red circle highlights the area around the compact HII region, RCW 36, which was excluded from polarization analysis for failing the null tests. The white contours highlight the regions divided by an $A_V=7$ mag threshold defined by [50].
Table 2.1: BLASTPol 2012 Observed Target List

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>Distance (pc)</th>
<th>Size (deg^2)</th>
<th>Approx. No. of B-vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela C</td>
<td>Nearby GMC</td>
<td>∼700</td>
<td>12</td>
<td>∼8000</td>
</tr>
<tr>
<td>Carina Nebula</td>
<td>Calibrator (GMC)</td>
<td>∼2300</td>
<td>2</td>
<td>∼3000</td>
</tr>
<tr>
<td>CG12</td>
<td>Low Mass Cloud</td>
<td>∼550</td>
<td>0.1</td>
<td>TBD</td>
</tr>
<tr>
<td>G331</td>
<td>Calibrator (GMC)</td>
<td>∼7000</td>
<td>2</td>
<td>∼4000</td>
</tr>
<tr>
<td>IRAS 08470-4243</td>
<td>Calibrator</td>
<td>∼700</td>
<td>0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Lupus I</td>
<td>Dark Cloud</td>
<td>∼155</td>
<td>1</td>
<td>∼200</td>
</tr>
<tr>
<td>Puppis Cloud Complex</td>
<td>Nearby Cloud</td>
<td>∼1900</td>
<td>0.4</td>
<td>TBD</td>
</tr>
</tbody>
</table>

2.2.1 Generating Data Suitable for Analysis

Mapmaking

The BLASTPol data analysis pipeline and TOAST iterative mapmaker is described in depth in [9]. The bolometer time-ordered data (TOD) was processed to remove detector glitches and cosmic ray events, deconvolved with the bolometer time constant, and the gains were corrected [9]. Other corrections included high-pass filtering the data to whiten the noise in the TOD below 5 mHz, and removing drifts caused by HWP rotation or telescope slew. Pixel-to-pixel gain variations were corrected using observations of the IRAS 08470-4243 bright compact source. The telescope attitude was then reconstructed from the BLASTPol pointing sensors in a method similar to what is outlined in Section 3.1.3. The telescope beam was measured during flight by observing both IRAS 08470-4243 and Saturn. The observations are used to deconvolve the beam from the maps via a Lucy-Richardson method. This method was previously used on the data from the BLAST 2005 flight [105]. The instrumental polarization (IP) is determined by splitting the map into two bins based on parallactic angle and for each detector individually. The polarization is then a combination of one component with respect to the sky and another (IP) fixed with respect to the
telescope. This causes a rotation in the Stokes $q - u$ plane with the rotation center being the amount of IP in $q$ and $u$. The IP is then removed with the mapmaker leaving an estimated minimum detectable fractional polarization $p$ at 500 $\mu$m of 0.1%. The mapmaker also requires a noise model, which was estimated using power spectra from observations of faint dust emission in the constellation Puppis, with simulated astrophysical signal subtracted. This model was consistent with white noise plus $1/f$ correlations that level out at low frequency due to data preprocessing. Signal and covariance maps with a selected pixel size of 10$''$ can now be generated.

**Background Subtraction**

After maps have been created from the TOD, several map-level calibrations and tests must be made before the data can be analyzed. First, to study the polarization data from Vela C, it must be isolated from any potential polarized background emission. The background subtraction is potentially hazardous as diffuse sightlines have been shown to have higher polarization fractions than denser cloud sightlines [95]. Two methods were used for Vela C background subtraction, one conservative and another more aggressive method. The conservative method assumes that most of the emission surrounding Vela C is associated with the cloud. The zero level background flux is chosen from a low flux region labeled “C” in Figure 2.2 and assumed to be the background level that is uniformly present behind the cloud. The Stokes I, Q, and U is calculated from that region and the mean result is subtracted from the maps. The aggressive method assumes that most of the emission surrounding the cloud comes from background sources. This subtraction method uses the two closer regions on either side of the cloud, labeled A1 and A2 on Figure 2.2 and uses a 2D linear fit to Stokes I, Q, and U to subtract a profile from the maps on a pixel-by-pixel basis. This
interpolation breaks down in regions far away from Vela C, and is only valid in the
dark blue contour on Figure 2.2. This method is likely to subtract some portion of
emission from the cloud. Since the ‘correct’ I, Q, and U maps are somewhere between
these two subtraction methods, most of the analysis is performed on both map types.

Null Tests

To reduce any possible systematic errors in the data, a series of null tests are
performed on the background-subtracted maps. These are described in detail in [37].
Most involve a series of jackknife tests where the data is split in half in time (later
in the flight vs earlier), array position (top half vs bottom or left half vs right), or
scan (every other) and subtracted from each other. If there are no systematics, the
jackknife maps should produce a residual map of uncorrelated noise. The tests were
passed if the residuals in the polarized intensity \( P \) or polarization fraction \( p \) were
less than one third the signal in a given map pixel. For the polarization angle \( \phi \), the
residual had to be \( < 10^\circ \). Most of the data in the dark blue contour in Figure 2.2
passed these null tests, except for the area near the bright compact HII region, RCW
36, which was excluded from some of the analysis.

Column Density versus Temperature from Herschel SPIRE Data

Column density and dust temperature maps were derived from Herschel SPIRE
data, which has identical wavebands to BLASTPol but at slightly higher spatial
resolution. The processing involved in discussed in depth in [39]. Herschel maps were
generated using Scanamorphos [104] and additional processing was performed using
the Herschel Interactive Processing Environment (HIPE). The maps were smoothed to
35.2\( ^\prime \) resolution and then re-gridded to match the BLASTPol 500 \( \mu m \) map. Modified
blackbody SED fits were made for each map pixel using the process described in [56, 54, 55], and using the dust opacity law with a dust spectral index of $\beta = 2$ [52]. The resulting column density (N) and temperature (T) maps are shown in Figure 2.3. N and T are very highly anti-correlated, which implies that the denser regions of the cloud are being shielded from radiation, thus lowering their temperature.

**BLASTPol Polarization Maps**

The BLASTPol Stokes I, Q, and U were used to generate maps of linearly polarized intensity ($P = \sqrt{Q^2 + U^2}$), polarization fraction ($p = P/I$), and polarization angle ($\phi = \frac{1}{2} \arctan (U, Q)$). The polarization angle is used to generate a map of the inferred
Figure 2.4: The BLASTPol 500 \( \mu m \) I map with the inferred magnetic field component (\( \Phi \)) overlaid as a “drapery” image. The drapery pattern is produced using a line integral convolution detailed in [13], and indicates the direction of the magnetic field as projected on the plane of the sky. Note that this figure was produced using the \( \Phi \) data from all sightlines and should not be used for quantitative analysis.

The inferred magnetic field direction, \( \Phi \), which is just the polarization angle rotated by \( \frac{\pi}{2} \). The magnetic field direction, \( \Phi \), is displayed using a line integral convolution [13], or “drapery” pattern, in Figure 2.4. The background is the 500 \( \mu m \) I map, with \( \Phi \) drapery maps superimposed. The next Section will attempt to model the disorder in magnetic field direction as a function of both N and T.

### 2.2.2 Dependence of Polarization Fraction on Column Density and Polarization-Angle Dispersion

In order to estimate the strength of the magnetic field, the relative disorder of the magnetic field angle should be measured [36]. To quantify the amount of disorder in \( \Phi \) at small scales, the polarization-angle dispersion function \( S \) is used. \( S \) is defined as
Figure 2.5: A map of the dispersion in polarization-angle (S) on 0.5 pc scales for the 500 μm band. Line segments show the orientation of the magnetic field as projected on the plane of the sky (Φ), while contours denote the intensity map.

The rms deviation of the polarization-angle φ(⃗x) for a series of points on an annulus of radius δ:

\[ S^2(⃗x, δ) = \frac{1}{N} \sum_{i=0}^{N} S_{xi}^2 \]  \hspace{1cm} (2.1)

\[ S_{xi} = φ(⃗x) - φ(⃗x + ⃗δ_i) \]  \hspace{1cm} (2.2)

where δ is the length scale of the dispersion and ⃗x is the position where the polarization-angle dispersion is evaluated. Figure 2.5 shows S for δ = 2.5′ (~0.5 pc), which is the smallest scale that can be resolved with the smoothed beam.

With maps of S, p, and N in hand, the goal is now to build an empirical model for the dependence of p on N and S for an early stage star-forming region. Therefore, only sightlines that are heated solely by the interstellar radiation field (ISRF) are
used, and any sightline that is heated by RCW 36 is excluded from the analysis. Figure 2.6 shows the median \( p \) (color map) for bins of \( S \) and \( N \) for ISRF-heated sightlines. There is a clear decrease in \( p \) for increasing \( N \) and \( S \). Since this data is plotted on a logarithmic scale, it also suggests applying a power law fit to the data. The joint power-law form:

\[
\log p(N, S) = \log p_0 + \alpha_N \log N + \alpha_S \log S
\]

is used with \( p_0, \alpha_N \) and \( \alpha_S \) are free parameters. The exponents derived from the fit are \( \alpha_N = -0.40 \pm 0.01 \) and \( \alpha_S = -0.60 \pm 0.01 \), with the uncertainties found using a bootstrapping method [118]. The empirical fit, \( p(N, S) \), reproduces 65% of the variance in the \( \log p \) map. This suggests that the model accounts for most of the physical effects that determine the variations in fractional polarization in Vela C. This model can be explained by either greater tangling along high \( N \) (or lower \( T \)) dust columns or by a decrease in the intrinsic polarization efficiency for high \( N \) sightlines. This model should help constrain numerical simulations of molecular clouds.

### 2.2.3 Polarization Spectrum of Vela C

The polarization spectrum of molecular clouds can also play a major role in constraining molecular cloud dust models. Currently, the simplest dust models [51, 10] predict a near flat polarization spectrum. However, all observations to date [51, 115, 116, 129] have shown a much more variable spectra that rises away from a minimum at 350 \( \mu \text{m} \) (see Figure 2.8). The background-subtracted BLASTPol polarization fraction \( (p) \) maps of Vela C produced in Section 2.2.1 have the ability to add crucial new information about the shape of the polarization spectrum [41].
Figure 2.6: Median $p$ in bins of $S$ and $N$ for all sightlines heated by the interstellar radiation field. The use of logarithmic scales for $p$, $N$, and $S$ suggests a power-law relationship.

**Spectrum Generation**

The *Planck* HFI instrument \[97\] obtained polarimetry data at 850 $\mu$m over the entire sky \[1\]. The data from this survey is publicly available on the Planck Legacy Archive\[1\] and was re-gridded to match the BLASTPol maps. The BLASTPol maps were then smoothed from 2.4$'$ to the 4.8$'$ *Planck* resolution.

In a similar procedure to the analysis performed in Section \ref{section2.2.2}, only the ISRF-heated sightlines in the cloud were used. This corresponds to only the area inside the white contours in Figure \ref{fig:cloud_contours} and the sightlines in the red dashed circle that are being heated by RCW 36 are also excluded. In addition, the polarization fraction was only used when it exceeded $3\sigma_p$ at all four wavelengths, and the polarization angles all agreed to within 10$^\circ$. This criterion has been used in previous studies \[116\], and reduces the chance that the different wavelengths are sampling different depths in the cloud. The choice of background subtraction method, will produce different numbers

\[\text{http://pla.esac.esa.int}\]
Figure 2.7: Histograms of the three polarization ratios, with the intermediate background subtraction technique. The red dashed lines plotted indicate the median values in the top right.

of points that pass the $p > 3\sigma_p$ criterion, however, none of the remaining data fail the $10^\circ$ cut. Ratios of $p$ were then calculated relative to $p_{350}$, which allows this data to be compared to the previous studies that also normalized their data to 350 \(\mu\)m.

The $p_{\lambda}/p_{350}$ ratios were found using by taking the rmedian value of all of the pixel values of $p$ in the map. The histograms are shown in Figure 2.7. The median absolute deviation (MAD) was used to quantify the scatter in the distribution, $\text{MAD} \equiv \text{median } (|x - x_m|)$, with $x_m$ being the median value of $x$. For the intermediate background subtraction method, the ratios are $p_{500}/p_{350} = 1.01 \pm 0.10$, $p_{250}/p_{350} = 0.93 \pm 0.06$, and $p_{850}/p_{350} = 1.07 \pm 0.15$. Another method that can be used to determine the ratio is to fit a slope to a scatter plot of $p_{350}$ vs. $p_{\lambda}$. A least absolute deviation is used instead of a least squares, as it is more robust to outliers. The uncertainty in the fit is determined by using a bootstrapping method [118]. The full results for both methods with each background subtraction technique is shown in Table 2.2.3 and are plotted in Figure 2.8. Both the histogram and slope results are very close to a flat spectrum.
Table 2.2: The median and slope-fit polarization ratios ($p_\lambda/p_{350}$)

<table>
<thead>
<tr>
<th>Subtraction method</th>
<th>Fit Type</th>
<th>250 $\mu$m</th>
<th>500 $\mu$m</th>
<th>850 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>Median</td>
<td>0.97 ± 0.13</td>
<td>0.93 ± 0.06</td>
<td>1.05 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.10 ± 0.02</td>
<td>0.89 ± 0.02</td>
<td>1.11 ± 0.04</td>
</tr>
<tr>
<td>Aggressive</td>
<td>Median</td>
<td>1.07 ± 0.08</td>
<td>0.93 ± 0.07</td>
<td>1.08 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.04 ± 0.01</td>
<td>0.87 ± 0.01</td>
<td>1.16 ± 0.04</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Median</td>
<td>1.01 ± 0.10</td>
<td>0.93 ± 0.06</td>
<td>1.07 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.06 ± 0.01</td>
<td>0.88 ± 0.01</td>
<td>1.12 ± 0.03</td>
</tr>
</tbody>
</table>

Figure 2.8: Polarization spectra from previous work (grey), with the new Vela C polarization ratios added (red). The points at 850 $\mu$m are separated horizontally for clarity. W51, OMC-1 $p_{100}/p_{350}$, and DR21 $p_{1300}/p_{350}$ are from [114]. All previous measurements at $p_{850}/p_{350}$ are from [116]. The solid grey circle represents a median ratio found for 15 clouds [116]. OMC-1 $p_{450}/p_{350}$ is from [115]. M17 is from [129]. Red triangle denote the median polarization ratios with MAD error bars, while the red circles are the best-fit slope values from the scatter plots.
Table 2.3: Polarization ratios of ISRF and RCW 36-Heated Sightlines

<table>
<thead>
<tr>
<th>Measurement Quantity</th>
<th>Fit Type</th>
<th>RCW 36</th>
<th>ISRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{250}/p_{350}$</td>
<td>Median</td>
<td>1.16 ± 0.09</td>
<td>1.01 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.01 ± 0.07</td>
<td>1.07 ± 0.01</td>
</tr>
<tr>
<td>$p_{500}/p_{350}$</td>
<td>Median</td>
<td>0.92 ± 0.04</td>
<td>0.93 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.02 ± 0.04</td>
<td>0.88 ± 0.01</td>
</tr>
<tr>
<td>$p_{850}/p_{350}$</td>
<td>Median</td>
<td>1.09 ± 0.18</td>
<td>1.07 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td>1.19 ± 0.19</td>
<td>1.12 ± 0.03</td>
</tr>
</tbody>
</table>

Effect of Radiation Environment

To determine whether the polarization spectrum is affected by the radiation environment, we can compare the spectrum of the ISRF-heated sightlines to those that have another radiation source. The dust around the bright HII region RCW 36 has been heated above the level due to the ISRF, and no longer follows the $N$ and $T$ anti-correlation discussed in Section 2.2.1. This region is significantly different than the regions only heated by the ISRF, and is a great probe of whether radiation has an effect on polarization spectrum. Therefore, the polarization fraction was computed for the 25 sightlines inside the red dotted circle in Figure 2.2 that are being heated by RCW 36. The same methods are applied and the results for the intermediate background subtraction are shown in Table 2.3. The RCW 36-heated sightlines are consistent with the ISRF-heated sightlines within their uncertainties.

Flat Spectrum Significance

Figure 2.8 shows the summarized results of polarization spectrum measurements for Vela C, as well as the spectra of other molecular clouds reported in previous works (see caption). Previous measurements all suggested a minimum at 350 $\mu$m, while the BLASTPol data is consistent with a flat spectrum from 250-850 $\mu$m, independent of fitting or background subtraction method.
There is a difference in measurement techniques between BLASTPol and previous measurements. The previous measurements were all conducted by ground-based observatories, while the data from BLASTPol and Planck were taken above the atmosphere. Due to the atmospheric absorption, the ground-based observations are limited to observing only the brightest areas of the clouds. BLASTPol and Planck were able to observe a wider area of the cold dust in quiescent cloud regions. For example, the median intensity of the data used in [116] is \(\sim 80\) times higher than the median intensity of the Vela C BLASTPol data. This would predict that the spectra from the RCW 36-heated sightlines would reproduce the ground-based observations, yet the spectrum is still consistent with being flat.

The polarization flat spectrum produced with BLASTPol and Planck is more consistent with current molecular cloud and diffuse dust models. The ground-based observations were in tension with leading models [129, 51]. The molecular cloud model in [10] is most consistent with our spectra. However, this cloud model predicts a lower 250 \(\mu\)m polarization fraction. This discrepancy might be due to the fact that the model is for a starless cloud, whereas in Vela C there is significant radiation from embedded stars. Measuring the polarization spectra at additional shorter wavelengths (such as with HAWC+ that operates at 50-220\(\mu\)m [30]) would help further constrain the model. In addition, future high resolution work, such as that undertaken in the next section, could look at the effect of embedded sources in Vela C by measuring the polarization spectrum of known protostars.
2.3 Ongoing Complementary Research

One of the key benefits of BLASTPol is the ability to map the large-scale magnetic fields of a molecular cloud. As shown in the previous sections, this can greatly constrain dust and molecular cloud models. Another area that could potentially benefit from BLASTPol data is in models of star formation. One hypothesis in star formation theory suggests that large-scale magnetic fields support molecular gas against collapse from self-gravity, regulating the rate and efficiency of star formation [107, 82]. This theory remains subject to debate. In the case of molecular cloud cores, if magnetic fields are important for supporting the cores, then the cores should be oblate structures with their minor axis parallel to the field [62]. This is due to the fact that magnetic forces cannot act along the field direction. If the dominant support mechanism in the cores is due to turbulent gas flow, then the core structure should have no correlation between projected magnetic field direction and apparent minor axis. Previous studies have seen an orientation between the two [122, 123, 16], but they have been limited to small sample sizes, optical polarimetry which samples fields far from the core, and extremely limited numbers of sub-mm polarization vectors. The detailed magnetic field maps produced by BLASTPol, coupled with high resolution maps of the structure of starless cores, has the ability to provide valuable data towards constraining star formation models.

20 targets were chosen from a catalog of 218 starless cores compiled by [44] using *Herschel* SPIRE/PACS maps. The 218 candidates were first reduced by requiring the core mass to be at least twice the Bonnor-Ebert Mass [11, 34], to ensure that the cores are likely to require extra support (be it turbulence or magnetic fields) from collapse. The next cut required the starless core to be located near at least one BLASTPol vector. This reduced the number of potential targets to 117 starless
cores. The selection of the final 20 target cores was guided by inspection of images of the cores made with *Herschel* at 70, 100, 160, 250, 350, and 500 µm and with *WISE* at 3, 4, 6, 12, and 22 µm wavelengths. Using these images, we selected any cores that were relatively isolated from other cores, so the effect of the magnetic field on the core is more unambiguous. Finally, the orientation of the nearby BLASTPol magnetic field vectors were required to have a clear local field direction, so that the core’s elongation can be more accurately correlated. This criterion allowed us to choose 20 starless cores in Vela C for observation. They range in estimated mass and size from 1.47 $M_\odot$ to 9.38 $M_\odot$ and 12.9″ to 29.3″.

In 2014, we were allocated 40 hours to observe the 20 starless cores with the Australian Compact Telescope Array (ATCA). ATCA is an interferometer that is composed of six 22 meter receivers. The observations are directed towards the NH$_3$ (1,1) molecular line at 23.69 GHz, with multiple spectral channels capable of velocity resolution to 0.15 km s$^{-1}$. ATCA was arranged in the compact H168 orientation, which has a synthesized beam FWHM of 11.5″. During observations, the emission was less than expected, because more of the *Herschel* emission was resolved out. The first 20 hours were spent observing mosaics of 10 targets. Since, the few high signal-to-noise core detections in the mosaic mode showed the cores were more compact than originally estimated. The remaining time was spent observing the second half of the targets in single pointing mode. One of the images of the cores (labeled Core 1052 in the [14] catalog) is shown in Figure 2.10. The current analysis of this data set does not show a correlation between the elongated cores and the BLASTPol large-scale magnetic field orientation. However, additional observations will help clarify this picture.

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2Accessed via the AllWISE data release: http://wise2.ipac.caltech.edu/docs/release/allwise/
3https://www.narrabri.atnf.csiro.au/
In 2015, we were allocated an additional 13 hours of ATCA time in the H75 configuration, which has a 20.5" synthesized beam. This allowed us to follow up on 10 cores that had most of the large scale core emission resolved out during the previous observations in the more compact configuration. Observations were made in late July 2015, and the data analysis is still ongoing.

2.4 Scientific Motivation for BLAST-TNG

One of BLAST-TNG’s main goals is to map the magnetic field morphology of a large sample of molecular clouds in order to account for projection effects and obtain robust statistics on magnetic field morphology. A large sample of molecular clouds will allow us to constrain star formation models. BLAST-TNG can provide valuable data that will aid in two major areas of star formation models: how ordered are the
Figure 2.10: Comparison of Core 1052 in 2’ maps of: dust emission (Herschel 250 µm), absorption (WISE 22 µm), ATCA NH$_3$ (1,1) integrated emission, and NH$_3$ (1,1) line of sight velocity ($v_{LSR}$) with only $>4\sigma$ pixels shown. Data analysis is still ongoing.
magnetic fields in the molecular cloud, and how does that field direction correlate with the filamentary structure within the clouds. Numerical simulations have shown that molecular clouds with strong magnetic fields show less polarization angle dispersion than clouds with weak fields [88, 49, 35, 108]. Recently, polarization maps have been used to characterize the magnetized turbulence power spectrum within molecular clouds [53, 59]. These analyses are based on a polarization angle dispersion function and can be used to characterize the relative strength of the ordered and turbulent magnetic field components. The same analysis can be applied to all the BLAST-TNG polarization maps, resulting in a more complete and accurate picture. BLAST-TNG will be able to investigate the alignment between the magnetic fields and intermediate and high density filaments seen in Herschel maps [55]. With an increased knowledge of the role of magnetic fields in molecular clouds, the scientific community will come one step closer to understanding how stars form.

BLAST-TNG, and its predecessor, BLASTPol, are the first instruments to combine the sensitivity and mapping speed necessary to trace magnetic fields across entire clouds with the resolution to trace fields down into dense substructures, including cores and filaments. Shown in Figure 2.11, BLAST-TNG provides the critical link between the Planck all-sky polarization maps with 5′ resolution and ALMA’s ultra-high resolution, narrow (20″) field of view [96, 95]. PLANCK will provide the largest spatial scales that BLAST-TNG is unable to measure. The smallest spatial scales probed by BLAST-TNG are the largest scales that are not resolved out by ALMA. BLAST-TNG will use Planck’s all-sky data to refine its target selection. ALMA will then be able to utilize BLASTPol maps to zero in on areas of particular interest. Together, these three instruments will be able to probe the inner workings of star formation with previously unreachable resolution, sensitivity and scope.
Figure 2.11: BLAST-TNG provides the critical link between Planck’s all-sky polarimetry at 850 µm with 5’ resolution and ALMA’s 0.01” resolution polarimetry at the same wavelength. The upper left is a Galactic-scale Planck image followed by the BLAST observation of Vela [84] and the magnetic field map for the IRAS 4A protobinary in Perseus acquired using the Submillimeter Array (a precursor to ALMA) [45]. BLAST-TNG will map polarization using a 22" FWHM beam at 250 µm. This beam nearly matches the ALMA 850 µm field-of-view and is more than 200 times smaller (in area) than Planck’s 850 µm beam.

BLAST was originally designed as an unpolarized instrument to study high redshift dusty infrared galaxies. The conversion to BLASTPol was intended as a proof of concept to see if the technique is viable. While BLASTPol was able to make groundbreaking initial measurements, its utility was limited. In order to make technological progress and fully exploit the targets made available by Planck, a next generation instrument powered by large arrays of state-of-the-art detectors must be built. In previous BLASTPol flights, ~5 deg² was mapped in total, while nearby star forming complexes such as Vela or Lupus are 10-100 deg². With BLASTPol we could only map a small fraction of a complex, but with BLAST-TNG, the ability to map the entire complex is readily achievable.
2.5 Detector Motivation for BLAST-TNG

The technological advances of the past decade have propelled scientific research into a new era of precision measurements. The Planck satellite has measured the fluctuations in the cosmic microwave background (CMB) to an unprecedented level of precision. These measurements have constrained the values of the fundamental parameters that govern the evolution of the universe [97]. In tandem, the ground-based telescopes ACTPol and SPTPol have measured the polarization signal in the CMB left by gravitational lensing to help determine the role dark matter played in the evolution of cosmic structures such as galaxies [83, 63]. Submillimeter telescopes, such as BLASTPol, have aided in learning about star formation in molecular clouds.

All of these applications are enabled by large arrays of cryogenic detectors. Cryogenic detectors, such as transition-edge sensors (TESs), have already reached a noise performance below the background limit. The depth or area of maps made by these experiments now scales as the square root of the number of detectors. To further push the scientific progress in the fields mentioned above, mapping ability must improve not by a factor of 2-3, but by 10-50. This has influenced the need for development of monolithic arrays of cryogenic detectors being fabricated on silicon wafers of increasing size. One of the limiting factors of these large arrays has become reading the detectors out. This is because the wires that run to the cryogenic arrays increase the thermal load to the stage. This, in turn, increases the size and complexity of the cryogenic coolers. The wiring is an even greater constraint for balloon and satellite payloads, which operate on a finite amount of liquid cryogens and power for readout electronics. Across the board, reducing the number of readout wires can greatly reduce the production and operational cost of an experiment, and can open up the possibility for innovative experiments that were previously unfeasible. In order to
reduce these wire counts, multiplexing is used. Multiplexing is the process of reading more than one signal or detector on the same channel or wire. The conventional NIST-developed method of time-domain multiplexing (TDM) has reached its technological maturity. Due to limits caused by the geometry of the detector arrays, TDM can at best provide a 100:1 reduction in wires [27]. The next generation of experiments will require a quantum leap in multiplexing ability. Microwave Kinetic Inductance Detectors (MKIDs) have the potential to provide that leap.

MKIDs are a leading detector candidate for future FIR/sub-mm satellite missions. The detectors consist of a superconducting film, typically Al or TiN, which has been patterned into a resonator circuit. When photons are absorbed in the superconducting film, they break apart the electron Cooper pairs to create a change in the complex impedance of the film that shifts the detector’s resonant frequency and quality factor [22]. Multiple MKIDs, each with their own distinct resonant frequency, can be capacitively coupled to the same RF feedline. The major benefits of MKIDs include built-in frequency domain multiplexing capabilities, the potential for simplified fabrication and the decreased complexity of low temperature cabling and focal plane inter-connects. Thousands of MKIDs, fabricated on a single layer wafer, can be coupled to one RF line and amplified by a low power (<5 mW), wide-bandwidth, cryogenic silicon germanium (SiGe) amplifier.

BLAST-TNG will drive the development of polarization-sensitive TiN MKIDs for submillimeter wavelengths. The detectors will be divided into three arrays of 955, 475, and 215 feeds at 250, 350, and 500 µm, respectively. Each feedhorn has two orthogonal polarization-sensitive detectors, allowing for simultaneous observations of both polarizations in the same spatial pixel. This design produces just over 3200 detectors in BLAST-TNG, > 12 times that of BLASTPol. These new MKID arrays
increase the net mapping speed of BLAST-TNG by a factor of 16 over BLASTPol. BLAST-TNG features one of the highest multiplexing factors for MKIDs to date, and will operate the first ROACH2 FPGA-based readout system. BLAST-TNG will be the first balloon-payload to fly both MKID arrays and a ROACH2-based readout system, which will raise the Technology Readiness Level (TRL) of the two technologies in anticipation of a future satellite mission.
Chapter 3

BLAST-TNG Instrument Overview

In this chapter, I will give a technical overview of each of the main BLAST-TNG components.

3.1 Instrument Overview

3.1.1 Gondola

On a balloon payload, the gondola provides a structure to attach the various telescope components to while also providing an attachment point to the flight train of the balloon. The BLAST-TNG gondola, shown in Figure 3.1, is divided into two main components, the inner and outer frame. The outer frame is very similar to the original BLAST design, however it has been strengthened to provide additional support for the increased weight of the inner frame components. The outer frame consists of a cradle area to house the support instrument package (SIP), a mount point for the reaction wheel motor, and two sawhorses which support the inner frame.
3.1.2 Pointing Control

The BLAST-TNG gondola uses the same elements to point the telescope as the previous iterations of BLAST. A Kollmorgen direct drive brushless motor\(^1\) is connected to the axis of the inner frame and controls the elevation of the telescope. The inner frame is balanced before flight to ensure that the minimum amount of torque is required to point, and a balance system controls for cryogen boil off during the flight. Telescope azimuth is controlled by both a reaction wheel and pivot. The reaction wheel is a 1.5 meter diameter wheel constructed of 7.62 cm thick Hexcel\(^\circledR\) aluminum honeycomb with 48 0.9 Kg brass cylinders installed around the perimeter to maximize its moment of inertia. This wheel is mounted directly to and driven by a brushless direct drive motor\(^2\). Changing the speed of the wheel rotation results in

\(^1\)Kollmorgen C053A-13-3305
\(^2\)Kollmorgen D063M-22-1320
a transfer of angular momentum from the wheel to the gondola. This allows us to scan in azimuth at rates of 0.05 deg/s while observing, and can slew the telescope to different targets at rates up to several degrees per second. The pivot is composed of a Parker BaySide K178200-6Y1 frameless DC motor mounted to a custom crown which provides connections to both the balloon flight train and the four gondola suspension cables. The pivot allows us to dump excess angular momentum to the flight train of the balloon if reaction wheel begins to reach its maximum speed. In addition, the pivot motor can independently point the telescope in azimuth as a redundancy for the reaction wheel.

### 3.1.3 Attitude Determination

BLAST-TNG utilizes a hierarchical algorithm that takes inputs in real time from multiple pointing sensors that have varying readout rates and accuracies to determine the pointing of the telescope. The details of the attitude determination and sensors used are explained in detail in [40]. The algorithm allows for an in-flight pointing accuracy of $\sim 30''$, with an absolute pointing accuracy of $< 5''$ which is obtained from a post-flight analysis. Table 3.1 shows the various sensors with their respective readout rates and accuracies that are used on BLAST-TNG. These sensors all provide an absolute attitude solution, while the integrated velocity data from two redundant sets of three orthogonally-configured fiber-optic gyroscopes$^3$.

**Day Time Star Trackers**

The main absolute pointing sensor is a pair of redundant day time star trackers which are colloquially referred to as star cameras, which are shown in Figure 3.2.

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$^3$DSP-1760. KVH Industries, Inc. 50 Enterprise Center Middletown, RI 02842
Table 3.1: Summary of Pointing Sensor Parameters \[40\]

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sample Rate (Hz)</th>
<th>Accuracy (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
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<td>0.1</td>
</tr>
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<td>Star Camera</td>
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<td>&lt;0.001</td>
</tr>
<tr>
<td>Elevation Encoder</td>
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<td>&lt;0.001</td>
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</tbody>
</table>

The star cameras were originally built for BLAST \[100\] and are enclosed in a pressure vessel which maintains the temperature of the components and was originally to allow for internal hard disk drives (these have been replaced by solid state drives). The star camera optics consist of a QImaging Retiga EXI CCD camera coupled to a Nikon 200 mm $f/2$ lens which has a Nikon R60 filter that filters out all light with wavelengths less than 600 nm. This greatly reduces the background due to sky brightness, with a minor reduction in star light. A carbon-fiber baffle with multiple radial disks is mounted to the front of the star camera to eliminate scattered light $>10$ deg from the optical axis while also preventing all light sources $>7$ deg from the optical axis from illuminating the window. The lens’ aperture and focus is controlled by two stepper motors to maintain the focus throughout temperature changes in flight. The back end of the star camera consists of the pc/104 single board computer components which acquire the images from the CCD, compute the pointing solutions, and send them to the data acquisition (flight) computers via Ethernet. The computer hardware was extensively upgraded for the BLASTPol 2012 flight. The star cameras now use Advantech PCM-3362 extended temperature edition single board computers coupled to solid state drives. In preparation for the upcoming BLAST-TNG flight, the star camera control software has been switched to STARS \[15\], which was developed by Daniel Chapman for the EBEX balloon-borne CMB polarization experiment \[99\]. This code acquires a picture of the sky from the CCD camera, identifies star
Figure 3.2: Exploded View of a Star Camera Assembly. The optics consist of a CCD camera coupled to a 200 mm $f/2$ lens with a $2\,\text{deg} \times 2\,\text{deg}$ field of view. All of the components are contained within a pressure vessel to maintain a constant temperature.

candidates in the image, and then matches them to a catalog to determine the stars positions. It then computes the absolute position and rotation of the image on the celestial sphere in equatorial coordinates. This information is then sent to the flight computer, via Ethernet, as an input to the in-flight pointing solution.

Fiber Optic Gyroscopes

BLAST-TNG flies two redundant DSP-1760’s, which each contain a set of three orthogonally mounted fiber optic gyroscopes. These gyroscopes provide the relative motion of the gondola which is used to interpolate the position between absolute pointing solutions obtained by the star cameras. BLASTPol flew single-axis DSP 3000 gyroscopes which were mounted orthogonally in custom built enclosures. These old gyroscopes had to be manually calibrated, and had an angular random walk of $\leq 0.1^\circ/\sqrt{\text{hr}}$. However, the new DSP-1760 gyroscopes for BLAST-TNG have an accuracy drift of $\leq 0.012^\circ/\sqrt{\text{hr}}$. In addition, the three orthogonal gyroscopes flight come packaged as a single assembly, which reduces the complexity of mounting, temperature control, and calibration.
Pinhole Sun Sensor

One of the more important coarse pointing sensors is an array of pinhole Sun sensors (PSSs). These sensors are constructed by mounting a photodiode behind a small pinhole. The response of the photodiode increases as the incidence of the sun becomes closer to normal of the PSS face. Twelve of these sensors are mounted radially around an axis which is parallel to the azimuthal axis, and are all read out via a LabJack T7. The PSS with the highest intensity is compared to its two nearest neighbors and fitted to a \( \cos \theta \) function to determine the azimuth relative to the Sun. The PSS array has a precision of 4' with an absolute accuracy of 5° at a data rate of 5 Hz [91].

GPS

The GPS is used to provide the geographic position of the gondola (latitude, longitude, and altitude), as well as attitude (pitch and roll), absolute time, and speed that the gondola is moving. The GPS also provides the 10 MHz and 1 pulse per second (PPS) signals that are used to sync the detector time streams to the gondola pointing information.

Magnetometer

The other coarse pointing sensors include a Honeywell 3-axis magnetometer which determines the azimuthal pointing of the gondola to \( \sim 5^\circ \). The low precision is due to the fact that the Earth’s magnetic field is highly inclined at the poles.

---

4LabJack Corporation: 3232 S Vance St, Lakewood CO, 80227
Elevation Encoder and Inclinometers

In addition to the encoder that is built into the direct drive elevation motor, we have installed a RESOLUTE absolute rotary optical encoder on RESA\textsuperscript{5} rings. This new encoder has over 10 times the angular resolution than the built-in motor encoder, which had 20″ pointing precision and was used during the previous flights. However, due to pendulation of the gondola, its use as an absolute pointing sensor is degraded to an overall accuracy of \( \sim 30′ \). However, since it is an absolute encoder, the elevation will never be lost due to an intermittent power or motor failure.

Biaxial inclinometers\textsuperscript{6} are mounted to both the inner and outer frame and are used as back-up sensors for the elevation encoder. It is able to measure the pendulation of the gondola. However, the sensors are not very precise and are subject to thermal drift. The clinometers are rarely used in determining a pointing solution.

3.1.4 Optics

The BLAST-TNG optics can be divided into two sections: the warm Cassegrain telescope, and the cold reimaging optics.

Warm Optics

The primary and secondary mirrors of BLAST-TNG are arranged in a Ritchey-Chrétien configuration, which is chosen to eliminate third-order spherical aberration and coma. The \( f/4.2 \) is identical to the BLASTPol prescription, with an enlarged 2.5 meter diameter carbon fiber reinforced polymer (CFRP) primary (M1) and a 52 cm diameter aluminum secondary mirror (M2). A rendering of the warm optics

\textsuperscript{5}Renishaw: 5277 Trillium Blvd, Hoffman Estates, IL 60192
\textsuperscript{6}Applied Geomechanics Clinometer Packs

38
is provided in Figure 3.3. The BLAST-TNG primary mirror is 40% wider than the aluminum primary mirror used for BLASTPol. This allows for a 40% increase in resolution. The interface for M2 is supported by three rigid CFRP struts which are connected to a CRFP optical bench. The optical bench’s primary goal is to support M1 and provide an interface to the gondola’s inner frame via 6 titanium flexures. An important addition to the warm optics is the incorporation of permanently-mounted optical targets along the perimeter of M1. This allows for rapid surveying of the telescope configuration with a laser tracker. The warm optics are being developed by Vanguard Space Technologies through a NASA Small Business Innovation Research (SBIR) grant and is expected to have an RMS surface error of < 10 µm during operation. The warm optics are scheduled to be completed in time for BLAST-TNG integration during the summer of 2017.

Cold Reimaging Optics

The warm telescope optics feed the $f/5$ beam into the reimaging optics, which refocus the beam to $f/5$. The cold optics consist of three cryogenic mirrors, an achromatic half-wave plate (HWP), and two dichroics which split the beam to the 250 and 350 µm arrays. The optical elements are all mounted to an optics bench which is kept at 4 K (shown in Fig. 3.4), and is covered by a MuMETAL® box. The entrance of the optics box is placed at the Cassegrain focus of the telescope. This minimizes the aperture of both the cryostat window and the size of the filter mounted to the entrance of the optics box while maximizing the amount of beam overlap at the HWP. This maximizes the uniformity in the polarization modulation. Since each detector ‘sees’ almost the same area of the HWP, any defects in the HWP are likely to be observed

\[ \text{www.vst-inc.com} \]
Figure 3.3: The design concept from Vanguard Space Technologies for the 2.5 meter carbon fiber primary and 52 cm secondary mirror and associated support structure. The mirrors are arranged in a Ritchey-Chrétien configuration. The secondary mirror has 3 linear actuators allowing for in-flight focusing. The optics bench is also made of carbon fiber and enables the mirror system to be mounted to the inner frame of the gondola via 6 titanium flexures.

uniformly in all detectors. The cold re-imaging optics design is similar to that of BLASTPol in that they both feature an Offner relay configuration. This produces an image of the primary mirror at M4 which serves as a Lyot stop and a mounting point for a calibration source. However, in BLASTPol, M3 and M5 were identical spherical mirrors. In BLAST-TNG, M3 and M5 are slightly different spherical mirrors which are used in a Gaussian beam configuration. The characteristics of each optical element is shown in Table 3.2. There are two dichroics that split the beam to the 250 and 350 µm arrays, which are mounted at 22.5 deg and 30 deg angles relative to the optical axis, respectively. This allows the telescope to observe in all three bands simultaneously. The cold optics produce a beam at f/5 at the focal plane of the detectors. An improvement over BLASTPol is the removal of all fold-flat mirrors, as well as the mounting of all optical elements to a single optics bench. A rendering
### Geometrical Characteristics

<table>
<thead>
<tr>
<th>Geometrical Charac.</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Shape</td>
<td>Paraboloid</td>
<td>Hyperboloid</td>
<td>Sphere</td>
<td>Sphere</td>
<td>Sphere</td>
</tr>
<tr>
<td>Conic Constant</td>
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<td>-2.182</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Radius of Curvature</td>
<td>4.161 m</td>
<td>1.067 m</td>
<td>655.6 mm</td>
<td>376.5 mm</td>
<td>794.4 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>∅2.5 m</td>
<td>∅0.516 m</td>
<td>∅28 cm</td>
<td>∅7 cm</td>
<td>∅28 cm</td>
</tr>
</tbody>
</table>

**Table 3.2: Summary of BLAST-TNG Optics Characteristics**

Figure 3.4: Schematic of the optical configuration of BLAST-TNG with an enlarged view of the cold optics. The on axis Cassegrain telescope feeds into a modified Offner relay. M3, M4, and M5 are spherical mirrors in a Gaussian beam configuration with M4 acting as both the Lyot stop for the telescope and as a mounting point for a calibration source. There are two dichroics which split the beam to the 250 and 350 µm arrays. The 250 µm dichroic is set to the ideal 22.5 deg relative to the optical axis while the 350 µm dichroic is set to 30 deg due to space constraints. The HWP is mounted between the Cassegrain focus and M3.

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IR-Blocking Filters and Band-Defining Elements

There are a series of alternating IR-blocking and low-pass edge (LPE) filters which are mounted on the windows of each temperature stage between the cryostat window and the entrance to the optics box. The filter elements and their locations in the cryostat are shown in Table 3.1.4. The filter stack is very similar to what was
Figure 3.5: A 3D rendering of the BLAST-TNG optics box which highlights the major components: the HWP, M3, M4 (Lyot stop), M5, and the two dichroics. The 250 and 350 $\mu$m arrays are mounted behind the optics bench and are not shown.
<table>
<thead>
<tr>
<th>Stage</th>
<th>Name</th>
<th>Description</th>
<th>Aperture Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K</td>
<td>300-IR-1</td>
<td>IR blocker over window</td>
<td>18.0975</td>
</tr>
<tr>
<td></td>
<td>300-AR</td>
<td>AR-coated HDPE window</td>
<td>18.0975</td>
</tr>
<tr>
<td></td>
<td>300-IR-2</td>
<td>IR blocker inside cryostat</td>
<td>11.43</td>
</tr>
<tr>
<td>VCS2</td>
<td>VCS2-IR</td>
<td>IR blocker</td>
<td>10.922</td>
</tr>
<tr>
<td></td>
<td>VCS2-LPE</td>
<td>100 μm LPE</td>
<td>10.922</td>
</tr>
<tr>
<td>VCS1</td>
<td>VCS1-LPE</td>
<td>LPE</td>
<td>10.4775</td>
</tr>
<tr>
<td>4 K</td>
<td>4K-LPE</td>
<td>154 μm LPE ($\theta_{offset} = 8^\circ$)</td>
<td>10.033</td>
</tr>
<tr>
<td>Optics Box</td>
<td>OB-LPE</td>
<td>LPE ($\theta_{offset} = 8^\circ$)</td>
<td>10.033</td>
</tr>
<tr>
<td></td>
<td>250-DC</td>
<td>$\lambda &lt; 215$ μm Dichroic</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>350-DC</td>
<td>$\lambda &lt; 300$ μm Dichroic</td>
<td>17.5</td>
</tr>
<tr>
<td>Array Filters</td>
<td>250-LPE</td>
<td>215 μm LPE</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>350-LPE</td>
<td>265 μm LPE</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>500-LPE</td>
<td>333 μm LPE</td>
<td>8.2</td>
</tr>
</tbody>
</table>

flown in BLASTPol, and serve to reduce loading to the cryogenic stages. The three observing bands are all defined at the low frequency edge by the waveguide cutoff. For the high frequency edge, the 250 μm array’s band is set solely by the LPE mounted on the feedhorn array which reflects at $\lambda < 215$ μm. The 350 and 500 μm arrays are set by the reflective edge of the proceeding beam-splitting dichroic and is reinforced by a LPE mounted on the feedhorns. The first dichroic, which splits the beam to the 250 μm array, is reflective at $\lambda < 300$ μm and transparent at longer wavelengths. The second dichroic, which splits the beam to the 350 μm array, is reflective at $\lambda < 400$ μm and transparent at longer wavelengths. The BLASTPol bands were measured using a fourier-transform-spectrometer, and are shown in Figure 3.6.

**Half-Wave Plate**

Since BLASTPol utilized pixels that were only sensitive to a single polarization, a source of polarization modulation was needed to measure Stokes Q and U. This
Figure 3.6: The detector bandpasses measured with an FTS for BLASTPol. The spectral response is partly due to water absorption lines. The BLAST-TNG bands should be very similar.

was accomplished by using an achromatic half-wave plate (HWP). During observations, spatial scans are made at four HWP rotation angles spanning $90^\circ$ ($22.5^\circ$ steps), enabling the measurement of all of the Stokes parameters through polarization rotation. This HWP was constructed of five 0.547 mm thick sapphire plates that are fused together with 6 $\mu$m thick interim layers of polyethylene, which was bonded together using a hot-pressing technique developed for filter construction [2]. A two-layer broad-band anti-reflection coating that is necessary to maximize the in-band transmission of the HWP, is also hot-pressed to the front and back surfaces of the assembled plate. This also used 6 $\mu$m layers of polyethylene. The finer details of the BLASTPol HWP construction and modeling are covered in [81].

The BLASTPol sapphire HWP was 100 mm in diameter with a clear aperture of 88 mm, which was set by the size of the anti-reflection coating. The larger BLAST-TNG optics require a 175 mm diameter HWP. However, there is a maximum size sapphire HWP which is caused from the mismatch between the differential thermal
contraction of the Sapphire and the anti-reflection coating. Therefore, for BLAST-TNG, a meta-material HWP was designed that does not exhibit this mismatch, and allows for HWP construction of arbitrarily large sizes. This is accomplished by embedding capacitive and inductive grids, which introduce differential phase shifts between the two orthogonal polarizations, into a dielectric material which acts as a substrate \[94\]. The grid-substrates are now thermally bonded with other layers of the same material that function as spacers with the same technique that is used to construct the filters \[2\]. This type of HWP has the added bonus of weighing significantly less than the previous sapphire HWP.

The HWP rotator consists of a stack of several rings which are suspended via a set of spring-loaded roller bearings. Each ring serves a specific purpose. A stainless steel v-groove ring slide is mounted at the bottom of the stack, and interfaces with the roller bearing suspension. The baffle and worm gear attach to the v-groove ring, and the HWP itself sits atop the worm gear. The HWP rotator is driven by the worm, which is mounted to an aluminum shaft. The shaft is held in place by two roller bearings, and is coupled by a G10 shaft to a warm motor which sits on the inside of the vacuum jacket. The position of the HWP is determined by reading the encoder on the motor. The G10 shaft reduces the thermal loading, and the spring loaded bearings ensure that the HWP does not get dislodged during launch.

### 3.1.5 Cryogenics

The detectors require a complex cryogenics system in order to be kept steady at their nominal operating temperature of 270 mK for 25 days. This is accomplished two integrated cryogenic systems. The first system, shown in Figure 3.8, is based around a 250 L tank of liquid helium (LHe) which is coupled to two heat exchangers that
Figure 3.7: Left: The HWP rotator and sapphire HWP that was used in BLASTPol. Right: The new HWP rotator for BLAST-TNG that features an 18 cm clear aperture. The rotator is mounted to the optics bench. The meta-material HWP is rotated via a worm gear which is driven by a G10 shaft attached to a warm motor that is mounted on the inside of the vacuum jacket.

maintain the temperature of two radiation shields to 60 K and 160 K. This provides a 4 K stage for mounting and heat sinking the optics box.

The second system, shown in Figure 3.9, consists of a LHe pumped pot, or a LHe reservoir that is held near vacuum, which sits at 0.7 K and provides an intermediate temperature stage for the detector thermal support structure as well as the condensing stage for the $^3$He adsorption refrigerator. The refrigerator is a closed-cycle system which is filled with $^3$He to 500 psi (at 300 K), and consists of a pump filled with activated charcoal, a cooled condensation point, and an evaporator (or still) [25]. The pre-cooling point of the condenser is mounted to the 4 K LHe tank. The condensation plate is thermally attached to the pumped pot, which sits at 0.7 K. To cycle the fridge, the gas-gap heat-switch which connects the charcoal to the 4 K LHe tank is turned off, and the charcoal is heated to 35 K. This allows the $^3$He to evaporate off
Figure 3.8: A cross-sectional view of the BLAST-TNG cryostat which highlights the optics box cavity, 250L LHe tank, and radiation shields with their heat exchangers.
the charcoal and travel down the 306 stainless steel tube, being cooled by the OFHC copper 4 K pre-cooler and 0.7 K condenser, where it eventually reaches the evaporator and remains as liquid. The heat-switch is then turned back on, allowing the charcoal to cool and return to adsorptive pumping on the evaporating $^3$He. If the condenser is kept at 0.7 K, the refrigerator should provide 3.9 Joules of cooling capacity.

In BLASTPol, the pumped pot was passively filled using a capillary. This produced a continuous 24 mW load on the pumped pot, which caused it to operate at 1.5 K. For BLAST-TNG, the pumped pot is actively filled via an 0.01 inch diameter capillary by opening a valve to the main LHe tank. By increasing the diameter of the capillary from the size used in BLASTPol, the pumped pot can be filled in about an hour. The capillary valve is then closed, which reduces the loading to the pumped pot and allows it operate at a lower temperature. Another potential addition to the BLAST-TNG cryogenic system is a scroll pump that would be attached to the pumped pot exhaust port during flight. This allows the 1 Torr ambient pressure at float to be further reduced in the pumped pot. A lower pressure and reduced passive capillary load allows the pumped pot temperature to be decreased by up to 400 mK. This lower condensing stage temperature enables the $^3$He absorption refrigerator to achieve a base temperature of 270 mK, or an improvement of 30 mK with respect to the passive capillary BLASTPol system. These improvements are crucial in order to achieve the desired detector performance and multiplexing density.

### 3.2 Instrument Performance

Once the detectors are installed into the cryostat and cooled down, a battery of tests are required to ensure that the receiver performs as intended. As these tests are
Figure 3.9: The sub-Kelvin cryogenic system, which features a $^3$He adsorption refrigerator that is backed by a 0.7 K $^4$He pumped pot.
used to evaluate specific aspects of the telescope’s performance and characteristics, they each require different components and apparatuses to perform them. In this section, I will give a brief overview of each of the major tests, noting what components of BLAST-TNG and the specific testing equipment are needed.

3.2.1 Beam Maps

Mapping the beam of the detectors is a great test for confirming that the optics are performing as expected. There are two types of beam maps that are used for BLAST-TNG, near-field and far-field beam maps. Far-field maps are used to check the alignment of the cold optics to the detectors, while near-field maps measure the beam through the entire optical system.

To generate the far-field beam maps, a movable XY-stage that is coupled to a chopped 77 K blackbody load is placed relatively close in front of the window of the cryostat. A raster scan across the beam of the detectors is performed and beam profiles for all detectors are generated. This beam shape will show the center section of a Gaussian beam profile with a hole in the center (both due to the Lyot stop). This test is useful for checking the alignment of the detectors, feedhorns, and reimaging optics. See Section 4.1.4 of Elio Angile’s thesis [5] for further details.

The near-field beam maps are useful for measuring the optical performance through the entire system. The cryostat is mounted in the inner frame, and is aligned with the primary and secondary mirror. The secondary is then stepped down to bring the focus of the telescope from infinity to 100 meters. The same XY-stage from the far-field beam maps is then placed 100 meters away from the telescope and another raster scan is performed over the expected location of the far-field beams. The far-field beam maps should exhibit a standard Gaussian profile.
Figure 3.10: The XY-stage with reimaging optics used to produce near-field Beam Maps without coupling to the warm telescope components.
In order to measure the near-field beam maps without coupling to the warm telescope optics, a set of reimaging optics is attached to the XY-stage. This setup is shown in Figure 3.10. The primary use of this test is to discern the location of each individual detector beam on the array.

### 3.2.2 Instrumental Polarization

Instrumental Polarization (IP) is the false polarization signal due to the telescope and instrument that is detected from an unpolarized source. If the instrument’s IP is small and constant, it can be easily subtracted during analysis [87]. In this test, we take a temperature stable, unpolarized chopped blackbody source, shown in Figure 3.12, and measure the signal at multiple HWP angles to see if there is any variation between the positions. The chopper consists of a thermally isolated load that is heated 2-5 K above ambient temperature. The puck is chopped at 1 Hz by a bow-tie style blade. Both the chopper blades and the puck are made from aluminum panels covered in Tesselating TeraHertz RAM[8] which feature a pyramid structure that ensures $\leq -35$ dBm reflectivity at our wavelengths. This chopper is placed directly in front of the cryostat window so that the signal completely fills all the detector beams. The amplitude of the chopped signal measured by the detectors is recorded at the four desired in-flight HWP positions ($0^\circ$, $22.5^\circ$, $45^\circ$, and $67.5^\circ$) and their back-ups ($-90^\circ$, $-22.5^\circ$, $-45^\circ$, and $-67.5^\circ$). The variation between each of the HWP positions corresponds to the level of our instrumental polarization. The IP from BLASTPol is presented in Figure 3.11.

The IP of the BLAST-TNG detectors has yet to be measured, as the HWP was not installed by the time of this publication. Typically, this ground calibration is not

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[8]Thomas Keating Ltd and QMC Instruments Ltd. Billingshurst West Sussex RH14 9SH UK
Figure 3.11: BLASTPol IP plotted with the normalized Stokes parameters, $q$ and $u$, as the x and y axis, respectively. The blue, green, and red points are the IP measured for each detector at 250, 350, and 500 $\mu$m, respectively, with 1 sigma error bars. The two contours show the levels for 0.5% and 1.0% IP.
used during the final data analysis as we expect to make an in flight measurement of IP by observing a bright source, such as Jupiter, at two parallactic angles. The apparent polarization of the source should rotate with sky angle, but the IP should stay the same. However, the ground tests are a good indicator of whether something is catastrophically wrong with the receiver. Chapter 5.1.1 of Tristan Matthew’s Thesis contains a more detailed description of the IP measurement procedure [75].

3.2.3 Polarization Efficiency and Zero Angle

The polarization efficiency of the detectors is a critical measurement as it helps determine the telescope’s mapping speed. It is measured in a very similar way to the IP measurement. The same chopped blackbody source is placed in front of the receiver. However, a rotatable polarizing grid that is mounted at a 45 degree angle from the window between the chopper and the cryostat. The polarizing grid is rotated at 10 degree intervals. In Figure 3.12, the chopper and input polarizer are coupled to an ADR cryostat that houses the BLAST-TNG 250 µm prototype arrays. We then measure the modulation change to the chopped signal and fit it to a sine wave. The polarization efficiency and fitted sine are defined in Equation (3.1):

\[
\text{Modulated Signal} = A \cdot \sin\left(\frac{\theta + \phi}{\omega}\right) + B \\
\text{Pol. Efficiency} = \frac{A - B}{A + B}
\]  

(3.1)

Where A is the amplitude of the sinusoidal signal, \(\theta\) is the polarized grid angle, and B is the offset, or cross-pol. The polarization grid angle which maximizes the modulated signal is chosen as the Zero-Angle, or 0° angle. See Section 5.4 for an analysis of the 250 µm polarization efficiency.
Figure 3.12: Polarization efficiency measurements at NIST on 250 μm prototype arrays. Left: Dr. Johannes Hubmayr rotates the input polarizer placed between the chopper and cryostat window. Top right: The chopper blade passes above the heated load, causing a change in signal. Lower right: the back of the chopper shows the bow-tie style chopper blade, which is rotated by the stepper motor in the center. Also shown is the resistor array used to heat the source, which has been thermally isolated by G10 supports.
3.2.4 Bandpass Measurements

A Martin-Pulpett [73] style Fourier Transform Spectrometer (FTS) is used to characterize the spectral response of the receiver, which includes the detectors, dichroics, window, and full filter stack. In practice, the FTS is operated under vacuum, positioned as close to the cryostat window as possible. In addition, dry Nitrogen is flowed through the small gap between the exit aperture of the FTS enclosure and the receiver window. This is because the water lines are extremely strong in these bands and will distort our overall bandpass measurements. The sinusoidal response from the detectors while the movable mirror is in motion is Fourier transformed to produce the bandpass. Depending on how robust the measurement needs to be, this can be done at multiple HWP positions, as well as the maximum and minimum response for the two detector polarizations. The bandpass measurements for the 2012 BLASTPol flight are shown in Figure 3.13. Section 4.1.1 of Elio Angile’s thesis [5] has an in-depth summary of these FTS measurements. Section 5.4 of this thesis has in-depth analysis of the 250 μm array bandpass measurements.
Figure 3.13: Top: The FTS is shown without the vacuum jacket. The source is coupled to the FTS at the bottom right of the image. A polarizer mounted at 45° splits the beam to the fixed and movable mirror, where it is then combined and sent to the cryostat (which would be at the top center of the image). Bottom: Bandpasses of the 250 (green), 350 (pink), and 500 µm (black) arrays taken before the 2012 BLASTPol flight that have been normalized. The large features in the bands are due to water absorption lines.
Chapter 4

Microwave Kinetic Inductance Detectors (MKIDs)

4.1 MKID Operation Principle

In this section, we will go through the principles and physics of MKIDs. I will then derive and define the properties related to their application as detectors.

4.1.1 Surface Impedance of Superconductors

In order to properly understand the principles of MKIDs, we must begin by delving into the fundamental interactions that take place within the superconductor. A superconductor is a metal which exhibits a critical temperature $T_c$ below which the material has zero resistance to DC current. This material property occurs when the electrons form Cooper pairs which allow them to act as bosons and all occupy the same quantum mechanical state. Interactions between the electrons and the phonon lattice generate a weak attractive force, which causes the electrons to combine into
Cooper pairs. As a free electron travels through the medium, it perturbs the phonon lattice and attracts a positively charged phonon. This phonon attracts another nearby electron, with the opposite spin, which causes both electrons to become correlated and act as a pseudo boson. In BCS theory \cite{6}, the electrons are bound by the state energy

\[ 2\Delta_0 = 3.52k_BT_c \]  

Where the gap energy of the superconductor, \( \Delta(T) \), has been approximated as the gap energy at zero temperature, \( \Delta_0 \), which is valid for temperatures well below \( T_c \). This binding energy is relatively weak and allows for thermal energy to break the Cooper pairs. Therefore, at any nonzero temperature, there exists a population of unbound electrons, called quasiparticles, which has a density given by

\[ n_{qp}(T) = 4N_0 \int_{\Delta}^{\infty} \frac{E}{\sqrt{E^2 - \Delta^2(T)}} f(E) dE \]  

where \( f(E) = \frac{1}{1 + e^{E/k_BT}} \) is the typical Fermi-Dirac energy distribution. At \( T \ll T_c \), \( \Delta \approx \Delta_0 \) and \( n_{qp} \) can be approximated as

\[ n_{qp} \approx 2N_0 \sqrt{2\pi k_BT \Delta_0} e^{-\frac{\Delta_0}{k_BT}} \]  

where \( N_0 \) is the single-spin density of states at the Fermi energy of the material. For TiN, \( N_0 = 3.9 \times 10^{10} \mu \text{m}^{-3} \text{eV}^{-1} \) \cite{43}.

Despite the fact that superconductors show zero resistance to DC current, they do show nonzero resistance and inductance to AC signals. This is because the quasiparticle population introduces a resistive loss to the AC signal while the unbroken Cooper pairs within the penetration depth (\( \lambda \)) of the superconductor add an inductive impedance. This follows from the first London equation \cite{71} and is due to the fact that the inertia of the Cooper pairs causes them to lag behind the changing AC
signal. The two combined effects are described using the two-fluid model [47], which describes the electrodynamics that results from the superposition of the response from both the quasiparticles and Cooper pairs. The complex surface impedance

\[ Z_s = R_s + jX_s \] (4.4)

can be calculated using the complex conductivity equations given in [76]. The real part and imaginary parts of the complex conductivity, \( \sigma = \sigma_1 - j\sigma_2 \), are given relative to its normal state conductivity, \( \sigma_n = 1/\rho_n \), by

\[
\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar \omega} \int_{\Delta}^{\infty} \frac{E^2 + \Delta^2 + \hbar \omega E}{\sqrt{E^2 - \Delta^2 \sqrt{(E + \hbar \omega)^2 - \Delta^2}}} [f(E) - f(E + \hbar \omega)] dE \quad (4.5)
\]

\[
\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar \omega} \int_{\Delta}^{\Delta + \hbar \omega} \frac{E^2 + \Delta^2 - \hbar \omega E}{\sqrt{E^2 - \Delta^2 \sqrt{(E - \hbar \omega)^2 - \Delta^2}}} [1 - 2f(E)] dE \quad (4.6)
\]

when \( \hbar \omega < \Delta \). These integrals can be simplified in the regime where \( k_B T \ll \Delta_0 \) and \( \hbar \omega \ll \Delta_0 \) [42] to

\[
\frac{\sigma_1(n_{qp})}{\sigma_n} = \frac{2\Delta_0}{\hbar \omega} \frac{n_{qp}}{N_0 \sqrt{2\pi k_B T \Delta_0}} \sinh(\xi) K_0(\xi) \quad (4.7)
\]

\[
\frac{\sigma_2(n_{qp})}{\sigma_n} = \frac{\pi \Delta_0}{\hbar \omega} \left[ 1 - \frac{n_{qp}}{2N_0 \Delta_0} \left( 1 + \sqrt{\frac{2\Delta_0}{\pi k_B T}} e^{-\xi} I_0(\xi) \right) \right] \quad (4.8)
\]

\[
\xi = \frac{\hbar \omega}{2k_B T} \quad (4.9)
\]

where \( \xi \) is the coherence length of an impure superconductor, which can be thought of as the effective size of the Cooper pair due to the uncertainty principle. \( \xi \) can be related to that of the coherence length in a pure superconductor by \( \xi_0^{-1} = \xi^{-1} - l^{-1} \), with \( l \) being the mean free path. In addition, \( I_0 \) and \( K_0 \) are the zeroth-order modified Bessel functions of the first and second kind, and (4.3) has been used to put the conductivity in terms of the total quasiparticle density from both thermal generation and by pair breaking from photons. We can now see that the complex conductivity of
the superconductor is linearly proportional to the quasiparticle density. This forms the detection mechanism for MKIDs in which quasiparticles that are created from the absorption of photons in the superconductor can be measured through the changes in the complex conductivity. Using (4.7) and (4.8) (and assuming $\delta f(E)$ has the same shape as $f(E)$ [131]), one can show that fractional changes in $\sigma_1$ and $\sigma_2$ are indeed equal to fractional changes in $n_{qp}$ [86]:

\[
\frac{\delta n_{qp}}{n_{qp}} = \frac{\delta \sigma_1}{\sigma_1} \quad (4.10)
\]

\[
\frac{\delta n_{qp}}{n_{qp}} = \frac{\delta \sigma_2}{\sigma_2 - \sigma_2(0)} \quad (4.11)
\]

Since the complex conductivity is not measured directly, and the surface impedance is the quantity being probed, we must relate the change in complex conductivity to the change in the complex surface impedance. However, most evaluations of $Z_s$ are complex and must be done numerically. $Z_s$ is evaluated in many different cases in [42]. In the limit where the London penetration depth $\lambda = \sqrt{\frac{mc^2}{4\pi ne^2}}$ and $l$ are much larger than the film thickness $t$, we can write $Z_s$ as [42]:

\[
Z_s = \frac{1}{\sigma t} \quad (4.12)
\]

\[
= \frac{1}{(\sigma_1 - j\sigma_2)t} \quad (4.13)
\]

\[
\approx \frac{\sigma_1}{t\sigma_2^2} + j \frac{1}{t\sigma_2} \quad (4.14)
\]

From (4.12), a fractional perturbation in conductivity is related to the fractional perturbation in $Z_s$ as

\[
\frac{\delta Z_s}{Z_s} = -\frac{\delta \sigma}{\sigma} \quad (4.15)
\]

In [86], it is suggested to consider a perturbation around zero temperature where the

\[^1\text{For TiN, } \lambda=275 \text{ nm and the films used for the work in this thesis have } t \leq 56 \text{ nm.}\]
quasiparticle density is negligible. It follows \( Z_s(0) = jX_s(0) \) and \( \sigma(0) = -j\sigma_2(0) \). If one assumes \( \sigma_1 \ll \sigma_2 \), one can write, to first order:

\[
\frac{\delta R_s}{X_s(0)} = \frac{\delta \sigma_1}{\sigma_2(0)} \tag{4.16}
\]

\[
\frac{\delta X_s}{X_s(0)} = -\frac{\delta \sigma_2}{\sigma_2(0)} \tag{4.17}
\]

By utilizing [4.10] and [4.11] the above two equations can be rewritten in terms of \( n_{qp} \):

\[
\frac{\delta R_s}{X_s(0)} = \frac{S_1(\omega)}{2N_0\Delta_0} \delta n_{qp} \tag{4.18}
\]

\[
\frac{\delta X_s}{X_s(0)} = -\frac{S_2(\omega)}{2N_0\Delta_0} \delta n_{qp} \tag{4.19}
\]

with \( S_1(\omega) \) and \( S_2(\omega) \) being defined in the limit \( \hbar \omega, k_B T \ll \Delta_0 \) as

\[
S_1(\omega) \approx \frac{2}{\pi} \sqrt{\frac{2\Delta_0}{\pi k_B T}} \sinh(\xi) K_0(\xi) \tag{4.20}
\]

\[
S_2(\omega) \approx 1 + \sqrt{\frac{2\Delta_0}{\pi k_B T}} e^{-\xi} I_0(\xi) \tag{4.21}
\]

with

\[
\beta = \frac{S_2(\omega)}{S_1(\omega)} = \frac{\delta \sigma_2}{\delta \sigma_1} = \frac{|\delta X_s|}{\delta R_s} \tag{4.22}
\]

being the ratio of the two perturbations. \( \beta \) determines which type of response will be greater. These perturbation relations will become important later when we begin to characterize the resonator properties in terms of absorbed radiation.

### 4.2 Probing Impedance via a Resonant Circuit

The impedance change due to incident radiation can be accurately measured by patterning the superconducting material into a resonant \( RLC \) circuit. The basic concept is shown in Figure 4.1. Photons with energy \( h\nu > 2\Delta \) break Cooper pairs
Figure 4.1: MKID Operation Principle. [22] a) As photons with energy \( h\nu > 2\Delta \) are absorbed by the superconductor, they break Cooper pairs and generate quasiparticles. The density of states for quasiparticles, \( N_s(E) \), is shown as the shaded area. b) The material can be patterned as an RLC circuit which is capacitively coupled to a microstrip feedline. Light is absorbed in the inductor, generating quasiparticles which increases the kinetic inductance, \( L_k \), and resistance of the film, \( R_s \). By measuring the complex transmission, \( S_{21} \), we can find the resonant frequency, \( f_r \), and quality factor, \( Q \), of the resonator. c) The change in \( L_k \) causes a shift in resonant frequency, \( \delta f_r \), while the change in \( R_s \) degrades the quality factor, \( \delta Q \), of the resonator. d) Both of these degradations contribute to the change in phase, \( \delta \theta \), of the probe tone used by the readout system.

inside the inductor section of the detector, shifting the circuit’s resonant frequency \( f_r \) and degrading its quality factor \( Q_r \). Multiple detectors, each with their own distinct resonant frequency, are capacitively coupled to a microstrip feedline (shown in Figure 4.2). A comb of microwave probe tones at each detector’s resonant frequency is sent down the microstrip line, and the complex amplitude of the \( S_{21} \) transmission signal changes by \( \delta S_{21} \) depending on the amount of incident light on the detectors. In this section, the properties of the resonator circuit will be derived in relation to the properties of the surface impedance discussed in the previous section.

### 4.2.1 MKID Resonator Parameters

A resonator circuit diagram is shown in Figure 4.1b. The single-pole approximation, derived in [86], of the forward complex transmission \( S_{21} \) from port 1 to port 2
as a function of frequency is

\[
S_{21}(\omega) = 1 - \frac{Q_r}{Q_c} \frac{1}{1 + 2jQ_r x}
\]

\[
x = \frac{(\omega - \omega_r)}{\omega_r}
\]

Here, \(w_r = 2\pi f_r\) is the resonance frequency, \(x\) is the fractional frequency, \(Q_c\) is the coupling quality factor, and \(Q_r\) is the resonator quality factor. \(Q_c\) is a measure of the coupling strength of the resonator to the feedline, and \(Q_i\) is the internal quality factor. The three quality factors are related to each other by \(Q_r^{-1} = Q_i^{-1} + Q_c^{-1}\). On the complex plane, Equation 4.23 maps to a circle, which is shown in Figure 4.3 and is colloquially referred to as the resonance circle. As the probe frequency moves away from the resonance frequency, the transmission approaches unity. On resonance, the transmission has a minimum value of \(\min(|S_{21}|) = 1 - \frac{Q_r}{Q_c}\). \(Q_r\) is found by taking the
Figure 4.3: The ideal $S_{21}$ transmission for a single MKID is a circle in the complex plane $\mathbb{C}$. The blue dots denote fixed probe frequency steps. The complex vectors that are tangent and normal to a point on the circle are denoted as $A(\omega)$ and $B(\omega)$. These two vectors correspond to the frequency and dissipation signals produced in the MKID.

The frequency-to-bandwidth ratio: $Q_r = \frac{f_r}{\Delta f}$. $Q_c$ and $Q_i$ are estimated by:

$$Q_c = \frac{Q_r}{1 - \min(|S_{21}|)} \quad (4.25)$$

$$Q_i = \frac{Q_r}{\min(|S_{21}|)} \quad (4.26)$$

When photons are absorbed by the MKID, it affects $f_r$ and $Q_r$ which changes the resonance circle. The changes on the resonance circle can be decomposed into two vectors, $A(\omega)$ and $B(\omega)$, that are tangent and normal to the circle. If the rate of change is slow, $A(\omega)$ and $B(\omega)$ can be expressed as

$$A(\omega) = \delta S_{21} \frac{\delta x}{\delta x} = 2jQ_c(1 - S_{21}(\omega))^2 = j\frac{Q_i}{2} \chi_c \chi_g e^{-2j\phi_g} \quad (4.27)$$

$$B(\omega) = \delta S_{21} \frac{\delta Q_i}{\delta Q_i} = \frac{1}{2j} A(\omega) = \frac{Q_i}{4} \chi_c \chi_g e^{-2j\phi_g} \quad (4.28)$$
These two directions are commonly referred to as the frequency and dissipation directions. The third form of $A(\omega)$ and $B(\omega)$ is written in terms of the phase angle $\phi_g$, the coupling efficiency factor $\chi_c$, and the generator detuning efficiency $\chi_g(\omega)$ from [131]. Combining $A(\omega)$ and $B(\omega)$ and solving for $\delta S_{21}$ yields the following expression:

$$\delta S_{21}(f) = \frac{1}{4}\chi_c\chi_g Q_i e^{-2j\phi_g} [2j\delta x(f) + \delta Q^{-1}_i(f)]$$

(4.29)

Two sources of noise can affect $\delta S_{21}$ and should be added to Equation 4.29. The first term, $\delta S_a(f)$, arises due to noise produced by the cryogenic amplifier in the RF chain. The second term, $S_{TLS}(f)$, is called two-level system (TLS) noise. TLS noise is the product of the random structure of amorphous materials, and has been modeled since the 70’s [93, 4]. It arises when an atom or group of atoms in different chemical bond configurations randomly quantum tunnel between two local energy potential minima. The amorphous material also suggests that the characteristic potential energy minima and barrier height are also random, which leads to a random, uniform distribution of TLS fluctuations. The atoms have an electric dipole moment, which allows the fluctuations to couple to the electric field of the resonator. This produces fluctuations in the resonant frequency. The origin and properties of TLS noise in MKIDs has been extensively studied and empirically modeled in [42]. Including these two terms, Equation 4.29 can now be rewritten as:

$$\delta S_{21}(f) = \frac{1}{4}\chi_c\chi_g Q_i e^{-2j\phi_g} [2j\delta x(f) + 2\delta x_{TLS}(f) + \delta Q^{-1}_i(f)] + \delta S_a(f)$$

(4.30)

4.2.2 Quasiparticle Generation

The quasiparticle population can be determined by balancing the generation and recombination rates [131]. Two quasiparticles recombine when they emit a phonon
that escapes the superconducting volume, $V$. The quasiparticle lifetime $\tau_{qp}$ is described by the empirical relation\,[131]:

$$\tau_{qp} = \frac{\tau_{\text{max}}}{1 + n_{qp}/n^*}$$  \hspace{1cm} (4.31)

Both the crossover density $n^*$ and maximum quasiparticle lifetime $\tau_{\text{max}}$ are determined experimentally, and the physics governing them is still an area of active research\,[103, 7, 8, 23, 64]. For TiN films, $\tau_{\text{max}} = 100 \ \mu s$ for $T_c = 1.1 \ \text{K}$ and increases with higher film $T_c$\,[67]. The general picture is that as the number of quasiparticles increases, $\tau_{qp}$ decreases as there are more potential partners with which to recombine.

Now, the change in the quasiparticle density is a simple rate equation:

$$\frac{dn_{qp}}{dt} = \Gamma_{\text{gen}} - \Gamma_{\text{rec}}$$  \hspace{1cm} (4.32)

where $\Gamma_{\text{gen}}$ and $\Gamma_{\text{rec}}$ denote the generation and recombination rates. By setting the rates equal, we can calculate the steady state population $n_{qp}$. The generation term has contributions from both thermal excited quasiparticles $\Gamma_{th}$ and excess quasiparticles $\Gamma_e$ which is from the optical incident power and the tone power from the readout system.

$$\Gamma_{\text{gen}} = \Gamma_{th} + \Gamma_e = \Gamma_{th} + \Gamma_{opt} + \Gamma_a = \Gamma_{th} + \frac{\eta_o P_{opt}}{\Delta_0} + \frac{\eta_a P_a}{\Delta_0}$$  \hspace{1cm} (4.33)

where $\eta_o$ and $\eta_a$ are the optical and readout power quantum efficiencies, $P_{opt}$ is the incident optical power, and $P_a$ is the readout power absorbed inside the resonator. Equation 4.32 implies the recombination rate is:

$$\Gamma_{\text{rec}} = \frac{n_{qp} V}{\tau_{\text{max}}} \left(1 + \frac{n_{qp}}{2n^*}\right)$$  \hspace{1cm} (4.34)
By equating $\Gamma_{rec}$ and $\Gamma_{gen}$ and solving for $n_{qp}$ gives the following expression:

$$n_{qp} = n^* \sqrt{1 + \frac{2\Gamma_e \tau_{max}}{Vn^*}} - n^*$$

(4.35)

Finally, perturbation of $N_{qp} = Vn_{np}$ in response to a perturbation in optical power $\delta P_{opt}$ is given by:

$$\delta N_{qp} = \frac{\delta N_{qp}}{\delta P_{opt}} \delta P_{opt} = \frac{\delta N_{qp}}{\delta \Gamma_e} \frac{\delta \Gamma_e}{\delta P_{opt}} \delta P_{opt} = \frac{\eta_{0} \tau_{qp}}{\Delta_0} \delta P_{opt}$$

(4.36)

### 4.2.3 Resonator Response

The next several steps will be used to calculate the relation between a perturbation in transmission $\delta S_{21}$ caused by a perturbation in incident power. This will require several intermediate perturbation steps, starting with the perturbation in resonant frequency and quality factor. The resonance frequency of the MKID is defined by:

$$f_r = \frac{1}{2\pi \sqrt{LC}}$$

(4.37)

A perturbation in inductance is related to a perturbation in frequency as:

$$\delta x = \frac{\delta f_r}{f_r} = -\frac{\delta L}{2L}$$

(4.38)

The total inductance $L$ is the sum of the fixed geometric inductance $L_m$ and the kinetic inductance $L_{ki}$ caused by the quasiparticles $L = L_m + L_{ki}$. Since only the kinetic inductance changes over time, $L_m$ can be neglected:

$$\delta x = \frac{-\delta L_{ki}}{2(L_{ki} + L_m)} = \frac{-\alpha \delta L_{ki}}{2 \frac{L_{ki}}{2} X_s} = -\frac{\alpha \delta X_s}{2 X_s}$$

(4.39)

where

$$\alpha = \frac{L_{ki}}{L_{ki} + L_m}$$

(4.40)
is called the kinetic inductance fraction and depends on both the material properties and the resonator geometry. By using Equation 4.17, we obtain a relation between $\delta x$ and $n_{qp}$:

$$\delta x = -\frac{\alpha S_2(\omega)}{4N_0\Delta_0} \delta n_{qp} \tag{4.41}$$

The same steps can be repeated for the internal quality factor perturbation. Starting with:

$$Q_i^{-1} = \frac{R}{\omega L} \tag{4.42}$$

perturbing resistance and substituting for $\alpha$ leads to:

$$\delta Q_i^{-1} = \frac{\delta R}{\omega L} = \alpha \frac{\delta R}{\omega L_{ki}} = \alpha \frac{\delta R_s}{X_s} \tag{4.43}$$

By using Equation 4.16, $\delta Q_i^{-1}$ is related to $\delta n_{qp}$ by:

$$\delta Q_i^{-1} = \frac{\alpha S_1(\omega)}{2N_0\Delta_0} \delta n_{qp} \tag{4.44}$$

It is also useful to define $\chi_{qp} = Q_i/Q_{qp}$ as the fraction of the resonator internal dissipation contributed by the quasiparticles. This forms a similar relation to that in Equation 4.44:

$$\delta Q_{qp}^{-1} = \chi_{qp} Q_i^{-1} = \frac{\alpha S_1(\omega)}{2N_0\Delta_0} n_{qp} \tag{4.45}$$

Finally, combining Equation 4.30 with Equations 4.22, 4.41, 4.44, and 4.45 yields a relationship between $\delta S_{21}$ and $\delta n_{qp}$:

$$\delta S_{21}(f) = \frac{1}{4} \chi_c \chi_g \chi_{qp} e^{-2j\phi_g} [1 + j\beta(\omega)] \frac{\delta n_{qp}}{n_{qp}} + je^{-2j\phi_g} \chi_c \chi_g Q_i \delta x_{TLS} + \delta S_a(f) \tag{4.46}$$
Now, all that’s left to do is to use equation 4.36 to insert the relation between incident power and quasiparticle density.

\[
\delta S_{21}(f) = \frac{1}{4} \chi_c \chi_g \chi_{qp} e^{-2j\phi_g} [1 + j\beta(\omega)] \frac{\eta_0 \tau_{qp}}{\Delta_0 N_{qp}} \delta P_0 + j e^{-2j\phi_g} \frac{\chi_c \chi_g}{2} Q_i \delta \chi_{TLS} + \delta S_a(f)
\]

(4.47)

Splitting this equation into its real and imaginary parts yields the responsivities in the frequency and dissipation directions:

\[
\frac{\text{Re}(\delta S_{21})}{\delta P_0} = \frac{\eta_0 \chi_c \chi_{qp} \tau_{qp}}{4 N_{qp} \Delta_0} \quad (4.48)
\]

\[
\frac{\text{Im}(\delta S_{21})}{\delta P_0} = \frac{\beta(\omega) \eta_0 \chi_c \chi_{qp} \tau_{qp}}{4 N_{qp} \Delta_0} \quad (4.49)
\]

This means that the responsivity in the frequency direction is a factor of \(\beta\) larger than the response in the dissipation direction. This makes a readout system that measures the frequency direction the better choice, assuming that the TLS noise is sub-dominant. It will be shown in Chapter 5 that appropriate steps were taken to meet this goal.

4.2.4 Resonator Sensitivity

In order to calculate the sensitivity of an MKID, all of the potential sources of noise will need to be considered and if possible, determined to be sub-dominant. The first source of noise to be considered is the photon noise equivalent power. \(NEP_{ph}\) is expressed in the shot noise limit [131]:

\[
NEP_{ph}^2 = 2P_0 h f (1 + n_0)
\]

(4.50)
where \( n_0 \) is the occupation number and is shown in Appendix A to be approximately zero. The amplifier contribution to \( NEP_{freq} \) is given by:

\[
NEP_{amp} = \sqrt{\frac{k_b T_{amp}}{P_{amp}}} \frac{\delta P_0}{\text{Im}(\delta S_{21})} = \frac{4 n_{qp} V \Delta_0}{\beta \eta_0 \chi_{qp} \tau_{qp}} \sqrt{\frac{k_b T_{amp}}{2 P_{amp}}} \quad (4.51)
\]

Where \( P_{amp} \) is the input microwave power and \( T_{amp} \) is the effective noise temperature of the amplifier. For the SiGe amplifiers used in BLAST-TNG, \( T_{amp} \sim 2 \text{ K} \). Next, the \( NEP_{TLS} \), derived in [86] from the fractional frequency responsivity and TLS spectral density, is given by:

\[
NEP^2_{TLS} = \frac{8 n_{qp}^2 V^2 \Delta_0^2 Q_i^2}{\beta^2 \eta_0^2 \chi_{qp}^2 \tau_{qp}^2} S_{TLS} \quad (4.52)
\]

Two more sources of noise arise from the random thermal generation of quasiparticles and the random recombination of quasiparticles \( NEP_{g-r} \) [131]. This generation-recombination noise will not be a significant source since \( hf \ll \Delta \).

Combining all these terms yields an expression for the \( NEP \) in the frequency direction:

\[
NEP^2_{freq} = 2 P_{opt} h \nu (1 + n_0) + NEP^2_{g-r} + \frac{8 n_{qp}^2 V^2 \Delta_0^2}{\beta^2 \eta_0^2 \chi_{qp}^2 \tau_{qp}^2} \frac{k_B T_{amp}}{P_{amp}} + \frac{8 n_{qp}^2 V^2 \Delta_0^2 Q_i^2}{\beta^2 \eta_0^2 \chi_{qp}^2 \tau_{qp}^2} S_{TLS} \quad (4.53)
\]

The \( NEP \) model will significantly aid in the design of the BLAST-TNG MKID detectors in the next chapter.
Chapter 5

BLAST-TNG MKID Design

5.1 General Design Considerations

The BLAST-TNG general design concept is to build horn-coupled, polarization sensitive, background-limited MKID detector arrays with 30% fractional bandwidth at 250, 350, and 500 µm wavelengths. The benefits of horn-coupling the MKIDs are two fold. First, the light can be funneled into the inductor, which is the portion of the resonator with the largest responsivity. Second, since our horns are spaced by $2f \lambda$, or 2.5, 3.5, and 5.0 mm, there is ample room to incorporate a very large area capacitor. This allows us to minimize the potential effects of TLS noise, a source of excess noise in MKIDs that scales as $|\vec{E}|^3$ [42]. Another benefit of large capacitors is the ability to design low resonant frequency MKIDs [110]. Recall that in Equation 4.53 the TLS noise term is inversely proportional to $\beta = \delta \sigma_2 / \delta \sigma_1 \approx 2kT/hf$. A reduction in resonant frequency should lead to further lowering the TLS noise level. Finally, since the digitization bandwidth of the readout electronics is a fixed 512 MHz, and the detector spacing is fixed to 10 times the resonator bandwidth to minimize collisions and electrical crosstalk, lowering the resonant frequencies increases the multiplexing
density. This multiplexing density can be written as

$$\frac{det}{ch} = \frac{BW_{ADC}}{10 * BW_{mkid}} = \frac{512 MHz}{10 * f_r/Q_r}, \quad (5.1)$$

and detector design with $Q_r \sim 30,000$ and $f_r \sim 1$ GHz, yields up to 1,500 detectors per readout channel. Therefore, low resonant frequency MKIDs with large area capacitors are the ideal starting design for BLAST-TNG.

### 5.2 Material Selection

Another choice that is required when designing an MKID is the material used to construct them. Most previous MKID arrays have been constructed from aluminum films [46, 14], which has a narrow $T_c$ range $\sim 1.2$ K. Al devices are well studied and their performance is well modeled. Recently, several experiments have built arrays using TiN [111, 106, 77]. This is due to the fact that the kinetic inductance is much higher compared to aluminum, which increases the responsivity of the detector, and they are low loss [67, 121], which allows for higher internal quality factors. Finally, the $T_c$ is tunable over a wider range (0.7-4.5 K) [67] than Al. Previously, tuning the $T_c$ of TiN films was accomplished by adjusting the nitrogen content during deposition, but there are problems achieving a uniform $T_c$ over a large wafer. This would prove to be a challenge for developing BLAST-TNG’s detector arrays. Fortunately, a Ti/TiN multilayer film has been developed that tunes the $T_c$ between 0.8-2.5 K by using the proximity effect [120]. These films have shown uniformity in $T_c$ to within 10 mK across a 75 mm wafer, allowing us to reliably tune both $T_c$ and film thickness by changing the number and thicknesses of the Ti/TiN layers.

Maximizing the optical coupling of the detectors requires the sheet impedance of
Figure 5.1: Room Temperature VNA Measurements of TiN in WR10 waveguide, compared to simulations and bare silicon. The results show > 80% absorption over the entire 30% band. Since RRR ∼ 1, these measurements should be valid at 270 mK as well.

the light absorbing inductor \( R_{s,eff} = R_{s,TiN}w/a \), where \( w \) and \( a \) are the width of the inductor and waveguide respectively) to match the impedance of the waveguide \( Z_{wg} = 377\Omega/\sqrt{1 - (f_c/f)^2} \approx 700 \, \Omega \) for 250µm, where \( f_c \) is the waveguide cutoff).

If the inductor geometry is set by other factors, the surface impedance can be tuned by changing the thickness by increasing or decreasing the number of Ti/TiN bilayers in the film. Since the residual resistivity ratio (RRR) of TiN ∼ 1, the waveguide-coupled TiN absorption can be determined at room temperature [60]. A prototype of the inductor design scaled to W-band (65-110 GHz) was fabricated, and the reflection parameter, \( S_{11}^2 \), was measured using a mm-wave vector network analyzer. Any \( S_{11}^2 < 1 \) is interpreted as absorption by the device. The results, compared to simulations and bare silicon, are shown in Figure 5.1. The results show > 80% absorption over the entire 30% band, enabling work to proceed on detector development.
5.3 Single Polarization Prototypes

After the optical coupling method was verified, 250 µm prototype arrays were developed and fabricated. Figure 5.2 shows the detector design, coupling cross-section, and package. These detectors are patterned from a 4/10/4 nm thick trilayer film of TiN/Ti/TiN, with a $T_c = 1.4$ K, which is grown on a silicon-on-insulator (SOI) wafer. The device layer, which defines the $\lambda/4$ backshort thickness, is 18 µm. This design, shown in Figure 5.2b, consists of five $f_r \sim 1$ GHz lumped-element style resonators, which features an interdigitated capacitor (IDC) in parallel with a single turn inductor. The IDC has a 5 µm finger and spacing widths with a total area of 0.9 mm$^2$, and the inductor is 8 µm wide with a total volume of 86 µm$^3$. These resonators are capacitively coupled to a 50Ω microstrip feedline which goes across the middle of the wafer. These devices have a measured $Q$ between 200,000-400,000 at $T = 75$ mK, and $Q_c \sim 30,000$. This $Q$ will be significantly reduced at the BLAST-TNG 270 mK operating temperature.

In this detector design, the inductor element of the $LC$ circuit also acts as the light absorbing element, and only absorbs light along its long axis. The detector is located $\sim 50\mu$m below the 200 µm diameter waveguide output of the feedhorn. The horns are a three step modified Potter horn, shown in Figure 6.3a, that has been designed for minimized beam asymmetries while achieving a 30% fractional bandwidth [98][130]. The sheet impedance is matched to the waveguide impedance, via the process mentioned in Section 5.2. In this design, only one polarization is fabricated in each spatial pixel to ease in fabrication and testing. The sample holder exhibits 10 µm alignment precision, which is defined by dowel pins and machining tolerance. The sample holder indexes the detectors to the feedhorn via two aluminum ‘bumpers’, which push the wafer into place while the package shrinks as it cools down.
Figure 5.2: The 250 µm Detector Prototype and Coupling Scheme. a) A photograph of the 5 pixel prototype array mounted in the sample holder with the feedhorn array above. Only five of the seven horns are populated with detectors. b) The prototype detector array design shows that the microstrip feedline couples to detectors. The gray box indicates where the backside silicon is etched away from the SOI wafer and metalized with niobium to produce a backshort. c) A enlarged view features a dotted circle which denotes the exit aperture of the feedhorn’s waveguide portion. d) A cross-section (not to scale) of the optical coupling scheme.

To ensure good optical coupling to the detectors, a λ/4 backshort is placed behind the inductor and capacitor. This is accomplished by deep reactive ion etching away the handle wafer up to the buried oxide layer of the SOI wafer. This produces a 19 µm thick silicon membrane, set by the device wafer thickness. The oxide beneath the inductor and capacitor is then removed with a CHF₃/O₂ plasma etch. A 500 nm thick layer of niobium is then deposited on the entire backside of the wafer by RF sputter deposition to create both the reflective backshort and a continuous ground plane.

The detector package is mounted to the 50 mK temperature-controlled stage of a Model 102 Denali pulse tube-backed Adiabatic Demagnetization Refrigerator (ADR) cryostat. A blackbody source, which is constructed out of the same THz tessellating tiles used for the chopper in Section 3.2.2 is placed directly in front of the detector.

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1High Precision Devices, Inc. 1668 Valtec Lane, Suite C Boulder Colorado 80301
package. The tile is epoxied into a copper housing which is weakly thermally linked to the 3 K stage of the cryostat. The load is able to be tuned to any temperature between 3 K and 25 K to $\sim 1$ mK stability by the use of a heater and calibrated thermometer.

The optical passband of the detectors is defined on the low frequency end by the 1 THz waveguide cutoff of the feedhorns. For the high frequency end, we utilized the 1.4 THz low-pass filter that was used for the BLASTPol 250 $\mu$m detector array [2]. This low-pass filter is mounted directly to the front of the feedhorns, and has the added benefit of having a well-characterized transmission profile [91]. The calculated in-band power emitted from the load is,

$$P_{BB} = \int_{\nu_1}^{\nu_2} d\nu \left( \frac{c}{\nu} \right)^2 B(\nu, T) F(\nu),$$

where it is assumed that the throughput is single-moded ($A\Omega = \lambda^2$). $B(\nu, T)$ is the Planck equation, and $F(\nu)$ is the filter’s measured transmission profile. This filter is known to have harmonic leaks at high frequencies above the cut-off [2], but the integrated power above the passband is $< 2\%$ of the total in-band power for any blackbody temperature used.

A homodyne setup, which is a type of single tone MKID readout system, is used to perform a frequency sweep and noise characterization at $P_{BB} = 5$ fW to 21 pW at $T_{Bath} = 75$ mK. The complex transmission, $S_{21}(f)$, obtained from the frequency sweep is used to fit $f_r$ as a function of optical load. This response is shown in Figure 5.3a.

At each temperature the thermal load is set to, the noise is measured at the microwave frequency that maximizes $\delta S_{21}/\delta f$. To avoid nonlinear response, the probe tone power is $\sim -85$ dBm, or about 13 dB below where the resonator becomes bifur-
Figure 5.3: a) Resonant frequency versus blackbody power. Note that the slope is linear with increasing power. b) Noise spectra taken with 5-21 K blackbody loads taken with $T_{bath} = 75$ mK. The solid lines are fits to a Lorentzian model developed by [61]. c) The blue points show the low frequency noise converted to a NEP via the responsivity. The red dashed line is the expected photon noise NEP. The black is the best fit NEP model developed by [61].

cated [109, 131]. The raw in-phase ($I$) and Quadrature ($Q$) data from the analog-to-digital converters (ADCs) is projected into the frequency and dissipation quadratures, and the noise is analyzed in the frequency quadrature. Some of the spectra from this analysis is shown in Figure 5.3b. The amplifier noise limit is seen above 100 kHz. Above 1 pW of optical load, the quasiparticle lifetime scales as $\tau \sim P^{-0.5}$, as expected in photon dominated limit of quasiparticle generation [24]. Just as is performed in [61], the spectra are fit to a Lorentzian function of white noise level $A$ and time constant $\tau$, associated with quasiparticle recombination, that is summed with an amplifier limiting background noise floor $B$, which is used with the responsivity to determine the measured $NEP$:

$$S_{\delta f/\delta f}(\omega) = \frac{A}{1 + \omega^2 \tau^2} + B$$  \hspace{1cm} (5.3)

$$NEP_m = \sqrt{\frac{A + B}{\delta f/\delta P}}$$  \hspace{1cm} (5.4)

These values are plotted as a function of blackbody power in Figure 5.3c. The red dashed line is the predicted photon noise which is calculated using Equation 5.2 with
\( \nu = 1.2 \text{ THz and } m < 0.1 \). At powers above 1 pW, the \( \text{NEP} \) scales as \( \sqrt{P} \), and the data matches the line which are both indicators of photon-noise limited sensitivity. The black dashed line in Figure 5.3: is the full noise model:

\[
\text{NEP}_m^2 = \text{NEP}_\alpha^2 + \frac{\text{NEP}_{\text{photon}}^2 + \text{NEP}_{\text{GR}}^2}{\eta_{\text{opt}}}
\]  

Where \( \text{NEP}_\alpha^2 \) is a constant noise term that is independent of \( P \). \( \text{NEP}_{\text{GR}}^2 \) is the noise contribution from quasiparticle generation-recombination, and \( \eta_{\text{opt}} \) is the single-polarization optical efficiency. This model is fit to the data in order to determine the single-polarization optical efficiency, which yields \( \eta_{\text{opt}} = 0.94 \). This is much higher than the optical efficiency expected from simulations. However, since the load is unpolarized, the detector could be absorbing light from the other polarization. HFSS simulations suggest a cross-polar coupling of 16% for this absorber design. When accounting for the cross-polar coupling, the co-polar coupling is reduced to a more reasonable 78%, which agrees with HFSS.

In order to verify the co-polar and cross-polar coupling, the old BLASTPol filter stack was installed into the ADR cryostat and the detector array was oriented so that light from outside the cryostat is coupled to the feedhorns. The polarization efficiency tests, described in Section 3.2.3 were performed. The data was normalized to the maximum response, and the results are shown in Figure 5.4. Multiplying the normalized cross-polar coupling of \( \sim 22\% \) by the fitted 78\% absolute co-polar coupling yields an absolute cross-polar coupling of 17\%, which agrees very well with the High Frequency Electromagnetic Field Simulation (HFSS)\(^2\).

\(^2\)ANSYS, Inc. 2600 ANSYS Drive Canonsburg, PA 15317

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5.4 Dual-Polarization Optimized Prototypes

Now that the detector design produces background-limited performance above 1 pW of optical loading, the next step is to improve the absorber design, and introduce the second detector in the same spatial pixel to construct a well-performing polarimeter.

In order to reduce the cross-polar coupling in the previous design, the inductor width must be significantly reduced. However, this will reduce the sheet impedance. By changing the TiN/Ti/TiN trilayer film to stacking a number of TiN/Ti bilayers, the same sheet resistance can be maintained without altering $T_c$. The TiN(Ti) thickness is 4(10) nm, which sets $T_c=1.35$ K. Four bilayers are stacked with the addition of a protective TiN cap layer, which produces $R_s = 20 \ \Omega/\square$ and $L_s = 22.5 \ \mu\text{H}/\square$. The TiN/Ti multilayer effectively reduces the sheet impedance by a factor of four as compared to the TiN/Ti/TiN trilayer films used for the single-pol devices.
in the previous section. This allows for a reduction of the absorber width by a factor of four in the new dual-polarization devices, which is critical to minimize their cross-polar coupling.

Fig. 5.5 shows the photolithography mask design used to produce dual-polarization-sensitive MKIDs from these films. There are two MKIDs per spatial pixel, one per linear polarization. Each MKID contains a 5 \( \mu m \) finger/gap interdigitated capacitor of total area 0.68 mm\(^2\) and a 3.2 \( \mu m \) wide inductor that spans the length of the 180 \( \mu m \) wide waveguide diameter for a total volume of 154 \( \mu m^3 \) and 230 \( \mu m^3 \) for the X and Y inductors, respectively. This combination of \( L \) and \( C \) produces resonance frequencies near \( f_r \sim 1 \) GHz. Each MKID couples to a 340 \( \mu m \) wide microstrip transmission line (the silicon wafer is the dielectric and the device box is the ground plane) via an interdigitated coupling finger of designed \( Q_c \sim 40000-50000 \).

The two inductors within a pixel are orthogonally aligned in order to obtain dual-polarization-sensitivity. By making the Y-polarization inductor discontinuous, both MKIDs are defined in one device layer without requiring electrical cross-overs. In electro-magnetic simulations of a simplified model of just the antennas, the inherent asymmetry of the design produces a band averaged (1-1.4 THz) co-polar coupling of 79 (75)% in the continuous (discontinuous) absorbing inductor. These simulations also suggest the expected cross-polar coupling to be <2%, but if the vacuum gap between the wafer and the feedhorn/waveguide becomes too large, other structures in the detector design could begin to produce an additional cross-pol contribution.

Five-pixel prototype arrays have been fabricated on a 2\( f \lambda \) (2.5 mm) detector pitch. The array couples to the same matching array of aluminum, direct-machined feedhorns that were used for the single polarization detector tests. However, a waveguide choke has been machined into the backside of the feedhorn array to improve opti-
Figure 5.5: Detector Design. Left: An overview of a single pixel. The microstrip feedline at the top of the figure is capacitively coupled to the two X and Y polarization lumped-element MKIDs. The large interdigitated capacitor comprises the majority of the MKID. The 180 $\mu$m diameter waveguide which illuminates the inductors is depicted by the shadowed circular region. Right: A magnification of the inductive meanders which act as the polarization-sensitive absorbers. The two 3.2 $\mu$m thick inductors are non-intersecting with the Y polarization detector ending 2 $\mu$m before intersecting the X polarization detector.

cal coupling and minimize crosstalk. In an identical setup to the single-polarization devices, the 1.0 THz low edge of the band is defined by waveguide. A quasi-optical low-pass filter mounts in front of the feedhorns, which defines the 1.4 THz high edge of the passband \[2\]. The detector package is again mounted to the cold stage of an ADR and is operated at 100 mK in the measurements described below.

5.4.1 Polarization Response and Passbands

Polarization characterization was performed on the prototype array described in Section 5.4 in a cryostat that is optically coupled to the room with appropriate quasi-optical filtering. In addition, a 1.8 mm thick piece of eccosorb MF-110 microwave absorber was installed as a neutral density filter (NDF) to decrease the optical loading on the detectors, ensuring their operability when viewing a 300 K thermal load. The optical setup is shown in a cross-section of the ADR cryostat in Figure 5.6. The microwave absorber has an anti-reflective coating and has a calculated band-averaged
transmission of 0.93%. The detectors are coupled to a 1050 C to 20 C chopped thermal source that underfills the beam of the feedhorns. A rotatable wire grid polarizer which has an induced cross-pol of less than 0.5% is placed between the chopped source and the cryostat window. We determine the polarization properties by measuring the amplitude of the response of the detectors as a function of the angular position of the polarizer. The result produces a sinusoidal signal, shown in Fig. 5.7. We determine the cross-polar coupling, or the minimum of the amplitude response, by fitting the data to a sine wave. The results of the fit suggests the detector cross-polar coupling is 2.6% and 2.8% for the X and Y polarizations, respectively. However, these values are most likely an upper limit as the fit lies above the minimum data points (1.7% and 1.9% for X and Y, respectively). Regardless, the result is consistent within the uncertainty of the HFSS simulations for this pixel geometry, and is an improvement over the 11% cross-polar coupling measured for BLASTPol [89].

The detector passbands are measured, in method similar to that described in Sec-
Figure 5.7: Polarization Efficiency Graph. The data points are the amplitudes of the chopped signal at each input polarization angle, normalized to the peak signal, while the lines are a fit to the data. The resulting cross-polar coupling is at most 2.6% and 2.8% for the X and Y polarization detectors, respectively.

By use of a Fourier Transform Spectrometer (FTS) which was purged with nitrogen gas to minimize atmospheric attenuation. The FTS is coupled to the same 1050°C thermal source used in the polarization measurements. In this configuration, the source fills the beam and is no longer chopped, and the input polarizer is removed. The bandpasses for each X and Y polarization detector are averaged over multiple FTS scans to reduce spectral noise, and the result is shown in Fig. 5.8. While the cut-off frequency (1.4 THz), which is defined by the low-pass filter, is uniform, there is a clear difference in cut-on frequencies between the two detector polarizations. The X polarization cut-on is 1054.1 GHz, while the Y polarization cut-on is 1033.7 GHz. This 20.4 GHz discrepancy in the low frequency edge in Figure 5.8 is likely due to a slightly oval-shaped waveguide (3.55 microns larger in Y-pol than X-pol), which is produced by using a standard twist drill bit. To address this problem on the full scale feedhorn array, the waveguides will be undercut and reamed to produce a uniform
Figure 5.8: Detector Bandpasses. The X and Y polarization bandpasses, averaged over multiple FTS measurements, are corrected for the spectral slope in the transmission of the microwave absorbing filter. The uniform high frequency cutoff is defined by a low-pass filter mounted directly on top of the feedhorns. The low frequency cutoff is defined by the feedhorn waveguide diameter. The non-uniformity in X and Y polarization detectors is due to the slight ellipticity in the waveguide due to machining techniques and will be addressed in the full-scale feedhorn array.

circle at the desired waveguide diameter.

5.4.2 Responsivity and Noise Verification

We determine the sensitivity to thermal radiation by coupling the detectors to a beam-filling temperature-controlled blackbody load. The measurement approach is the same used with the single polarization devices in Section 5.3. While the detectors were held at a bath temperature of 100 mK, the frequency noise and detector response was measured as a function of blackbody temperature 3 K to 22 K. The previous trilayer films [61] as well as other devices fabricated from TiN [79, 86] show a near linear responsivity to photon load. The same phenomenon is observed in these multilayer films, as shown in Figure 5.9. The device responsivity ranges from -20 to
Figure 5.9: Detector Responsivity and Sensitivity. The horizontal axis of both plots is power emitted from the blackbody load, which is calculated based on the temperature of the blackbody load using the Planck function and assuming single-mode, single-polarization coupling from 1.0-1.4 THz. Left: A sample of responsivities from the 5 pixel prototype array. These devices show a near linear responsivity to photon load. Right: The noise equivalent power (NEP) of the detectors at a range of blackbody temperatures from 3 K-22 K. The blue points are noise data taken at increasing blackbody temperatures, while the dashed line is the blackbody’s expected NEP. The black curve is a fit to the NEP of the detector which is used to calculate and optical coupling efficiency of $\sim 75\%$. The expected photon noise of the instrument for the 250$\mu$m array is shown as the blue bar at 13.8 pW.

-24 ppm/pW for a sample of MKIDs in the 5-pixel array. The frequency noise of the detector taken at each temperature step is converted to an NEP by utilizing the local slope of the detector responsivities in Figure 5.9. The results are again fitted using Equation 5.5. The fit suggests that the detector optical coupling efficiency is $\sim 75\%$, which agrees with simulations. These results also confirm that the multilayer films demonstrate the same photon noise limited sensitivity seen previously in the devices made with the trilayer film.

**Implications of Linear Responsivity**

While our TiN MKIDs follow the relations derived from Mattis-Bardeen theory [76] to 1st order, they exhibit some anomalous behavior under optical load [71 61 28].

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For MKIDs constructed from conventional materials, such as Al, the responsivity should roll off at higher optical powers. This is due to the fact that the quasiparticle lifetime is proportional to the quasiparticle density. However, the linear responsivity measured in TiN MKIDs suggests that either the responsivity is independent of the quasiparticle lifetime, or the quasiparticle lifetime is independent of the quasiparticle density. One current theory is that higher bath temperatures or optical powers causes an intrinsic disorder-induced change in the superconducting state, which broadens the quasiparticle density of states \[31\]. Another complementary theory \[12\] suggests that the disorder causes the superconducting energy gap $\Delta$ to vary slightly throughout the material. The effect of this is that at lower bath temperatures or optical powers, the quasiparticles become trapped in the high $\Delta$ pockets, which artificially lowers $\tau_{qp}$. However, as the temperature or power increases, these pockets fill and the quasiparticles become free to move and the material will start to behave as predicted by Mattis-Bardeen. They estimate that the root mean square of the variation of the gap to be $\approx 44 \mu eV \ [12]$. These are promising theories but it is still an area of active research.

**Low Frequency Noise**

Since BLAST-TNG is a polarization mapping experiment with a stepped HWP, the stability requirements of the detectors is determined by both the scan speed (which also determines the readout rate) and the length of the scan. For a 10° wide scan at 0.2° per second, the detectors must be stable to $> 0.01$ Hz. Unfortunately, current blackbody load low frequency noise analysis suggests that there is considerable $1/f$ noise below 1-2 Hz. However, the low frequency noise measurements were all taken with the homodyne setup. Since the blackbody load is not in the Rayleigh-Jeans
limit, any small temperature fluctuation will result in a large signal variation. This could potentially cause a large $1/f$ noise contribution. In addition, fluctuations in the bath temperature and readout noise can both contribute to the $1/f$ noise. These noise sources are the same in all of the detectors, allowing for common-mode subtraction techniques [85] to be used, provided all the detectors are read out simultaneously. By using the multiplexing readout electronics discussed in Chapter 7, we can monitor all of the detectors on the array simultaneously, allowing for common-mode subtraction of bath temperature fluctuations (from dark detectors), potential readout noise (from off-resonance tones), and blackbody load fluctuations (from light detectors). This technique was demonstrated in the dark at NIST earlier this year, and the results are shown in Figure 5.10. By using a common-mode subtraction technique, the $1/f$ knee can potentially be moved to $\sim 0.05 \text{ Hz}$. This would still require a faster scan speed, and is yet to be verified on the detectors at the expected optical loading. In addition, it may be shown that trapped magnetic flux in the detectors causes some noise degradation as well. This may be counteracted by magnetic shielding or using a nulling coil during cooling through $T_c$. This is all still an area of active research and will hopefully be completed soon.

5.5 Full Scale Arrays

Transitioning the working 250 $\mu \text{m}$ dual-polarization detector prototypes to full-scale arrays for installation in the BLAST-TNG receiver is not a straightforward task. There are many issues to account for when fabricating a full-scale array. One of the largest issues is keeping a 100 mm diameter wafer at the lowest cryogenic temperature possible. This is accomplished by gold plating the entire backing structure of the Focal
Figure 5.10: Common mode subtraction in the dark at 100 mK bath temperature using the BLAST-TNG multiplexing readout electronics. The red line is the detector’s raw spectra, while the green line is the noise from the readout electronics. The gray line is the detector noise after common-mode subtraction. The $1/f$ knee moves to roughly 0.05 Hz.

Plane Array (FPA), which is discussed in detail in Chapter 6. In addition a perimeter of gold is patterned along the bare edges of the wafer, enabling a number of gold wirebonds to be made between the wafer and the backing structure. This substantially increases the conductivity between the wafer and the backing structure. The $T_c$ of the detectors is raised from 1.35 K to 1.6 K in order to accommodate the higher operating temperature of $T_{Bath} = 270$ mK. Another challenge lies in designing the resonant frequency of each detector to minimize electrical crosstalk. First, separating the resonant frequencies of the detectors by 10 times the resonator bandwidth ensures that the electrical crosstalk from adjacent resonant frequencies is $<-20$ dB. However, since $BW = f_r/Q$, the minimum frequency spacing between resonators increases as their resonant frequencies increase. Another potential source of crosstalk is between the two resonators in the same spatial pixel. The array is designed to space the
Figure 5.11: Left: The design for the 250 µm pixel design in unit cell form. This cell is patterned identically along feedline to populate an entire rhombus. The IDC fingers are then trimmed to set the detector’s unique resonant frequency. Both X and Y polarization detectors have the same arc on the exterior of the absorber to maintain identical inductances. Right: A detector Rhombus made of 306 pixel cells. The full 250 µm array consists of three identical rhombuses that are rotated 120 degrees from each other. These design considerations significantly minimize complexities in the fabrication.

resonators that occupy the same spatial pixel by ~250 MHz. This is accomplished by setting the resonant frequencies of all X polarization detectors from 750 MHz to 1.0 GHz, while the Y polarization detectors are set between 1.0 GHz to 1.25 GHz. From pixel to pixel, the X detectors increase in frequency while the Y detectors decrease, maintaining a space of ~250 MHz. Finally, an inductor arc around the perimeter of the waveguide is added to the X polarization detector, ensuring that every resonator has the exact same inductance (see Figure 5.11).

In order to significantly reduce the complexities of array fabrication, two major techniques were used. First, since the detector count for the 250 µm array exceed the current capabilities of the ROACH2 readout system, the array was split into three identical 306 pixel rhombuses, rotated 120 degrees with respect to each other. This drastically reduces the burden of the array design. In addition, each rhombus is built up from identical pixel unit cells with fully extended IDCs. When patterning the
Figure 5.12: The 250, 350 and 500 $\mu$m full scale detector array layouts (from left to right). While the 250 $\mu$m array has been fabricated and installed in the BLAST-TNG receiver, the 350 and 500 $\mu$m arrays are still in a state of active development. Since the 350 and 500 $\mu$m arrays can be read out on a single readout channel, the rhombus strategy is not used. Note the features for the hole and slot for the alignment pins, as well as the gold pads on the perimeter to aid in thermal conductivity to the FPA backing structure.

The frequencies span a factor of 2, meaning the highest frequency resonator has only one quarter of the original IDC fingers remaining ($f_r \propto [\text{IDC fingers}]^2$). The pixel unit cell and rhombus are shown in Figure 5.11 and the layouts for the full arrays are shown in Figure 5.12. The 350 and 500 $\mu$m detector arrays are read out on one readout channel and do not utilize the rhombus strategy. However, they are both still built using a pixel unit cell that is scaled to the appropriate size for their longer wavelength incident radiation. These arrays also have another pixel unit cell designed that has the X and Y orientations rotated by 45 degrees. These two designs are alternated for every other pixel, ensuring that the receiver can still sample both Stokes Q and U, should a problem arise with the HWP. The 350 and 500 $\mu$m array designs are nearing completion, and are slated to be installed in the BLAST-TNG receiver by the end of 2016.
Chapter 6

Focal Plane Arrays

6.1 Overview

The detectors are mounted and housed in a focal plane array (FPA), which is an 8-sided polygonal structure (shown in Figure 6.1). The FPA must provide a method to align the detectors to the feedhorns, couple the RF lines to the wafer, and heat sink it to the 270 mK $^3$He absorption refrigerator while providing a thermally isolated mounting point to the 4 K optics bench. This chapter details the development of the FPAs, which is split into the construction of the backing structure, the feedhorn arrays, and the CFRP support structure.

6.2 Backing Structure

The backing structure is an aluminum octagonal block that features a 0.187” thick rim for mounting the thermal standoff and SMA feedthrough connections to the sides. The feedhorn array mounts to the top of this rim. The backing structure is gold plated to allow for gold wirebonds to be made directly to the structure and
Figure 6.1: Focal Plane Array (FPA) design and assembly. Left: A rendering of the FPA in its two-stage CFRP thermal standoff. The lower ring sits at 1 K and provides a mount point for the DC blocks and 20 dB attenuators while the FPA sits at 270 mK. Right: An exploded view of the FPA. The detector wafer is mounted directly to the holder, and is fixed in X/Y via a pin and slot method, and in Z via several beryllium copper spring tabs. The feedhorns are mounted on top, as well as a bandpass filter.

to maximize thermal conductivity. The plating is done without a zinc seed layer to minimize stray magnetic fields. The heat strap to the 300 mK absorption fridge is attached directly to the center of back side of the backing structure. This ensures that the FPA is radially cooled from the center to minimize trapped flux in the detectors.

The detector wafer is mounted inside the backing structure via a pin-and-slot method to constrain the detectors in X/Y. The alignment concept is shown in Figure 6.2. When the FPA is warm, the detector wafer sits offset by 178 µm from the center of the FPA. As the FPA cools down, due to the differential thermal contraction of the aluminum, the wafer is pushed towards the center of the FPA via the close fit pin. The contraction equation from 300 K to 270 mK for silicon is \(\sim 0\), while for aluminum, it’s \(\delta l/l = -4154.5 \times 10^{-6}\). Once cold, the centers of the FPA backing structure, feedhorn array, and detector wafer are all aligned. To fix the Z dimension, the wafer is held down via a set of beryllium copper spring tabs. The detector wafer is oversized to
Figure 6.2: The FPA pin-and-slot alignment technique. Due to the fact that aluminum and silicon have different coefficients of thermal contraction, an alignment technique must be used to control for the aluminum contracting more than the silicon. Left is the FPA and wafer at 300 K. The center of the wafer (black index) is intentionally offset 178 μm from the center of the FPA (orange index) in the radial direction between the close fit and slotted pins. The slotted pin starts at the outer edge of the slot. As the array contracts during cooling, the close fit pin pushes the silicon wafer towards the center of the FPA, while the slotted pin contracts towards the center. On the right is the alignment once the contraction ends and the FPA and wafer are cold. The two indices are aligned and the slotted pin is at the inside edge of the slot.

allow for aluminum wirebonds to the microstrip feedlines, as well as gold heat-sinking wirebonds. The wirebonds are made to increase the thermal conductivity to the wafer and help keep the detectors cold. Next, as shown in Figure 6.1, the feedhorn array attaches to the outer rim of the backplate and is constrained via the same close-fit pins that index the detector wafer. Finally, a bandpass filter that defines the high frequency cutoff of the band is attached directly on top of the entrance aperture of the feeds.
Figure 6.3: a & d) The feedhorn profile and choke design. b) A zoom-in shows the circular photonic choke that is embossed from the feedhorn c), as well as the air gap between the exit aperture and the face of the array. The parameters for d) are shown in Table 6.3.

6.3 Feedhorns

Optical coupling to the front side of the detectors is achieved via an aluminum feedhorn array. The previous BLASTPol feedhorns were the conical *Herschel* SPIRE feedhorn design [17]. These feedhorns have an asymmetry in X and Y polarizations due to the difference in the E and H fields. This beam asymmetry was a source of cross-polarization in BLASTPol. Therefore, a 3-step modified Potter horn was designed that minimized beam asymmetries and still maintains a 30% bandwidth [98, 130]. The horn profile is shown in Figure 6.3d. The beam profile was measured at both Cardiff and NIST and agrees well with HFSS simulations. The Cardiff results from September 2014 compared to HFSS simulations are shown in Figure 6.4.
Table 6.1: Feedhorn and Choke Parameters

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</tbody>
</table>

Figure 6.4: The response, measured at Cardiff in September 2014, from 840 - 1050 GHz with an inherent 2 degree offset in the measurement setup. This represents a lower frequency than the BLAST band and the horn design which is from 1000 - 1350 GHz. Below 1000 GHz, the horn has more asymmetry and sidelobes than in band and the simulation matches the measurement. Both the FWHM and Sidelobes agree with the HFSS simulation.
The feedhorns arrays, shown in Figure 6.6, are achieved via a set of custom-made profiled drill bits. The set of roughing feed drill bits machine the majority of the profile, while a finishing set of bits completes the last several microns to ensure a uniform, smooth profile across the feedhorn array. The feedhorn array is then turned over, and the waveguides are then completed by using a roughing drill coupled with finishing reamer to ensure a completely circular waveguide. A circular choke is machined around the waveguides, and the excess material is machined away, leaving cylindrical bosses [126]. This is done to ensure that the aluminum backside of the feedhorn array does not interact with the detectors.

The feedhorn array is indexed using the same two pins that index the detectors to the backing structure. However, unlike in the detector wafer, both pins are close fit into the feedhorn array. This is because there is no mismatch between the thermal contraction of the feedhorn array and the backing structure, since both are made of aluminum. In addition, the feedhorns positions are radially spaced further from the center than the detectors to account for their thermal contraction (Warm spacing is 2.50143 mm to achieve a cold $2f\lambda$ spacing of 2.5 mm). The collar of the feedhorn array is machined precisely to constrain the 15 $\mu$m gap between the surface of the detector wafer and the exit aperture of the waveguides. HFSS simulations, shown in Figure 6.5, suggest that a larger air gap will allow the optical radiation to couple to other structures, degrading the co-polar coupling and increasing the cross-polar coupling. In addition, too small of an air gap reduces co-polar coupling on the long wavelength end of the band.
Figure 6.5: HFSS simulations of the gap between the exit aperture of the waveguide section of the feedhorn and the 250 µm absorber. Left shows the co-polar and cross-polar coupling to the X-axis, or continuous absorber, at gaps of 10 and 50 µm. Right shows the same for the Y-axis, or discontinuous absorber. The gap is machined to the 15 µm optimum determined by simulations.

Figure 6.6: The 500, 350 and 250 µm feedhorn arrays. The feeds are aligned in this figure along their scan axis. The bandpass filters are mounted directly onto the face of the feedhorns via the circular 4-40 tapped hole pattern.
6.4 Thermal Isolation and Support Structure

One of the more challenging aspects of receiver design is the mounting of the detector arrays. They are required to be held at 270 mK, while also maintaining a very precise and rigid mounting position. With balloon, sounding rocket, and satellite payloads, these suspensions must also be able to withstand excessive forces and vibrations during payload delivery or retrieval. These somewhat conflicting goals create a unique engineering challenge. In the following section, I will go through the selection process for the BLAST-TNG carbon fiber reinforced plastic (CFRP) support structure.

6.4.1 Previous Design

The previous BLAST receiver employed the same support system as the SPIRE instrument on the Herschel satellite [48]. The SPIRE arrays required a high degree of thermal and vibrational isolation to both endure launch and to maximize the operational lifetime of the instrument. This resulted in the use of two pre-tensioned 3000-denier Kevlar cords to suspend the 300 mK arrays from the 2 K base structure. Since Kevlar has a high tension mechanical strength, and very low thermal conductivity, it allowed for a structure that has an expected heat load of $< 1.6 \mu W$ per array, yet has a resonant frequency of $> 200$ Hz.

While this suspension system is extremely rigid and has very little heat load, there are several disadvantages. Kevlar has a tendency to stretch out, or creep, over time. Since the Kevlar’s mechanical strength is in tension, the system must be periodically re-tensioned to counteract the creep. Also, the thermal isolation system usually applies a high tension spring system to both maximize the mechanical strength, and
counteract Kevlar’s negative coefficient of thermal expansion. These systems are often exceedingly complicated to design and construct. The new FPA design provided a great opportunity to explore other materials for the construction of the suspension system.

6.4.2 Material Selection

Since BLAST-TNG has less stringent thermal loading and vibrational dampening constraints, other alternatives to Kevlar were pursued. In the BLAST-TNG system, the detector arrays sit at 270 mK and are mounted off of the 4 K stage, with access to an additional 1 K stage. At these two temperature transitions, several materials are less conductive than others. Table 6.2 shows the conductivities, k in milliwatts per meters Kelvin, of several materials at the low and high temperatures of the system. Both graphite and Kevlar stand out as the least conductive materials. Since BLAST-TNG has a higher load tolerance than Herschel, we will select graphite over Kevlar. This will allow us to use rigid rods instead of strings in tension.

6.4.3 Current Design

The thermal standoff consists of two interlocking sets of thin-walled CFRP rods. The rods have a 0.015 inch wall thickness and are custom made and cut to our desired lengths by Clearwater Composites

\[1\quad 4429 \text{ Venture Ave. Duluth, MN 55811}\]
Figure 6.7: The differential thermal conductivity of the CFRP provided by Clearwater Composites, measured in multiple configurations and measurement setups, compared to the NIST thermal conductivity data. DR Test denotes thermal conductivity measurements performed on a CFRP sample piece at various base temperatures. Prototype test denotes thermal conductivity measurements performed on a full scale CFRP FPA support structure. Finally, graphite [128] and graphite_a [70] denote two thermal conductivity models for AGOT graphite, a “nuclear” grade petroleum coke based high-purity extruded graphite. Our measured conductivities are higher than the AGOT data due to the epoxy which is used to hold the graphite together. This data is used to fit for a simple power law conductivity, \( k = 0.0075 \cdot T^{1.2715} \), which is valid from 0.1-5 K.
The first set of eight rods are 2.45 inches long and isolate the 4 K optics box to a temperature intercept ring fixed at 0.7 K. The incoming set of SMA cables is heat sunk to the 0.7 K stage via an SMA bulkhead feedthrough. Next, a set of eight one inch long rods isolate the 1 K stage from the FPA which is cooled to 270 mK. The thermal conductivity of these CFRP rods has been measured multiple times in various configurations and measurement apparatuses, the summary of which is shown in Figure 6.7. The measurements were used to generate a power law fit to the conductivity of the rods, \( k = 0.0075 \cdot T^{1.2715} \), which is valid from 0.1-5 K and was used for all subsequent array thermal conductivity calculations. These calculations show that the load from the CFRP structure to the 270 mK and 1 K stages will be \( \sim 3 \mu W \) and \( \sim 64 \mu W \), respectively, for all three arrays. A prototype thermal standoff was constructed and the total thermal conductivity was measured. The data from that is shown as ”Prototype Test” in Figure 6.7. The results agree with previous conductivity tests of this material. With the additional loading from the RF cabling, the 270 mK and 0.7 K loads amount to \( \sim 6 \mu W \) and \( \sim 70 \mu W \), respectively, for all three arrays. Neglecting any parasitics, the \(^3\)He absorption refrigerator would have an estimated 295 hour long hold time. Finite element analysis on the carbon fiber support structure shows \(< 1 \mu m \) of deflection and a lowest-order resonant frequency of \( \sim 340 \) Hz during normal operation. This amount of thermal loading and deflection is well within our tolerances.
Figure 6.8: The CFRP support structure without the FPA installed. In this orientation, the 0.7 K ring is at the top of the Figure, and the array would face downwards.
Chapter 7

Room Temperature Multiplexing

Readout Electronics

7.1 System Requirements

The basic requirements of the readout system is that it must be able to read out the detectors at a rate determined by scan speed of the telescope and not become an additional source of noise. The system must contain five independent sets of readout channels, one each for the 350 and 500 \( \mu m \) arrays, and three for the 250 \( \mu m \) array. The detector count of the 350 \( \mu m \) array sets the most stringent multiplexing requirement, while the NEP of the 500 \( \mu m \) array sets the most stringent readout noise requirement. Finally, the entire electronics system must be able to survive in the extreme environmental conditions present during flight. The overall readout requirements for each readout channel are shown in Table 7.1.
Table 7.1: Readout System Requirements

<table>
<thead>
<tr>
<th>Array</th>
<th>250 µm</th>
<th>350 µm</th>
<th>500 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readout Channels</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of Tones per Channel</td>
<td>612</td>
<td>950</td>
<td>544</td>
</tr>
<tr>
<td>Single Tone Phase Noise Level, $S_\theta (rad/\sqrt{Hz})$</td>
<td>$2.5 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Readout Rate</td>
<td>488 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.2 Hardware Overview

The details for the readout hardware will be broken into two sections, the electronics that are used, and the ROACH Motel enclosure that houses them, manages their power requirements and incoming and outgoing signals, and regulates their temperature.

7.2.1 Electronics

The readout for BLAST-TNG is based on the Reconfigurable Open Architecture Computing Hardware (ROACH2), a digital signal processing (DSP) board produced by CASPER, the Collaboration for Astronomy Signal Processing and Research [124]. The experiment uses five ROACH2s, three for the 250 µm array and one each for the 350 and 500 µm arrays. Its purpose during flight is to produce a comb of microwave frequencies for each of the BLAST-TNG pixel arrays, perform I/Q demodulation of the sky signal, and log the I/Q data to the flight computer at data rate required by the scan speed of the telescope, which will be 488 Hz. The electronics, shown conceptually in the top of Figure 7.3 consists of a ROACH2 Virtex-6 FPGA based board coupled to a MUSIC DAC/ADC board [32] via the two ZDOK connectors. A PowerPC (PPC) running a Linux kernel is used to interface between the FPGA and a data acquisition computer (DAQ). The DAC/ADC board includes two 12-bit
550 mega-samples per second (Msps) Texas Instrument ADC chip\(^1\) and two 16-bit 1000 Msps Texas Instruments DAC chips\(^2\). Data can be streamed from the ROACH2 board through two multi-gigabit transceivers, one is connected to the PowerPC and the other is connected directly to the FPGA. The Valon two-channel external analog synthesizer\(^3\) provides the 512 MHz clock (CLK) for both the DAC/ADC board and the FPGA (which runs at 256 MHz), as well as the $\sim750$ MHz local oscillator (LO) for the external intermediate frequency (IF) system.

The IF system provides the mechanism to up and down-convert the microwave frequency comb from the baseband frequencies used by the DAC/ADC card (0-256 MHz each) to the radio frequency band (RF) where the resonant frequencies of the detectors lie (500 MHz-1.12 GHz). An IQ modulator\(^4\) combines the baseband I/Q signals output by the DACs and mixes them with the LO to up-convert to RF. In addition, an IQ demodulator\(^5\) utilizes the same LO to down-convert the RF signal from the cryostat back into the baseband I/Q signals so they may be digitized by the ADCs. There are two digital attenuators\(^6\) that are on both the output and input RF signals in order to match the amplitude of the waveforms to the optimal detector tone power and to utilize the full-scale dynamic range of the ADCs. The Valon and digital attenuators are controlled by a Beaglebone Green single board computer\(^7\). This allows either flight computer to issue commands over the Ethernet via socat\(^8\) through the Beaglebone to the Valon and digital attenuators. Finally, there is an amplifier\(^9\) on

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\(^1\)ADS54RF63, Texas Instruments Inc.  
\(^2\)DAC5681, Texas Instruments Inc.  
\(^3\)5008 Dual-Frequency Synthesizer, Valon Technology Inc. 750 Hillcrest Drive Redwood City, CA 94062  
\(^4\)AM0350A, Polyphase Microwave. 1983 Liberty Dr, Bloomington, IN 47403  
\(^5\)AD0105B, Polyphase Microwave.  
\(^6\)RUDAT-6000-30, Mini-Circuits. 13 Neptune Ave Brooklyn, NY 11235  
\(^7\)Seeed Development Limited. 1933 Davis Street, Suite 266, San Leandro, CA 94579  
\(^8\)“Netcat++” or SOcket CAT http://linux.die.net/man/1/socat  
\(^9\)ZKL-1R5+, Mini-Circuits.
Table 7.2: ROACH2 power dissipation shown by largest contributors and displayed in Watts. The FPGA dissipates as much as the rest of the ROACH2 board combined.

the RF input which also helps optimize the signal for the full scale dynamic range of the ADCs.

### 7.2.2 ROACH2 Motel

The ROACH2 Motel is an enclosure that contains five sets of readout electronics. The ROACH2 Motel must distribute power to all of the various RF and electronic components listed in 7.2.1 and due to the balloon environment, allow for a thermal path to the inner frame of the gondola where the power generated by the electronics can be dissipated and radiated to space. Table 7.2.2 shows the various components on the ROACH2 and the MUSIC DAC/ADC board that generate a notable amount of power.

The ROACH2 components are all of the industrial variety and rated to fail at over 85°C. The ROACH2 Motel needs to properly heat sink the FPGA, Power PC, and ADCs in order to prevent them from exceeding this temperature and failing during flight. It should be noted that the RAM is not heat sunk as it is not used during data acquisition and is a fairly large device which allows any heat it generates to be conducted away through the ground plane on the PCB. Also, any component that dissipates $< 2$ W is also assumed to conduct through the traces on the PCB, and is
not given an additional thermal strap. Since the FPGA is the largest source of heat, it requires a fairly large thermal strap to conduct away the power. Two 5 mm diameter water filled, sintered copper wick heat pipes\(^{10}\) are installed into custom heat sinks via Bismuth Tin solder paste (shown in Figure 7.2). BiSn is used because its relatively low melting point of 138°C allows it to flow before damaging the heat pipe. The dimensions of the FPGA heat pipe design were input into the conductivity calculator provided by \cite{3}. The results, shown in Figure 7.1, confirm that two heat pipes in their existing configuration are rated to carry \(\sim 30\) W safely at \(\sim 40^\circ\)C, which allows for plenty of overhead before device failure. The PowerPC is heat-sunk to the FPGA heat sink via a conventional 1/64” thick, 2/3” wide copper strap. The ADCs are heat strapped directly to the 1/4” Aluminum backing plate by two 10 AWG copper wires. The DACs, which are robust enough to operate without heat straps, are also strapped to the backing plate by a single 14 AWG copper wire for good measure.

In addition to the ROACH2 and ADC/DAC board, there are several other components which are mounted to the aluminum backing plate: the input and output attenuators, the clock and LO, the IQ modulator and demodulator, and a second stage amplifier. All of these components are encased in their own RFI-tight aluminum enclosures and are mounted directly to the backing plate, shown in Figure 7.2. The Beaglebone dissipates an inconsequential amount of power, and only needs to be mounted in place via aluminum standoffs.

After mounting all of the components to the Aluminum backing plate, and routing all required thermal paths to it, the ROACH2 Motel still needs to remove the heat from all five of these plates and provide a path to dissipate it to the inner frame of the gondola, where it will be radiated to space. This is accomplished by treating all

\(^{10}\)HP-HD05DI25000BA, Enertron Inc. 90 N William Dillard Dr., Suite 121 Gilbert, AZ 85233
Figure 7.1: The conduction limits for copper sintered wick heat pipes for the FPGA heat pipe geometry, shown at various heat pipe diameters and operating temperatures. Two 5 mm diameter heat pipes can safely conduct up to 30 W of power at 40°C. If the power unexpectedly increases, the temperature of the FPGA will rise until the heat pipe can handle the increased load.
Figure 7.2: An overview of a single readout channel in the ROACH2 Motel. The overall dimensions of the ROACH2 motel with all five channels is 14.75” x 2.75” x 24”. The FPGA is heat sunk via a custom heat pipe assembly. The PowerPC is heat strapped to the FPGA heat sink, while the ADCs and DACs are strapped directly to the Aluminum backing plate. Also shown are the input and output attenuators, second stage amplifier, Beaglebone, I/Q modulator, and I/Q demodulator. The Valon is mounted underneath the I/Q modulator.
<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPC</td>
<td>56</td>
</tr>
<tr>
<td>FPGA</td>
<td>41</td>
</tr>
<tr>
<td>Evaporator</td>
<td>37</td>
</tr>
<tr>
<td>Condenser</td>
<td>33</td>
</tr>
<tr>
<td>Inlet</td>
<td>44</td>
</tr>
<tr>
<td>Outlet</td>
<td>36</td>
</tr>
<tr>
<td>ADC</td>
<td>39</td>
</tr>
<tr>
<td>DAC</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 7.3: Various temperatures of ROACH2 Motel components under vacuum. Every component is well within thermal tolerances, and the highest temperature component, the PPC, is 29°C below its maximum allowable temperature.

Thermal Verification

The ROACH2 Motel thermal design was vetted by running multiple stress tests inside a vacuum chamber. Since the inner frame is unable to fit inside the vacuum chamber, two water heat exchangers are mounted on top of the brackets, and are kept fixed at the expected temperature of the inner frame during flight. The vacuum chamber setup is shown in Figure 7.3. During the vacuum test, the four completed systems are powered up, and the firmware is uploaded to the FPGA. The readout software is run continuously in RF loopback mode, where the RF output is connected directly to the RF input, allowing the system to monitor itself for any irregularities that may arise. The component temperatures after the ROACH Motel reached equilibrium are displayed in Table 7.3. All components behaved as expected, and the hottest element, the PPCs, were still 29°C below their maximum allowable temperature.

After the ROACH2 Motel underwent thermal vacuum testing, the results were used to calibrate the ROACH2 Motel thermal model. These data were incorporated into a full simulation of the BLAST-TNG gondola thermal environment dur-
Figure 7.3: Vacuum Testing the ROACH2 Motel. The ROACH2 Motel was stressed tested thermally by running continuously in the vacuum chamber for several days. The inner frame of the gondola was simulated by keeping two heat exchangers at the same temperature as the inner frame during flight. Temperatures on all critical components stayed well below their failure levels.
Figure 7.4: Right: The Thermal Desktop model which reproduces the temperatures in Table 7.3 which were measured in the vacuum chamber. Right: The thermal simulation of the gondola at float, with the ROACH2 Motel attached. Simulations suggest the ROACH2 Motel will passively cool to \( \sim 40 \) C.

This model is designed and simulated with Thermal Desktop\(^{11}\). Thermal Desktop\(^{\circledR}\) creates a node and conduction network from a CAD model, interfaces with SINDA/FLUINT \(^{21}\) for the solution, and interprets and displays the results. The Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA/FLUINT) is the NASA standard software system for computationally simulating heat transfer and fluid flow networks. The results of a simulated 30 day flight, shown in Figure 7.4 which incorporates all critical hardware components and the proper sunshield design, suggest that the inner frame of the gondola is able to safely conduct and radiate away all of power generated by the ROACH2 Motel, provided its sides are painted white.

**ROACH2 Motel Power and Interfacing**

Along with providing a mounting point and thermal path for all of the electronics, the ROACH2 Motel also distributes all of the power and electrical signals. Each ROACH2 Motel front panel, shown in Fig. 7.3 has SMA ports for the 10 MHz

\(^{11}\)C&R Technologies. 2501 Briarwood Dr, Boulder, CO 80305
reference, 1 PPS, an (unused) external LO, RF input and output, and a spare. There are also several LEDs which show the state of the ROACH2. There is both a power and reset switch which must be ‘armed’ using a third switch to ensure the ROACH2 isn’t accidentally powered down during operation. Finally, there is an Ethernet port which connects the flight computers to the Beaglebone for that system.

On the back panel, there is a 4-pin military connector which takes the 28V supply from the gondola’s power distribution system. This power is split out to several Vicor DC-DC converters which are mounted on the backplane and provide the +5V, -5V, and 12V supplies for the I/Q modulator, demodulator, attenuators, Valon, and amplifier. The +28V, which is fed to the PicoPSU ATX power supply for the ROACH2, 12V and +/-5V supplies are fed into each individual readout channel through a 12 pin D-sub backplane connector. Finally, there are two Ethernet and one USB ports for each readout channel on the back panel. One Ethernet is for the PowerPC control port, while the other is for the FPGA port. The USB port is fed into a ROACH2 diagnostic port which is used for debugging in the event of a catastrophic system failure.

7.3 Firmware Overview

The BLAST-TNG ROACH2 firmware is a highly multiplexed, 1024 channel digital spectrometer, which is based on the algorithm implemented in the ARCONS ROACH1-based readout [78]. It performs all required signal processing tasks within base-band range (± 256 MHz). It is written using the MSSGE (MATLAB\textsuperscript{12} / [12]Mathworks, 1 Apple Hill Drive Natick, MA 01760)
Simulink\textsuperscript{13} / System Generator\textsuperscript{14} / EDK\textsuperscript{15} toolflow developed by the CASPER collaboration. Software registers hard coded into the firmware allow for user inputs, some of which will be automated during flight (see Section 7.4). CASPER 'snap' blocks allow pre-specified amounts of data to be pulled from the firmware stream at key points, which is converted into figures of merit to be used for making on-the-fly adjustments to either the IF electronics, or carrier frequencies.

The Virtex-6 FPGA derives its clock by halving the 512 MHz signal provided to the DAC/ADC board via one channel of the Valon 5008 Synthesizer. Although the 550 Mega-samples per second (Msps) ADCs have a Nyquist-limited bandwidth of 256 MHz, decomposing the RF signal and digitizing \( I \) and \( Q \) independently allows for a total RF and system bandwidth of 512 MHz. Firmware operations range from carrier comb generation to User Datagram Protocol (UDP) packetization and transmission to the flight computer. Figure 7.3 shows both the RF and DSP chain of the readout system. In the following, we divide each operation into two distinct stages of the firmware; those occurring before and after modulation.

### 7.3.1 Pre-Modulation

**Carrier Waveform Buffer**

The baseband carrier waveform look-up-table (LUT) buffer occupies two of the ROACH2’s four quad-data-rate (QDR) SRAMs\textsuperscript{16}, which are designated as QDR\( _I \) and QDR\( _Q \). During operation, the real (imaginary) component of the carrier buffer is stored and read from QDR\( _I \) (QDR\( _Q \)). The waveform buffers are generated in software

\textsuperscript{13}Mathworks
\textsuperscript{14}Xilinx ISE 14.7 Design Suite
\textsuperscript{15}Xilinx Embedded Development Kit
\textsuperscript{16}Cypress, CY7C2565KV18
Figure 7.5: Top: A block diagram of the BLAST-TNG RF chain. Bottom: A block diagram of the BLAST-TNG DSP chain.

prior to being uploaded to QDR SRAM, and contain frequencies from -256 MHz to +256 MHz (see Section 7.4). The I,Q\textsubscript{DAC} and I,Q\textsubscript{DDS} LUTs contain 2\textsuperscript{21} samples each, of data type double. Dividing this length into the 256 MHz FPGA clock rate results in a tone frequency resolution of 244 Hz.

Each QDR SRAM contains 2\textsuperscript{19} addresses, which point to four 36-bit slots. Since the KATCP protocol can write 64-bit at a time, 128 out of the 144 bits per address will be used for data, while the rest are initialized to zero. To facilitate uploading the two LUTs to each QDR SRAM, the I and Q components are interwoven into two separate LUTs (QDR\textsubscript{I}, QDR\textsubscript{Q}) of 2\textsuperscript{22} samples each. The order of values for the I (Q) LUTs is: I\textsubscript{DAC}\textsuperscript{1}, I\textsubscript{DAC}\textsuperscript{0}, I\textsubscript{DDS}\textsuperscript{1}, I\textsubscript{DDS}\textsuperscript{0}, ..., I\textsubscript{DAC}\textsuperscript{n}, I\textsubscript{DDS}\textsuperscript{n-1}, I\textsubscript{DDS}\textsuperscript{n} (same for Q), where subscripts refer to sample order, and each word has been cast into a 16-bit string to be written with KATCP. The sample order has been pair-wise reversed because KATCP will switch them back into sequential order upon writing. Each LUT is treated as a
structure of $2^{20}$ quartets of 64-bit words. The writing process is initialized by toggling a software register that resets the address counter. The entire buffer is then filled by incrementing one address every other clock cycle, so that two quartets are written to each of the $2^{19}$ addresses.

After writing is complete, the 64-bit quartets are extracted from the QDR SRAM buffers, sliced into their 16-bit components and recast as a signed fixed-point 16.15 number. In this fixed-point notation, the first number is the total bit width, while the second number is the decimal bits. All numbers in this notation are assumed to be signed unless otherwise noted. On each clock cycle, eight consecutive samples are read out from QDR$_I$ (QDR$_Q$): $I_{DAC}^1$, $I_{DAC}^0$, $I_{DDS}^1$, $I_{DDS}^0$ (same for Q). The DDS LUT samples will only be used post-modulation, and are sent to the digital-down-conversion section of the firmware. The DAC LUT samples are presented to the $I$ and $Q$ inputs of the 16-bit DACs; two consecutive samples on each FPGA clock cycle, since the DACs are clocked at twice the rate of the FPGA. The $I/Q$ DAC inputs are synchronized using the same register that resets the QDR address counter. Once through the DACs, the analog signal is processed by the IF electronics, up-converted to RF (0.5 - 1.12 GHz), and passed through the detector feed-line for modulation.

### 7.3.2 Post-Modulation

Each step of the post-modulation process is shown in the bottom block diagram in Figure 7.3.

**Re-Digitization**

After $I$ and $Q$ have been demodulated through the IF electronics, they are passed into the two ADCs and re-digitized. The resulting base-band frequency comb contains
frequency information spanning DC to 512 MHz. The I/Q ADCs are synchronized with the same software register as the DACs. Each ADC outputs two consecutive time samples per FPGA clock cycle: \( I_{ADC}^0, I_{ADC}^1 \) \( (Q_{ADC}^0, Q_{ADC}^1) \). The I and Q pairs are concatenated into pairs of 24-bits, and sent to the first stage of channelization. Firmware snap blocks collect some of the re-digitized time stream, which is used to gauge whether or not I and Q occupy the full scale of the ADCs (1.2 V). The input attenuator may then be adjusted accordingly.

**Coarse Channelization and Bin Selection**

Before applying the FFT, the base-band time stream is filtered to minimize the occurrence of spectral leakage and scalloping loss. For this purpose, we use the CASPER Polyphase Filter Bank (PFB) block. The block is configured to take a set of 1024 samples and multiply it by a 1024-bin Hamming window with eight taps. The filtered output time stream is recast into 18.17 and is passed to a 1024-bin biplex FFT.

On each clock cycle, the biplex FFT takes two consecutive time sample pairs, and outputs the complex amplitudes \((i \text{ and } q)\) of two consecutive frequency bins. One 1024-bin FFT is processed in 512 clock cycles, with a bin width of 500 kHz. A pulse is emitted with the final bin of each successive FFT, and this signal is used to synchronize all following stages of the firmware. Since the average individual detector bandwidth is \(\sim 50 \text{ kHz}\), several detectors may safely fall within a single FFT bin, provided they are sufficiently spaced. Each bin pair output by the FFT is concatenated into a single 72-bit word \((4\times18 \text{ bit})\) with order \(i_{odd}, q_{odd}, i_{even}, q_{even}\), before being stored in the block RAM (BRAM) in the FPGA for channel selection.
Bin selection and channelization

Since some FFT bins might contain multiple detectors, while others are empty, it is necessary to choose the bins that are desired for further channelization. During software synthesis of the $I/Q$ waveform buffers, a list of up to 1024 bins is pre-calculated based on known resonator positions and loaded into a ‘bin select’ BRAM. Bin numbers can be called multiple times, and any unused RAM addresses are initialized to zero. After the bins have been chosen, they are referred to as channels, with the channel order corresponding to the order of the original list. During operation, the bin indexes for two consecutive channels (even index, odd index) are read out in parallel. Each bin index is halved to represent the clock cycle (‘clock address’) corresponding to its offset in cycles from the zeroth FFT bin, and these values are sent to the channel selector. The least significant bit of each bin index is used to indicate the parity of each bin number to the channel selector.

Channel selection requires that up to 1024 channels from the FFT bin stream be selected within 512 clock cycles. To manage this while continuously streaming data, a buffered switch is constructed using dual-port BRAM. In write mode, 1024 i/q pairs are written to 512 address slots using the clock address of the even numbered bin in each pair. In read mode, the data is read out using the clock addresses sent from the ‘bin select’ BRAM. Two bin pairs are extracted on each clock cycle, the first pair corresponding to the clock address of channel 1, the second corresponding to channel 2. Since only one bin of each pair is intended to be used as a channel, the bins are immediately split apart, and the parity bit of each one is used to select the correct bin. After a pair of channels has been selected, they are passed through a MUX selector and sent to the first stage of digital down conversion (DDC).
Digital Down Conversion

The FFT operates on the re-digitized ADC time stream once every 512 clock cycles, and therefore any tones in the carrier waveform which are non-periodic in this length will exhibit phase rotation over the course of several FFTs. The result is amplitude modulation of the FFT bin time streams, where the frequency of each bin oscillation is the difference between a bin center and the location of a carrier tone within the bin. One way to avoid this issue is to constrain the waveforms to the centers of the FFT bins. MUSIC [33] utilizes a large $2^{16}$ point FFT which allows for a tone resolution of roughly 7.5 kHz. Since our firmware utilizes relatively large FFT bins where multiple detectors may fall in the same bin, we must correct for this oscillation in a process known as digital down conversion (DDC). The following sections of the firmware perform the three basic functions of a digital down converter: Down-convert, low-pass filter and down sample.

To down-convert the channelizer output, the $i/q$ time stream is multiplied with $I$ and $Q$ from the DDS LUT. The DDS LUT contains the precalculated FFT beat frequencies for each channel. It is synthesized in the same manner as the DAC LUT, except the sampling frequency is the FPGA clock rate divided by 512, the number of cycles per FFT. The $I/Q$ samples are transposed so that the time stream can be used channel-wise.

In firmware, the down-converter is implemented as a complex multiplier, where two consecutive channels are operated on in parallel. A single cycle of the operation involves performing the calculation: $(i + jq)(Q_{DDS} + jI_{DDS})$. Here, $i/q$ are data type 18.17, $I/Q_{DDS}$ are 16.15, and the resulting $i/q$ output is 19.17. Channels containing multiple tones will be down-converted once per tone. Low-pass filtering is needed to complete the fine channelization (see subsection: Accumulation).
For successful down-conversion, the DDS LUT must line up properly with the incoming channelizer $i/q$ stream. Upon programming them into the QDR SRAMs, the DDS and DAC LUTs are synchronized by a user input to a software register. Since the DDC portion of the firmware is synchronized by the FFT pulse, by the time the first $i/q$ stream arrives at the down-converter the DDS LUT will have been shifted channel-wise by an initially unknown number of clock cycles between 0 and 512. This 'DDS shift' is constant, albeit different, between different compilations of the image file. After its value is determined, it is coded into a variable delay block via software register input immediately after uploading the firmware image to the ROACH2.

The value of the DDS shift can be determined using a variety of methods. We have found that it is preferable to use snap block data for this purpose, since this same data can also be used to verify that the down-conversion has succeeded. One method, which can be automated in software, is to step through each possible DDS shift using the variable delay block while monitoring the snap block data for a single channel. An FFT is taken of the snap block data at each step, which includes $i$ and $q$, as well as $I_{DDS}$ and $Q_{DDS}$. When the delay has been set properly, the DDS channel frequency will match that of the $i/q$ time stream, as revealed by comparing the two FFTs.

**Accumulation**

The low-pass filtering and down-sampling stages of the DDC are achieved by channel-wise accumulation of $i$ and $q$. The length of the accumulation is set by user input via software register, which determines the readout bandwidth of the ROACH board. For BLAST-TNG, the accumulation length is set to $2^{19}$ clock cycles, which
equates to 1024 FFT outputs. The readout bandwidth equals the FPGA clock rate divided by the accumulation length, which is 488.28 Hz for BLAST-TNG. The maximum readout frequency is the 500 kHz FFT output.

Two consecutive channel outputs from the down-converter are accumulated independently, as $i$ and $q$, in CASPER vector accumulators of length 512. The resulting data type is 32.17. During accumulation, extra tones within each channel which were not previously down-converted are averaged down (once the averaging has been applied in software) to negligible levels.

**Ethernet Packetization and Time Stamping**

Following accumulation, the $i/q$ stream is prepared for UDP packetization. Since the data rate for each ROACH board is low ($\sim 3$ MB), the ROACH2’s one-gigabit Ethernet interface (GbE) is used for data transmission to the flight computer. In firmware, UDP packetization is performed by the CASPER 1GbE block. The source MAC, IP address and UDP port are hard coded into the block before compilation, and the destination IP and port are user configurable.

The UDP frame, including its header, are built within the GbE block. Since the input data width is one byte, each 32-bit $i$ and $q$ must be sliced byte-wise before being input to the block. After slicing, 8192 bytes of data are input to the block per frame. The data is ordered as: $i_{\text{even}} \times N_{\text{channels}}$, $q_{\text{even}} \times N_{\text{channels}}$, $i_{\text{odd}} \times N_{\text{channels}}$, $q_{\text{odd}} \times N_{\text{channels}}$, where $\text{even}$ and $\text{odd}$ refer to the parity of the channel indices.

In addition to a relative counter value, each UDP packet is tagged with a course and fine absolute time stamp which is derived from a pulse-per-second (PPS) input fed into the ROACH2’s SMA GPIO port. The PPS is synchronized with the flight computer’s GPS system. The course count is the number of elapsed PPS pulses since
initialization via a user input. The fine count comes from a clock counter which gets reset at the start of each PPS pulse. The number of elapsed clock cycles since the zeroth count are appended to the packet as the fine time stamp, with provides a time resolution of ∼ 4 ns. Rather than inserting the time stamp values into the UDP header, they are tagged onto the last two channels of the \(i/q\) stream, since in the case of BLAST-TNG these channels are known to be empty.

### 7.4 Software and Flight Operation

While the firmware runs autonomously and continuously once uploaded to the FPGA, software must be written to control it through the PowerPC in order to get coherent data. The Karoo Array Telescope Communication Protocol (KATCP) \[117\] is the Ethernet-based communications protocol used by the host computer to talk to the PowerPC on the ROACH2. It has been developed by the Square Kilometer Array South Africa (SKA SA) collaboration for use on their CASPER hardware-based correlators and beam formers. All ROACH2 boards host a daemonized KATCP server. KATCP can upload firmware to the ROACH2 flash memory and program it onto the FPGA, read and write to the various software registers, and monitor the temperature sensors. This small set of commands are the basis for controlling and operating the readout. Higher level functions, such as programming the frequency comb or calibrating the QDR, are built out of these smaller register level commands.

While the readout section of the flight computer software is written in C, it is mainly a port from the python software we have written to control the ROACH2 and test MKIDs in a laboratory setting. The python control software utilizes casperfpga, a KATCP python wrapper that adds more functionality to the standard set of KATCP
commands.

The principal operation begins with generating an S21 trace by using a frequency comb of 550 evenly spaced tones and sweeping the LO over 1 MHz. We then use simple peak finding algorithm, the results of which are shown in Figure 7.6 to find the tones. When there are multiple tones found in a single channel, we take the two resonances with the largest Qs. Due to issues finding the MKID resonances on the edges between two tones, we then shift the LO by 0.5 MHz and repeat the process again, discarding any redundant tones. After all of the resonances have been found, we reprogram the frequency comb, and run a targeted sweep of 100 KHz. This produces an IQ loop for each resonance which is used to both locate the centers of the IQ loops and to generate the phase to frequency shift conversion. After these tuning procedures are complete, the readout streams I/Q data for each detector to the flight computer, and the telescope can begin science observations. During scanning, the LO is periodically shifted by 1/2 of a resonator width. By using Equation 7.1 from [14], we can use the LO shift to get an on-the-fly correction to the frequency shift, $\Delta f_0$:

$$
\Delta f_0 = \frac{(\Delta I, \Delta Q) \cdot (dI/df, dQ/df)}{(dI/df, dQ/df)^2} \cdot \delta f_{LO}
$$

(7.1)

In addition to the periodic LO shift, we also periodically apply the calibration lamp. This illuminates the detectors and provides an instantaneous responsivity measurement. If either the LO shift or calibration lamp shows that the detector responsivity has substantially decreased, the software performs another IQ loop and re-tunes the detectors.
Figure 7.6: An $S_{21}$ trace of one of the three detector rhombuses on the 250 $\mu$m detector array. The resonances found by the KID finding algorithm are highlighted with red stars. The slope of the $S_{21}$ trace is due to the response of the readout electronics and has been fitted out in later software versions.
7.5 Verification

After the completion of the firmware and accompanying software pipeline, the readout system was tested at NIST on the BLAST-TNG 250 µm detector array. These tests were conducted while the array was dark and held at $T_{bath} = 50$ mK, to confirm that the readout was able to see the absolute noise floor of the detectors. The MKID-finding algorithm was first used to find the detector’s resonant frequencies. Next, an IQ sweep was performed to retrieve the loop centers and $\frac{\delta \phi}{\delta f}$. With this information in hand, a proper noise analysis could begin. A 10 second segment of data was collected simultaneously on 574 resonators. The LO was then shifted by 300 kHz, so that the tones were completely off-resonance, and another 10 seconds of data were taken. The results, shown in Figure 7.7, show that the lowest detector noise is greater than a factor of 10 above the noise floor of the readout system. Therefore, the readout system is more than capable of handling the requirements of the BLAST-TNG detector arrays.
Figure 7.7: The Noise spectrum, in rad²/Hz, for a typical readout channel given on and off resonance. Top left shows the resonance in both magnitude (top) and phase (bottom). Top right shows the corresponding resonance IQ circle. The green (blue) points in these plots shows the location of the tones used to generate the noise spectra on (off) resonance. The bottom noise spectra shows that the intrinsic dark detector noise is greater than a factor of 10 above the noise floor of the readout.
Chapter 8

Conclusions

The scientific results derived from the 2012 BLASTPol flight documented in this thesis highlights the potential scientific gains that can be made BLAST-TNG. By mapping an area that is 32 times larger than that made by BLASTPol, almost every area of molecular cloud and star formation physics can be probed over a larger range of spatial scales. BLAST-TNG will crucially link ALMA and Planck, synergistically expanding the scientific capabilities of both instruments.

The detector arrays, and their warm readout electronics have further pushed the field of MKIDs, demonstrating their capability in a space-like environment. This is a crucial step towards an MKID-based satellite payload. In addition, by utilizing a ROACH2-based readout system, BLAST-TNG has expanded the potential MUX factor for MKID arrays. Coupled with new ADC/DAC boards that are currently under development [80] that have double the digitizing bandwidth, it has the potential to read out all of the BLAST-TNG detector arrays on just a single channel.
8.1 Future Work

By the time this thesis has been published, many of the tests outlined in §3.2 will have been completed, and the 250 $\mu$m array will be fully characterized in the BLAST-TNG receiver. In the following months, the 350 and 500 $\mu$m arrays will be fabricated, tested, and integrated into the receiver. Next, the warm telescope optics, consisting of the CFRP primary and aluminum secondary, will be integrated with the gondola and receiver. Following a lengthy series of tests, BLAST-TNG will have entered its flight configuration in anticipation of a 2017 Antarctic campaign.
Appendix A

BLAST-TNG Optical Load

One of the most important aspects of any telescope design is understanding the operational loading on the detectors. Overestimating the optical power will result in loss of sensitivity, thus degrading the mapping speed, while overestimates will lead to a saturated detector that won’t function at all. Another critical number is the photon noise equivalent power ($NEP_{\text{photon}}$). In this section, I will go through the various steps that I took to calculate the detector loading and accompanying $NEP_{\text{photon}}$ for the three BLAST-TNG bands. Finally, I’ll comment on the temperature stability required for the blackbody load tests performed in Sections 5.4 and 5.3 that was discussed in Section 5.4.2.

A.1 Calculating the Loading from Each Optical Element

We first begin our optical load calculation by determining the blackbody power produced by each optical element at temperature, $T_e$, within each of our three bands.
Since BLAST-TNG operates between 250-500\(\mu m\), we are not able to use the Rayleigh-Jeans limit. We must integrate the Planck blackbody spectrum over the BLAST-TNG wavebands \((\lambda_0 \text{to} \lambda_1)\) to obtain a flux density,

\[
I_e(T) = \int_{\lambda_0}^{\lambda_1} \frac{2hc^2}{\lambda^5 \left( e^{\frac{hc}{\lambda k_B T_e} - 1} \right)} d\lambda \text{ (W/(sr m}^2\))
\]  

(A.1)

where \(k_B\) is Boltzmann’s constant, and \(T_e\) is the temperature of the element in the optical system. Since BLAST-TNG is a diffraction limited telescope, we may use the relation \(A\Omega = \lambda^2\) to convert \(I_e\) into a radiated power, \(P_e\), in Watts. This blackbody power can then be multiplied by the object’s emissivity, \(\epsilon_e\), to obtain the emission-corrected loading.

Once the appropriate emission-corrected loading has been calculated for each optical element, we must correct this for losses from each subsequent optical element in the system. For any reflective surface in the optical system, I assume an optical efficiency of 99.5\%. For any dielectric, such as a low-pass filter, I treat them as two 0.1\% reflective surfaces with a 0.1\% loss in between. IR blockers are assumed to have negligible absorption and are 0.1\% reflective. I treat the bandpass filters as 95\% efficient. Ideally, one would request transmission and absorption specifications from the filter manufacturer\(^1\), or measure it directly with a Fourier-transform spectrometer. The detector quantum efficiency, along with the horn and waveguide coupling efficiencies (\(\eta_{det}\)) can be taken directly from the blackbody load measurements performed in Section 5.4. For the BLAST-TNG telescope, the optical efficiency from source to detector is \(~ 40\%\). The emission and optical efficiency-corrected loading from each

\(^1\)http://www.terahertz.co.uk/
Load Contributors (pW)

<table>
<thead>
<tr>
<th>Element</th>
<th>250 Micron</th>
<th>350 Micron</th>
<th>500 Micron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky</td>
<td>10.583</td>
<td>4.433</td>
<td>2.261</td>
</tr>
<tr>
<td>Primary Mirror</td>
<td>4.078</td>
<td>2.992</td>
<td>2.152</td>
</tr>
<tr>
<td>Secondary Mirror</td>
<td>4.099</td>
<td>3.007</td>
<td>2.163</td>
</tr>
<tr>
<td>Struts</td>
<td>0.639</td>
<td>0.069</td>
<td>0.337</td>
</tr>
<tr>
<td>Window</td>
<td>4.844</td>
<td>2.474</td>
<td>1.266</td>
</tr>
<tr>
<td>Low-Pass Filter</td>
<td>2.061</td>
<td>1.567</td>
<td>1.158</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27.715</strong></td>
<td><strong>16.089</strong></td>
<td><strong>10.234</strong></td>
</tr>
<tr>
<td><strong>Total per pol</strong></td>
<td><strong>13.858</strong></td>
<td><strong>8.044</strong></td>
<td><strong>5.117</strong></td>
</tr>
</tbody>
</table>

Table A.1: Load contributions of key elements in the BLAST-TNG optical chain (in picowatts). The powers listed is the amount that is absorbed by the detectors. Note: The total includes lesser power contributions from other optical elements that are not listed.

The optical element is given as

\[ P_e(T_e) = \epsilon_e \eta_e \int_{\lambda_0}^{\lambda_1} \frac{2hc^2}{\lambda^5 \left( e^{\frac{hc}{k_B T_e}} - 1 \right)} d\lambda \ (W) \]  

We now have achieved a list of power contributions by various sources in the optical system. The primary load contributor for the BLAST telescope are shown in Table A.1. As you can see, the power contributions from the struts dominates the loading on the detectors. It is imperative that one design a strut that limits the radiation emitted, and develops an accurate model of how the struts will emit said radiation.
A.2 Calculating \( NEP_{\text{photon}} \)

The general expression for the NEP of a background limited bolometer (BLIP) can be found in, for example [65]

\[
NEP_{\text{photon}}^2 = \frac{2}{\eta_{\text{det}}} \int P_\nu h\nu d\nu + 2 \int \frac{P_\nu^2 c^2 d\nu}{mU_\nu \nu^2} \left( \frac{W^2}{Hz} \right) \quad (A.3)
\]

where \( P_\nu \) is the total amount of loading in the system calculated using A.2 (see Table A.1), \( m \) is the number of polarizations being detected, and \( U_\nu = A\Omega\nu^2/c^2 = 1 \) (for diffraction-limited telescopes). The second term in the equation is due to the bunching of photons when the number of photons per mode is large. The number of modes, \( n_\nu \) can be found by:

\[
n_\nu = \frac{1}{e^{(h\nu/k_B T)} - 1} \quad (A.4)
\]

Since the number of modes is temperature and wavelength dependent, \( n_\nu \) varies for each optical element and band. To approximate \( n_\nu \) for the system, one may take the occupation of the largest power contributor as an approximate value for the whole system. For BLAST-TNG, this corresponds to an \( n_\nu \) of 3.7, 5.37, and 7.87 for 250, 350, and 500 \( \mu m \), respectively. Since these values are small for BLAST-TNG, we can safely ignore the bunching term in equation (A.3). Furthermore, if the observing bandwidth is small, (A.3) can be further reduced to:

\[
NEP_{\text{photon}}^2 \approx \frac{2}{\eta_{\text{det}}} P_{\text{rad}} h\nu \quad (A.5)
\]

where \( P_{\text{rad}} \) is the total optical power contributed from all optical elements in the BLAST-TNG telescope. In Table A.2 below, I have listed the noise in each regime for all three BLAST-TNG bands. As you can see, the shot noise approximation and the shot noise term of equation (A.3) agree to \( > 99.9\% \). Since \( n_\nu \) is small for all three
<table>
<thead>
<tr>
<th>Noise ($W/\sqrt{Hz}$)</th>
<th>250 µm</th>
<th>350 µm</th>
<th>500 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot Noise Limit</td>
<td>2.056E-16</td>
<td>1.324E-16</td>
<td>0.883E-16</td>
</tr>
<tr>
<td>Shot Noise Term</td>
<td>2.059E-16</td>
<td>1.326E-16</td>
<td>0.885E-16</td>
</tr>
<tr>
<td>Bunching Term</td>
<td>5.858E-21</td>
<td>5.029E-21</td>
<td>5.279E-21</td>
</tr>
<tr>
<td>Full Noise Integral</td>
<td>2.059E-16</td>
<td>1.326E-16</td>
<td>0.885E-16</td>
</tr>
</tbody>
</table>

Table A.2: A comparison of several noise calculations in different regimes for each BLAST-TNG band. The approximate shot noise term and the full noise integral agree to > 99.9%.

bands, the bunching term is also shown to be negligible.

### A.3 Calculating the Blackbody Load Fluctuations

Since the excess low frequency noise observed in the blackbody load tests is of great concern to the BLAST-TNG science goals, great care must be taken to confirm that it is intrinsic to the detectors and not a systematic noise contribution. The power fluctuations of the blackbody may be calculated by taking the derivative of (A.1) with respect to temperature:

$$
\frac{\delta I_\nu}{\delta T}(T_{bb}) = \int_{\lambda_0}^{\lambda_1} \frac{2c^3h^2}{k_B\lambda^4T_{bb}} \frac{e^{c_{bb}/k_B\lambda_{bb}}}{(e^{c_{bb}/k_B\lambda_{bb}} - 1)^2} \delta \lambda \ (W) \quad (A.6)
$$

When inserting the relevant blackbody load temperatures ($T_{bb} = 19 - 21$ K), the temperature stability that is required on all frequency scales is $\sim 40 \ \mu$K, or one part in one million. This stability is unlikely given traditional temperature controllers. Another option is to operate the blackbody load at a temperature that is in the Rayleigh-Jeans limit and introduce an NDF to achieve the desired loading.
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