2018

Building The Next Generation Blast Experiment

Nathan Patrick Lourie

University of Pennsylvania, nathan.lourie@gmail.com

Follow this and additional works at: https://repository.upenn.edu/edissertations

Part of the Astrophysics and Astronomy Commons

Recommended Citation

https://repository.upenn.edu/edissertations/3147

This paper is posted at ScholarlyCommons. https://repository.upenn.edu/edissertations/3147
For more information, please contact repository@pobox.upenn.edu.
Abstract
Maps of the polarized thermal emission from dust in our galaxy hold the keys to unlock multiple astrophysical and cosmological questions. For measurements of the polarized cosmic microwave background (CMB), this dust emission is the dominant foreground. Subtracting this dust signal from the data is a critical step in the search for the weak primordial signatures of cosmic inflation. Mapping the magnetic field morphology of galactic dust can also shed light on the evolution of the giant molecular clouds which are the hotbeds of star formation in the galaxy. The Next Generation Balloon-Borne Large Aperture Submillimeter Telescope (BLAST-TNG) is a submillimeter mapping experiment which features three microwave kinetic inductance detector (MKID) arrays operating over 30% bandwidths centered at 250, 350, and 500 μm. These highly-multiplexed, high-sensitivity arrays, featuring 918, 469, and 272 dual-polarization pixels, are coupled to a 2.5 m diameter primary mirror and a cryogenic optical system providing diffraction-limited resolution of 30″, 41″, and 50″ respectively. The arrays are cooled to \(~275\) mK in a liquid-helium-cooled cryogenic receiver which will enable observations over the course of a 28-day stratospheric balloon flight from McMurdo Station in Antarctica as part of NASA’s long-duration-balloon program, planned for the 2018/2019 winter campaign.
Acknowledgements

I would like to express my deep gratitude for the assistance, advice, and support from my many colleagues, friends, and family over the last six years. Without your continued patience and understanding, the completion of this thesis, my contributions to the BLAST team, and my graduate studies would not have been possible.

First, I would like to thank my Ph.D. thesis advisor, Mark Devlin. Mark’s drive, expertise, and intuition has been invaluable, and has served as an inspiration to never let up until the job is finished. I am grateful for the trust Mark has placed in me throughout my graduate work, his willingness to let me try new ideas, and his support not just during my proudest moments, but during my biggest (and most expensive) mistakes.

I am also especially grateful for the mentorship and friendship of Jeff Klein. Jeff’s enthusiasm and systematic, dogged, approach to solving problems both great and small is infectious. I have learned so much from, and will always hold dear, our many rambling discussions, exasperated arguments in front of the white board, and late nights pulling our hair out over the cryostat electronics. I promise, it is just ice cream.

I would also like to thank Philip Mauskopf and Giles Novak, who have served as mentors during my graduate studies. It has been fantastic to learn from your wealth of experience. Thanks to those whose patient conversations about complicated systems were crucial to my understanding of the project, especially Chris McKenney and Brian Catanzaro. Thanks to the BLAST post-docs who have taught me so much: Elio Angile, Laura Fissel, Federico Nati, Joy Didier, and Javier Romualdez, and to my fellow grad students Peter Ashton, Sam Gordon, Adrian Sinclair, and especially the Team Highbay crew: Tyr Galitzki, Brad Dober, and Ian Lowe.
I could not have made it through my research and my coursework without the help and friendship of my classmates at Penn, especially Anthony Chieco, Sara McCamish, Michele Kim, Carl Naylor, Rob Fletcher, Steve Gilhool, and my bandmates Eric Wong and Will Parkin.

Finally, I would like to express my deepest appreciation to those closest to me for their unwavering support, encouragement, and assistance. My parents Benjamin and Christine, and my brothers Owen and Sasha: you and your pursuits of knowledge [6; 78; 80; 77] have truly been an inspiration. To you, and to my sisters-in-law Erin and Faith, my nieces Lucy, Ingrid, and Ellie, my nephews Martin and Colin, and my partner Abby, I cannot thank you enough for all of your love, support, and understanding throughout this process, for your interest in my studies, and for helping me to keep everything in perspective.
Maps of the polarized thermal emission from dust in our galaxy hold the keys to unlock multiple astrophysical and cosmological questions. For measurements of the polarized cosmic microwave background (CMB), this dust emission is the dominant foreground. Subtracting this dust signal from the data is a critical step in the search for the weak primordial signatures of cosmic inflation. Mapping the magnetic field morphology of galactic dust can also shed light on the evolution of the giant molecular clouds which are the hotbeds of star formation in the galaxy. The Next Generation Balloon-Borne Large Aperture Submillimeter Telescope (BLAST-TNG) is a submillimeter mapping experiment which features three microwave kinetic inductance detector (MKID) arrays operating over 30% bandwidths centered at 250, 350, and 500 µm. These highly-multiplexed, high-sensitivity arrays, featuring 918, 469, and 272 dual-polarization pixels, are coupled to a 2.5 m diameter primary mirror and a cryogenic optical system providing diffraction-limited resolution of 30″, 41″, and 50″ respectively. The arrays are cooled to ~275 mK in a liquid-helium-cooled cryogenic receiver which will enable observations over the course of a 28-day stratospheric balloon flight from McMurdo Station in Antarctica as part of NASA’s long-duration-balloon program, planned for the 2018/2019 winter campaign.
# Contents

Abstract ........................................ iv  
List of Tables ..................................... vii 
List of Figures .................................... viii 

1 Introduction ................................... 1

2 The Submillimeter Polarized Sky ............... 5  
2.1 How Did We Get Here? .......................... 5  
2.2 Lifecycle of Dust in the ISM .................... 7  
2.3 Optical Properties of Interstellar Dust ........ 9  
2.4 Magnetic Fields in Molecular Clouds .......... 13  
2.5 The BLAST-TNG Experiment .................... 18  
2.5.1 Star Formation in Molecular Clouds .......... 19  
2.5.2 CMB Foregrounds ........................... 22

3 The BLAST-TNG Telescope ....................... 23  
3.1 BLAST-TNG Optical Architecture ............. 25  
3.2 NASA/SBIR Commercial Partnership ............. 28  
3.3 Telescope Requirements ....................... 29  
3.3.1 Diffraction-Limited Performance .......... 30  
3.3.2 Statistical Models of Optical Performance .. 33  
3.3.3 Telescope Optical Requirements .......... 38  
3.4 Telescope Design and Fabrication ............. 42  
3.4.1 Optical Bench and Support Structures ....... 43  
3.4.2 Primary Mirror ............................ 47  
3.4.3 Secondary Mirror ........................... 50  
3.4.4 Unsuccessful Manufacturing R&D Efforts .... 53  
3.5 Metrology .................................... 55  
3.5.1 Primary Mirror and Mold Metrology ........ 56
3.5.2 Secondary Mirror Metrology ........................................ 63
3.6 Expected Performance .................................................. 70
3.6.1 Lyot Stop Pupil ....................................................... 71
3.6.2 Feedhorn Beam Pattern .............................................. 71
3.6.3 System Pupil Function .............................................. 74
3.6.4 PSF Normalization .................................................... 78
3.6.5 Results ............................................................... 78

4 The Balloon-Borne Platform ............................................ 80
4.1 Mechanical Requirements ............................................ 81
   4.1.1 Expected Mass Budget ............................................ 83
4.2 Finite Element Modeling ............................................. 86
   4.2.1 Modeling Parameters ............................................ 86
   4.2.2 Summary of FEM Simulations ................................... 89
4.3 Outer Frame ........................................................... 91
   4.3.1 Modifications to Existing Hardware ............................ 91
   4.3.2 Structural Analysis ............................................... 95
4.4 Inner Frame .......................................................... 103
   4.4.1 Design Philosophy ............................................... 104
   4.4.2 Inner Frame Design and Fabrication ........................... 107
   4.4.3 Structural and Frequency Analysis ............................. 112
   4.4.4 Modeling Pointing Misalignment ............................... 119
4.5 Suspension System ................................................... 123
   4.5.1 Suspension Cables ............................................... 126
   4.5.2 Spreader Bar ...................................................... 127
   4.5.3 Spreader Bar End Fitting ....................................... 130
   4.5.4 Pivot Motor Housing ............................................. 132
   4.5.5 Pivot Bearing and Rotor Shaft ................................ 144
   4.5.6 The Universal Joint ............................................. 152
4.6 Pointing Control ...................................................... 159
   4.6.1 Pointing Motors and Electronics ............................... 159
   4.6.2 Pointing Sensors ................................................ 163
4.7 Sun Shields ............................................................ 167
4.8 Thermal Model ........................................................ 167
   4.8.1 Case Study: ROACH Enclosure Thermal Model ............... 170

5 The Cryogenic MKID Receiver ......................................... 174
5.1 Cold Optics ............................................................ 174
5.2 Cryostat Design ....................................................... 175
5.3 Sub-Kelvin Refrigeration System ................................... 179
5.4 Receiver Performance ................................................. 181
5.5 MKID Detector Arrays ............................................... 183
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>BLAST-TNG Telescope Optical Prescription</td>
<td>27</td>
</tr>
<tr>
<td>3.2</td>
<td>BLAST-TNG Telescope Performance Specifications</td>
<td>40</td>
</tr>
<tr>
<td>3.3</td>
<td>Lyot Stop Parameters</td>
<td>71</td>
</tr>
<tr>
<td>3.4</td>
<td>Expected Telescope Performance Summary</td>
<td>79</td>
</tr>
<tr>
<td>4.1</td>
<td>Material properties used for FEM simulations of the suspension elements</td>
<td>89</td>
</tr>
<tr>
<td>4.2</td>
<td>Summary of Mechanical Element Simulation Results</td>
<td>90</td>
</tr>
<tr>
<td>4.3</td>
<td>Suspension cable geometry and forces experienced under critical load cases</td>
<td>124</td>
</tr>
<tr>
<td>4.4</td>
<td>Summary of the suspension cable and spreader bar design summary</td>
<td>124</td>
</tr>
<tr>
<td>5.1</td>
<td>BLAST-TNG Focal Plane Arrays</td>
<td>184</td>
</tr>
<tr>
<td>6.1</td>
<td>Model Assumptions of Noise Characteristics for BLAST-TNG’s Wavebands</td>
<td>206</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Preferential Absorption and Emission of Aligned Dust Grains</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>Simulations of Molecular Clouds with Different Magnetic Field Strengths</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Magnetic Field Orientation Measured by BLAST-Pol Toward Vela C</td>
<td>16</td>
</tr>
<tr>
<td>2.4</td>
<td>Histogram of Relative Orientation between Magnetic Field and Density Structures Toward Vela C</td>
<td>17</td>
</tr>
<tr>
<td>2.5</td>
<td>Comparison of Planck, BLAST-Pol, and ALMA Resolution</td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>BLAST-TNG Optics Design</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>Zemax Spot Diagrams for BLAST-TNG Optics</td>
<td>26</td>
</tr>
<tr>
<td>3.3</td>
<td>Estimated Ratio from Ruze Formula in Normalized Wavelength Units</td>
<td>36</td>
</tr>
<tr>
<td>3.4</td>
<td>Estimated Ratio from Ruze Formula over BLAST-TNG Wavebands</td>
<td>37</td>
</tr>
<tr>
<td>3.5</td>
<td>Optimistic Preliminary WFE Budget for BLAST-TNG Telescope</td>
<td>41</td>
</tr>
<tr>
<td>3.6</td>
<td>Pessimistic Preliminary WFE Budget for BLAST-TNG Telescope</td>
<td>42</td>
</tr>
<tr>
<td>3.7</td>
<td>BLAST-TNG Telescope Design Overview</td>
<td>43</td>
</tr>
<tr>
<td>3.8</td>
<td>Telescope Optics Bench Assembly</td>
<td>44</td>
</tr>
<tr>
<td>3.9</td>
<td>Primary Mirror Support Struts</td>
<td>46</td>
</tr>
<tr>
<td>3.10</td>
<td>Secondary Mirror Assembly Render</td>
<td>47</td>
</tr>
<tr>
<td>3.11</td>
<td>Primary Mirror Support Struts</td>
<td>49</td>
</tr>
<tr>
<td>3.13</td>
<td>Primary Mirror Manufacturing Process</td>
<td>51</td>
</tr>
<tr>
<td>3.12</td>
<td>Secondary Mirror Blanks</td>
<td>52</td>
</tr>
<tr>
<td>3.14</td>
<td>Secondary Mirror Diamond Turning Progress</td>
<td>53</td>
</tr>
<tr>
<td>3.15</td>
<td>Laser Tracker Measurements of M1 Mold Surface</td>
<td>58</td>
</tr>
<tr>
<td>3.16</td>
<td>Laser Tracker Measurements of M1 Surface from 01/25/2017</td>
<td>59</td>
</tr>
<tr>
<td>3.17</td>
<td>Laser Tracker Measurements of M1 Surface from 02/22/2017</td>
<td>60</td>
</tr>
<tr>
<td>3.18</td>
<td>Laser Tracker Measurements of M1 Surface from 03/04/2017</td>
<td>61</td>
</tr>
<tr>
<td>3.19</td>
<td>PSD of Measured M1 Surface Errors</td>
<td>62</td>
</tr>
<tr>
<td>3.20</td>
<td>Secondary Mirror Metrology Setup</td>
<td>64</td>
</tr>
<tr>
<td>3.21</td>
<td>Laser Tracker Surface Measurements of Secondary Mirror Blanks</td>
<td>67</td>
</tr>
<tr>
<td>3.22</td>
<td>Secondary Mirror Blanks - Radial Dependence of Residuals from the Reference Optics Prescription</td>
<td>68</td>
</tr>
</tbody>
</table>
6.6 Comparing BLAST-TNG’s Visibility with Other Telescopes - Celestial Coords .......................................................... 203
6.7 Comparing BLAST-TNG’s Visibility with Other Telescopes - Centered on BLAST-TNG Field .......................................................... 204
6.8 All-Sky Dust Simulation at 250 µm ............................................ 210
6.9 All-Sky Dust Simulation at 350 µm ............................................ 211
6.10 All-Sky Dust Simulation at 500 µm ............................................ 212
6.11 Selected Foreground Observation Patches ....................................... 214
6.12 Foreground Observation Scenario 0: 96 hrs on 5° x 5° Patch (Patch 0) ............................................. 215
6.13 Foreground Observation Scenario 1: 48 hrs Each on Two 2° x 2° Patches (Patch 1a/1b) ............................................. 215
6.14 Foreground Observation Scenario 0: 96 hrs Each on a 1° x 10° Patch (Patch 2) ............................................. 216
6.15 HI Map of CNM Structure Towards Patch 0 ................................ 217
6.16 HI Map of CNM Structure Towards Patch 1a ................................ 218
6.17 HI Map of CNM Structure Towards Patch 1b ................................ 219
6.18 HI Map of CNM Structure Towards Patch 2 ................................ 220
Chapter 1

Introduction

Maps of the polarized thermal emission from dust in our galaxy hold the keys to unlock multiple astrophysical and cosmological questions. For measurements of the polarized cosmic microwave background (CMB) such as Planck and BICEP2, this dust emission is the dominant foreground. Subtracting this dust signal from the data is a critical step to in extracting the weak primordial signatures of inflation [13]. The dust spectrum varies smoothly as a function of wavelength, and can be removed from CMB measurements, but only by interpolating dust measurements made at a wide range of wavelengths, from the infrared through the submillimeter and into the microwave. Mapping the magnetic field morphology of galactic dust can also shed light on the formation and evolution of the giant molecular clouds which are the hotbeds of star formation in the Galaxy.

My graduate research was dedicated to designing and building The Next Generation Balloon-borne Large Aperture Submillimeter Telescope (BLAST-TNG), a NASA-funded experiment which will make high-resolution maps of the magnetic field
morphology of a large sample of molecular clouds, as well as key regions of the diffuse interstellar medium (ISM) for CMB foreground characterization. BLAST-TNG will observe the submillimeter sky from the stratosphere, flying high above 99% of the Earth’s atmosphere suspended from a high-altitude long-duration balloon. It will be launched from McMurdo Station in Antarctica in the Austral summer where it will observe the southern sky. With a long-hold-time cryogenic receiver, BLAST-TNG is designed to observe for 28 days, and make high-sensitivity maps at sub-arcminute resolution, enabled by arrays of superconducting Microwave Kinetic Inductance Detectors (MKIDs) and a 2.5 m carbon fiber primary mirror.

I have been a member of Dr. Mark Devlin’s BLAST-TNG group at the University of Pennsylvania (Penn) from the very beginning of the project. I joined Dr. Devlin’s lab in 2013, the year first year of NASA funding for the experiment. Throughout my graduate career I have played a role in the design, production, integration, and testing of nearly every hardware system in the experiment.

I designed the telescope mechanical mount and balloon suspension system, and rebuilt and adapted existing structures from the BLAST-Pol balloon gondola to accommodate the huge increases in the size and weight of the telescope and receiver from the previous generation experiment, and prepared the mechanical certification for the NASA Columbia Scientific Balloon Facility required for launch clearance. I developed the thermal model for the entire payload and designed and assembled the Sun shields. I worked closely with the engineering team at Alliance Spacesystems, our commercial partner who built the telescope, writing the interface control document and developing requirements for the optical and mechanical interfaces. I developed
the field integration and alignment plan for the telescope, made measurements to verify the shape secondary mirror and analyzed metrology data from the primary and secondary mirrors to predict the performance of the telescope in flight.

For the last several years I have led the cryogenic receiver development, and the integration of the detector arrays in the BLAST-TNG cryostat. I designed, tested, and built (by hand!) the 1 K cryogenic system. Running the flight receiver is expensive, due to the high cost of the liquid cryogens needed for operation, and time consuming, due to the large mass of the camera optics. To reduce costs and turnaround time for testing various components, I fixed, wired, and set up two small cryostats for testing the fridges and arrays, one pulse-tube system for testing the MKID arrays, and a small liquid nitrogen/helium system for optimizing the 1 K system. When tragedy struck and the flight receiver blew up, I led the rebuild effort, making modifications to the mechanical design to improve performance, designing multilayer insulation (MLI) blankets for commercial fabrication, developing improved safety procedures, spent countless days leak checking, and oversaw the assembly and integration and testing. I helped design and test the cryostat housekeeping electronics, refitted the BLAST-Pol detector readout cards to read the cryostat thermometry, and helped develop and build a new thermometry data acquisition and heater control system based on commercial off-the-shelf electronics.

This thesis is organized around the design of the BLAST-TNG hardware, the requirements to achieve the scientific goals of the experiment, and my contributions to the observation planning for the scheduled upcoming flight in December 2019. In Chapter 1, I describe the scientific motivation for building BLAST-TNG, and how
the experiment is designed to improve on previous generation instruments. Chapters 3 - 5 describe the main hardware systems of the experiment I was involved in: the telescope, the gondola, and the cryogenic receiver. In Chapter 6 I present the CMB foreground observing plan for the upcoming flight, based on foreground modeling and simulations I worked on with Joy Didier at the University of Southern California. A brief summary follows, with the planned schedule for the upcoming launch.
Chapter 2

The Submillimeter Polarized Sky

2.1 How Did We Get Here?

This is the driving question of all of astrophysics. How did the universe change from its fluid-like state after the big bang, so hot and dense that only the most fundamental particles could exist without being ripped apart, into the structured, ordered, universe we observe today with galaxies, stars, planets, and cheese steaks?

Research over the last decades suggests a vivid picture of the earliest moments after the big bang, in which quantum fluctuations were stretched apart faster than the speed of light to cosmic size scales in a process known as inflationary expansion. These cosmic fluctuations planted the seeds for the formation of structure in the universe. As universe began to cool, hydrogen and helium, the first molecules, began to form. This primordial gas began to clump and cool in the denser regions of space, and drift away from the less dense regions of space. Observations indicate that structures formed in a hierarchical manner, with small objects clumping together forming bigger and
bigger objects, eventually becoming the first stars. These stars clustered together in
the first galaxies, and eventually clusters of galaxies. The first generation of stars were
composed entirely of hydrogen and helium, but they would produce the other elements
which would be recycled into later generations of stars and eventually planets like our
own.

There are still many mysteries about the nature of stellar evolution. The details
of the astrophysical processes which govern the formation of structure with galaxies
remain largely unknown. How do stars form in the interstellar medium (ISM)? What
role do magnetic fields and turbulent forces play in the formation of structures in
the ISM? How does the ISM evolve and how does matter move between the dense
and diffuse regions of the galaxy? What are the timescales of various astrophysical
processes, and which of the structures we observe today are persistent objects and
which are in the process of dispersing or collapsing?

Our approach to untangling these questions is to make detailed measurements of
different regions of our own Milky Way. Though the forces which shape the evolution of
stars and galaxies are universal, our own galaxy offers the best view of these processes
in action. Only by studying nearby objects can we look deep within the environments
where stars form, and resolve the complicated filamentary structures that make up
the interstellar medium. We can trace these filaments by making detailed maps of
emission of interstellar dust grains. The polarization of the light emitted by this
dust traces the magnetic field which pervade the ISM. By mapping the correlations
between galactic magnetic fields and the structure of the ISM, we can make statistical
inferences about the physical forces which shape our interstellar environment.
2.2 Lifecycle of Dust in the ISM

The study of interstellar dust can help unravel many unresolved questions about the nature of the evolution of galaxies, and the physical processes that govern the formation of stars and structures within the ISM. Interstellar dust grains make up less than 1% of the mass of the ISM, yet the life cycle of this dust traces the evolution of the ISM itself. These tiny, ~0.1µm grains are ubiquitous, and have been observed throughout the process of star formation, in the protoplanetary disks of new stars where it will eventually form exoplanets and other satellites, in the debris disks of later-stage stars, and in the outflows of supernovae [100].

Stars create the metals that are building blocks of interstellar dust. These elements enter the ISM either as dust particles formed in the ejecta of planetary nebulae and late-phase, cool, giant and supergiants stars, or in the gaseous phase from stellar winds from young, hot stars where they precipitate [34]. The degree of precipitation out of the gas phase can be estimated by comparing the relative abundance (to neutral hydrogen) of these elements in the ISM to that measured stellar environments. This observed decrement of an elemental population compared to solar abundances can be characterized depletion ratio, $D_X$:

$$D_X = \frac{(X/H)_{\text{observed}}}{(X/H)_{\text{solar}}}$$  \hspace{1cm} (2.1)

where $(X/H)$ is the relative abundance of element $X$ compared with neutral hydrogen. Elements that exhibit a high degree of depletion in the ISM compared to solar abundances are thought to have condensed out of the gas phase and precipitated...
into dust grains [35]. Studies of the elements assumed to be in interstellar dust grains suggest depletion ratios of 58% for carbon, and above 90% for silicon, iron, and magnesium [38]. The depletion ratio is suppressed in high-velocity gas with a high degree of turbulent shear, suggesting that in these environments dust grain growth is suppressed by grain-grain collisional processes or “sputtering,” which turn the dust grains back into gas [68]. These measurements indicate that dust grains have a relatively short lifetime in the ISM, compared to age of the Galaxy, and suggest that dust must form continuously in the ISM to explain observed lack of gaseous metals in dusty clouds [34].

While the exact rates of dust grain accretion and erosion are not known, models suggest that they vary greatly between different phases of the ISM. In molecular clouds, the coldest (15-30 K) and densest phase of the ISM, dust is shielded from photo-destruction by ultraviolet (UV) photons, and low gas velocity reduces collisional erosion [34]. Molecular clouds exhibit high depletion rates, the highest degrees of grain growth, and the lowest degrees of grain destruction. In contrast, the warm neutral medium (WNM), comprising diffuse regions with temperatures of 6,000-8,000 K, exhibits the highest rates of grain destruction. However, most of the mass in the ISM not residing in molecular clouds is in the phase considered the cold neutral medium (CNM), with densities and temperatures between that of the WNM and molecular clouds. Conservation of mass in the ISM during transitions between the gaseous and solid form of these metals requires large amounts of mass transfer between ISM phases [35].

Interstellar dust traces the evolution of the ISM. Understanding the nature of dust
formation and composition gives insight into the microphysical forces which shape the structure of molecular clouds, the CNM, and the interstellar environment. The best models of dust evolution are still unreliable, and require more observational data to be refined. However, the optical properties of interstellar dust offer a wealth of information, and infrared and submillimeter observations can help improve our understanding of these complex physical properties.

2.3 Optical Properties of Interstellar Dust

The optical properties of astronomical dust at once enables and confounds the observation of the ISM. At optical wavelengths dust is opaque, shielding stars and other sources from view. The extinction of optical light as it travels through dusty regions can be used to probe the column density of dust clouds [110]. This wavelength-dependent extinction scatters shorter wavelengths more readily, causing reddening of observed starlight. Molecular clouds appear as dark regions in optical observations. In these regions the dust reprocesses the UV and optical radiation from stars and re-emits it in the infrared and submillimeter. It is estimated that as much as 30% of energy emitted by stars is absorbed and reemitted by in the infrared and submillimeter [11]. This thermal dust emission from interstellar dust dominates the submillimeter sky, and is a powerful tool for probing the physics of the ISM and stellar evolution.

The spectral features of interstellar dust give clues to its composition. Dust spectra exhibit strong absorption lines in the far-infrared (FIR), including 9.7 and 18 μm features associated with silicate compounds, and a number of absorption and emission features associated with carbonaceous compounds between 3 and 11 μm. A strong
spectral feature at 2175 Å seen in extinction measurements is also associated with polycyclic aromatic hydrocarbon (PAH) molecules [35]. These features are broader than expected for crystalline materials, and suggest that the grains precipitate as amorphous smoke-like particles. Studies of laboratory-manufactured dust grain analogs have reproduced these broadened spectral features with various iron-rich carbonaceous and silicate compounds [100].

The continuum emission from dust takes the shape of a modified blackbody, peaking in the submillimeter. This spectral energy distribution (SED), $\alpha_\nu$, is typically fit with a blackbody modified by an emissivity function described by a single spectral index, $\beta$:

$$\alpha_\nu(\nu) = \nu^\beta B_\nu(\nu)$$

(2.2)

where $B_\nu(\nu)$ is the Planck blackbody SED. The temperature and spectral index lead to a degeneracy in fitting. Based on cross-correlation studies, and assumptions about the dust grain populations, the Planck satellite has measured the average spectral index over the whole sky at millimeter wavelengths for the dust SED to be $\beta_I = 1.51 \pm 0.01$ for unpolarized emission and $\beta_P = 1.59 \pm 0.02$ for polarized emission [94]. Different values for the spectral indices of the polarized and unpolarized emission are not surprising. The strength of the polarized emission depends both on the total intensity of the dust and the degree of polarization, which is inversely proportional to the column density of the surrounding gas.

The polarization properties of interstellar dust can be used to trace the direction

---

1 Using a far-infrared integrating sphere reflectometer I built for my undergrad thesis
of magnetic fields. Amorphous dust grains are highly irregular in shape. If the grains have some degree of helicity, in an anisotropic radiation field, differential scattering from starlight will cause the grains to spin about its principle spin axis, and tend to precess about the magnetic field [74]. Through a process known as radiative torques (RATs), the spin axis will align with the B-Field direction, with the long axis of the grain aligned perpendicular to the magnetic field direction. Aligned dust grains act as a polarizing grid, preferentially absorbing and emitting linearly polarized light along the direction of this long axis. The efficiency of this preferential absorption depends on the degree of grain alignment[4]. As shown in Fig. 2.1, the dust grains preferentially absorb light from sources from within and behind the dust clouds along their long axis. This effect causes a net polarization of infrared and optical light from background stars along the direction parallel to the magnetic field. This absorbed light is reemitted in the submillimeter, again along the long axis of the grains. This leads to a net polarization in the submillimeter emission along the direction perpendicular to their long axis. The extinction of visible light and the emission of infrared and submillimeter light can both be used over the same regions providing there are background stars, to produce complementary measurements of the magnetic field direction [102].

Measuring the spectral dependence of the fractional polarization of this submillimeter emission is a powerful tool for tuning and evaluating analytical models of dust grain composition [37]. This spectrum has been exhaustively measured in the millimeter range by *Planck* [92], but limited data in the submillimeter has left these models largely unconstrained at shorter wavelengths[36]. Recent results from the 2012 BLAST-Pol experiment represent the first submillimeter polarization spectrum.
measurements over the full extent of a molecular cloud [53], and of a translucent molecular cloud [7].

Figure 2.1: Schematic of the preferential absorption and emission of aligned dust grains from [104]. Left: the grains preferentially absorb radiation from background sources along their long axis, leading to a net polarization parallel to the magnetic field. Right: the grains reemit absorbed radiation in the submillimeter along their long axis, leading to a net polarization in emission perpendicular to the magnetic field.

BLAST-TNG, like its predecessor BLAST-Pol, uses the submillimeter polarimetry approach to measure the magnetic field morphology of dusty regions of the ISM. While this approach does not measure the strength of the magnetic field directly, the dispersion of the polarization vectors depends on the strength of the field [25] and the equipartition of the turbulent and magnetic field energies [83]. High-resolution maps of the magnetic fields in molecular clouds can be used to make statistical inferences about the role of magnetic fields in star formation and their relative strength compared
with the thermal and turbulent pressures, and gravitational forces [46].

2.4 Magnetic Fields in Molecular Clouds

For decades, there has been much debate as to why star formation is such an inefficient process, and why observed star formation rates in molecular clouds are many times lower than that predicted by simple gravitation collapse models. The internal structure of molecular clouds are shaped by a competition between gravitational attraction, magnetic fields, and pressure forces from turbulence, thermal energy, and cosmic ray flux [83]. The relative strength of the magnetic and turbulent energy densities is extremely important for predicting the evolution of structures within molecular clouds, as seen in Figure 2.2. In the strong-field limit, the magnetic field energy density dominates the effect of turbulence, while in the weak-field limit, the magnetic field is dominated by the turbulent energy density. At their most extreme, these strong and weak-field regimes set up two distinct paradigms for star formation in molecular clouds.

In the turbulence-dominated, weak-field regime, molecular clouds are not persistent structures. Gas will still coalesce into dense clouds under gravitational attraction, but will drag the magnetic field along with it. In this regime, the turbulent velocity of the gas plays a much stronger role, as shock waves and turbulent flows will regulate where and when dense structures are allowed to form. These dense clouds are still the locus of star formation in the galaxy, but there is no need for a theoretical framework to explain long-term cloud support against gravitational collapse [83].

In the strong-field regime, the flow of matter is dictated by the magnetic field
morphology. There will always be some fraction of the gas that will be ionized due to photoionization from UV radiation fields around hot stars. These ionized particles will drag the surrounding gas along the magnetic field lines. Dense structures will still form under gravitational attraction, but because the mass is constrained to move along the magnetic field, the densest structures will form perpendicular to the field lines[83]. In this model, molecular clouds are persistent structures supported by the magnetic fields against gravitational collapse.

Figure 2.2: Figure from Soler et al, 2013 [106] of simulations of a molecular cloud with a fixed initial turbulent component and a set magnetic field strength that is varied between runs. Color shows the logarithm of the column density along the line of sight with higher column density structures in red and lower in blue. A line integral convolution is performed between the column density map and the magnetic field psuedo-vectors which produces the ripple-like pattern (Cabral and Leedom, 1993). Left: The case with a weak magnetic field that is much lower than the turbulent energy. The magnetic field orientation is chaotic, and is correlated with the structure over a broad range of column densities. Right: A simulation with a much stronger magnetic field that dominates the turbulent energy. The magnetic field is more coherent over the map and is correlated with the orientation of the densest structures.
Combining magnetic field observations from submillimeter polarimetry with simulations offers the best method for determining the relative strengths of the magnetic and turbulent forces. By comparing statistical metrics for the degree of alignment between the magnetic field vectors and the iso-density contours and filamentary structures from simulations to measurements from molecular clouds with different properties we can begin to evaluate the relative strength of the magnetic field. Data from the *Herschel* satellite have shown that the interstellar medium (ISM) is pervaded by long, gravitationally-bound filamentary structures [64] which are rich with dense prestellar cores. Data from polarimeters like *Planck* and BLAST-Pol [90; 109] have shown that the magnetic fields are highly coherent and aligned with the density contours.
Figure 2.3: Figures from [109], showing alignment of magnetic field and density structures towards the Vela C molecular cloud, as measured by the 2012 BLAST-Pol experiment. **Top:** the line-integral convolution of magnetic field vectors measured by BLAST-Pol with high-resolution maps of column density of neutral hydrogen from *Herschel*. The column density is represented by the color scale. The named regions correspond to areas with different optical properties studied by [64]. The region colored red represents a hot ionized region around one or more young, hot stars. This photoionized region exhibits different properties than the surrounding cloud and is not included in analysis of the molecular cloud physics.
Figure 2.4: The histogram of relative orientations (HRO) between the magnetic field vectors and isodensity contours in the molecular cloud, [109]. The data is averaged over the four labeled regions in the plot at right. The blue, green, and red curves correspond to the analysis of the BLAST-Pol observations at 250, 350, and 500 µm, respectively. The vertical axis is the relative orientation parameter, $\xi$, which describes the mean orientation between the magnetic field and the density structures and the horizontal axis plots increasing column density. $\xi > 0$ corresponds to mostly parallel alignment between the field and structures, while $\xi < 0$ corresponds to mostly perpendicular alignment. For the regions toward Vela C, the most diffuse regions tend to be aligned parallel to the magnetic field, and the densest structures tend to be aligned perpendicular, suggesting the magnetic fields play an important role in shaping the cloud.

As shown in Figs. 2.3 and 2.4, the degree and orientation of this alignment depends on the column density along the line of sight, with the most diffuse areas of the cloud oriented parallel to the field, and the densest structures oriented perpendicular to the field [109]. These results agree with simulations from Soler et. al, 2013 [106], shown in Figure 2.2, in which the magnetic field plays a strong role in shaping the structure of the cloud.

Making a more precise evaluation of the role of magnetic fields in star formation
requires deeper maps (to observe into dimmer, more diffuse regions) from many more molecular clouds (to obtain a statistically significant sample of targets) observed at higher resolution than were possible with *Planck* and BLAST-Pol (to trace fields into the densest filaments). The BLAST-TNG experiment is designed to achieve exactly these goals.

### 2.5 The BLAST-TNG Experiment

The Next Generation Balloon-Borne Large Aperture Submillimeter Telescope (BLAST-TNG) is a submillimeter mapping experiment which features three microwave kinetic inductance detector (MKID) arrays operating over 30% bandwidths centered at 250, 350, and 500 \( \mu m \). These highly-multiplexed, high-sensitivity arrays, featuring 918, 469, and 272 dual-polarization pixels, for a total of 3,318 detectors. These arrays are coupled to a 2.5 m diameter primary mirror and a cryogenic optical system providing diffraction-limited resolution of 30\( '' \), 41\( '' \), and 50\( '' \) respectively. The arrays are cooled to \( \sim 275 \) mK in a liquid-helium-cooled cryogenic receiver which will enable observations over the course of a 28-day stratospheric balloon flight from McMurdo Station in Antarctica as part of NASA’s long-duration-balloon (LDB) program, planned for the 2018/2019 winter campaign. BLAST-TNG is the successor to the BLASTPol and BLAST balloon-borne experiments which flew five times between 2005 and 2012[88; 47].

Achieving diffraction-limited, sub-arcminute resolution and telescope pointing accuracy is one of the highest priorities for the success of the BLAST-TNG mission. Although the science goals of BLAST-TNG are similar to the 2012 BLAST-Pol mission, most of the major instrument systems have been rebuilt and improved since the last
flight. A new 2.5 m aperture Cassegrain telescope featuring a lightweight carbon fiber reinforced composite (CFRP) primary mirror designed and built by Alliance Spacesystems\textsuperscript{2} will enable an increase in resolution from 2.5′ to 30″ at 250 µm. This increased resolution will, for the first time, give BLAST-TNG the ability to probe the magnetic fields within the thin, \~0.1 pc wide, filamentary structures within molecular clouds. With improved detector sensitivity and a increase in detector count by a factor of 12, BLAST-TNG will have 16 times the mapping speed of BLASTPol. The new cryostat has demonstrated a 28 day “hold time,” the length of time the cryostat can stay cold before all the liquid cryogens boil away. This extended hold time enables observations of many more targets at greater depth than were possible during the \~13 day BLASTPol 2012 flight.

2.5.1 Star Formation in Molecular Clouds

The primary science goal of BLAST-TNG is to map the polarized thermal emission from galactic interstellar dust around star-forming regions and in the diffuse interstellar medium (ISM). These maps will yield \~250,000 polarization vectors on the sky, allowing us to explore correlations between the magnetic field dispersion, polarization fraction, cloud temperature, and column density. Quantifying the relationships between these variables over a large sample of clouds will yield testable relationships which can be fed back into numerical simulations.

The \textit{Planck} satellite has observed strong correlations between orientation of Galactic magnetic fields and large-scale ISM structures [94], as well as the interior of giant

\textsuperscript{2}4398 Corporate Center Dr, Los Alamitos, CA 90720
molecular clouds (GMCs)[93]. While BLAST-Pol was able to observe the magnetic fields within GMCs at higher resolution than Planck [47; 109], BLAST-TNG will be the first experiment with the ability to measure both the large-scale magnetic fields around GMCs, and probe the fields within the characteristic filamentary structures within GMCs observed by Herschel [64]. BLAST-TNG will trace these field lines down to much smaller scales to measure the dispersion of the fields within and along the filaments themselves with unprecedented resolution. These measurements will complement the sub-arcsecond resolution submillimeter measurements that can be made by the ALMA telescope of field lines around prestellar cores forming within these structures [90; 66].
Figure 2.5: BLASTPol provides the critical link between Planck’s all-sky submillimeter polarimetry and ALMA’s sub-arcsec resolution polarimetry at similar wavelengths. At upper left is a Galactic-scale Planck magnetic field map employing the “drapery” method for displaying field directions followed by the BLASTPol Vela C map (Fissel et al. 2016; Soler et al. 2017) and a very recent ALMA magnetic field map for the protostellar source Ser-emb 8 in the Serpens molecular cloud (Hull et al., 2017, submitted). BLASTPol will map magnetic fields using a 25 arcsec FWHM beam at 250 microns. This beam nearly matches the ALMA field-of-view and is more than 200 times smaller (in area) than Planck’s beam.

Combining the BLAST-TNG data with molecular cloud simulations [106] and numerical models of dust grains [37] will give unprecedented insight into the interplay between gravitational, turbulent and magnetic field contributions to star and cloud formation, as well as the physics of grain alignment and mass flow within the clouds.
2.5.2 CMB Foregrounds

Polarized dust emission is also the dominant foreground for observations of the cosmic microwave background (CMB). Characterization of these foregrounds is one of the most important requirements in the search for the gravitational wave signature of cosmic Inflation [2]. While the power spectrum from polarized dust foregrounds is thought to be lowest at small angular scales, there are limited high-resolution observations of the diffuse ISM [93; 19]. BLAST-TNG will be able to make the deepest maps to date of the dust emission in the darkest patches of the sky observed by state of the art CMB polarization experiments, at angular scales not well-characterized to date, and explore correlations between diffuse dust emission and structures in the cold neutral medium [54]. The intensity of thermal dust signal rises steeply as a function of frequency in the submillimeter. With its high pixel count and photon-noise-limited detectors, BLAST-TNG will produce maps of diffuse ISM with higher fidelity than the highest frequency Planck maps at 353 GHz.
Chapter 3

The BLAST-TNG Telescope

Achieving diffraction-limited, sub-arcminute resolution and telescope pointing accuracy is one of the highest priorities for the success of the BLAST-TNG mission. Although the science goals of BLAST-TNG are similar to the 2012 BLAST-Pol mission, the telescope is being entirely redesigned and rebuilt from the ground up, with new optics, a long-hold-time cryogenic receiver, monolithic detector arrays of thousands of dual-polarization-sensitive microwave kinetic inductance detectors (MKIDs), and an improved, more stable gondola which will greatly increase the pointing accuracy.

In order to meet our angular resolution requirements, BLAST-TNG must feature large-aperture, lightweight telescope mirrors. Building large aperture balloon-borne telescopes optics is particularly challenging. With inadequate support, gravitationally-induced sag can introduce serious aberrations, yet support structures must be small enough to fit on NASA launch vehicles, and light enough not to compromise altitude during flight. Achieving diffraction-limited performance in the submillimeter requires highly accurate optics with rms wavefront errors of order $\sim 10\mu m$. Traditional mirror
fabrication techniques are inadequate to meet all the requirements for BLAST-TNG within the budget of a balloon mission. To date, most balloon payloads operating in the millimeter/submillimeter wavebands have used aluminum mirrors, but have been limited by mechanical constraints to less than 2 m in diameter, including BLAST-Pol (1.8 m) [88] and EBEX (1.5 m) [85]. The SOFIA instrument features the largest sub-orbital primary mirror to date, at 2.7 m [14], made out of Zerodur, a ceramic silicate material that is lighter and stiffer than aluminum. However, while SOFIA’s nearly 880 kg primary mirror is well-suited for a large airplane, it is unacceptably heavy for a balloon experiment. Low-density metals, such as the beryllium alloy used in the construction of the JWST mirrors [60] are extremely expensive, making them risky to use on a balloon mission where they may not be recovered after flight.

The CFRP mirror which will fly on BLAST-TNG represents a significant technological development and research effort. CRFP composites have many advantages over traditional metal mirrors. They have a strength-to-weight ratio many times that of aluminum, they also have a near-zero coefficient of thermal expansion, which is especially desirable for a balloon platform, as the thermal environment in flight can be unstable. Large-aperture composite mirrors with high surface accuracy have been demonstrated in the submillimeter. The first launch of the BLAST experiment featured a 2 m composite primary mirror developed for the Herschel space telescope [24], although its performance in flight was degraded due to a lack of active focusing control. With a 2.5 m aperture, the BLAST-TNG primary mirror will be both the largest mirror ever flown on a balloon experiment, and the largest CFRP telescope mirror operating at submillimeter wavelengths (THz frequencies). This mirror was
being designed in partnership with a commercial collaborator, Alliance Spacesystems, under a NASA Small Business Innovation Research (SBIR) contract.

### 3.1 BLAST-TNG Optical Architecture

The BLAST-TNG optics design is based on a 2.5 m aperture on-axis Cassegrain telescope, with a CFRP composite primary mirror and an aluminum secondary mirror. The secondary mirror is mounted on three linear actuators which can move the secondary in piston/tip/tilt to account for changes in telescope focus due to differential thermal contraction of the telescope mirrors, CFRP support struts, and the aluminum gondola. The optical design is shown in Figure 3.1.

![Ray trace of the BLAST-TNG optics design from Zemax design software.](image)

**Figure 3.1:** Ray trace of the BLAST-TNG optics design from Zemax design software. The left-hand side shows the on-axis Cassegrain telescope formed by the primary (M1) and secondary mirrors (M2). The Cassegrain focus lies within the 4 K optics box, shown in the small rectangle, as well as the blown up inset. Light enters the optics box towards the top left side of the enclosure where it passes through the window of the cryogenic receiver and a series of filters. After these filters, the first optical element is the broadband achromatic half wave plate (AHWP), followed by the modified Offner relay formed by the three mirrors M3, M4 (the Lyot stop), and M5. The location of the three focal plane arrays are shown schematically.
The telescope feeds a cold (4 K) reimaging optics system which refocuses the beam onto three focal plane arrays. The cold optics are arranged in a modified Offner relay configuration, shown in the inset of Figure 3.1. A similar configuration was flown in the BLAST/BLAST-Pol optics box. This configuration has several advantages, namely (1) it is compact, a necessary condition for running the optics in a liquid-helium-cooled cryostat, (2) the main optical elements all lie in a single plane, allowing all the elements to be mounted to a single sturdy optics bench, (3) the modified relay can remap the beam such that the beam on the focal planes has a different F/# than the telescope beam, and (4) the cryogenic Lyot stop allows us to limit the illumination of the primary mirror which reduces the thermal loading on the detectors. The cold optics simultaneously illuminate three focal plane arrays of Microwave Kinetic Inductance detectors, which are optically coupled via single-mode feedhorns. The feedhorns were designed and machined at Arizona State University, based on a modified Potter design [98], and were drilled from a monolithic aluminum block with custom-manufactured drill bits.

Figure 3.2: Spot diagrams from Zemax showing the modeled beam profile on various optical surfaces. **Left**: The beams of the central field of the focal plane and four edge fields on the Lyot stop. All fields fill the Lyot stop perfectly. **Center**: Illumination of the primary mirror for the central field. **Right**: Illumination of primary mirror from center and edge fields.
The cold Lyot stop at an image of the primary mirror acts as the limiting aperture of the system. The Lyot stop limits the central beam illumination of the primary mirror to 2.27 m. The detector feedhorns provide a near-Gaussian beam which overfills the Lyot stop, and tapers the illumination by 4.6 dB the edge of the Lyot to reduce ringing in the beam. The illumination of the primary and secondary mirrors and the Lyot stop are shown in Fig. 3.2. While all of the feedhorn beams from each of the focal plane arrays overlap on the Lyot stop, they do not illuminate the same area of the primary mirror. A summary of the BLAST-TNG telescope optical design is given in Table 3.1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Mirror</td>
<td>Clear Aperture</td>
<td>2500.0 mm</td>
</tr>
<tr>
<td></td>
<td>Radius of Curvature</td>
<td>4132.10766 mm</td>
</tr>
<tr>
<td></td>
<td>Conic Constant</td>
<td>-1.000</td>
</tr>
<tr>
<td>Secondary Mirror</td>
<td>Clear Aperture</td>
<td>573.0 mm</td>
</tr>
<tr>
<td></td>
<td>Radius of Curvature</td>
<td>1209.82622 mm</td>
</tr>
<tr>
<td></td>
<td>Conic Constant</td>
<td>-2.380136</td>
</tr>
<tr>
<td>Telescope</td>
<td>Primary Vertex to</td>
<td>1590.0 mm</td>
</tr>
<tr>
<td></td>
<td>Secondary Vertex</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EFL</td>
<td>9698.82 mm</td>
</tr>
<tr>
<td></td>
<td>F/#</td>
<td>3.87953</td>
</tr>
<tr>
<td></td>
<td>FOV</td>
<td>23 arcminutes</td>
</tr>
<tr>
<td></td>
<td>Obscuration Ratio</td>
<td>7.871%</td>
</tr>
<tr>
<td></td>
<td>Strut Obscuration Ratio</td>
<td>2.618%</td>
</tr>
</tbody>
</table>
3.2 NASA/SBIR Commercial Partnership

The BLAST-TNG telescope was developed through a commercial partnership with an aerospace carbon fiber composites company, enabled through the NASA Small Business Innovation Research (SBIR) contract. In the 2013 Phase I proposal, written jointly by the BLAST team at the University of Pennsylvania and Vanguard Space Technologies (VST), (now Alliance Spacesystems LLC \(^1\)), Vanguard proposed to develop a lightweight (<100 kg), large-aperture (2.5 m), high-surface accuracy (<10\(\mu\)m WFE), low-recurring cost (<$300k) telescope for BLAST-TNG. The telescope was to serve as a technology pathfinder to develop low-cost composite telescope optics for future CMB space missions. The NASA SBIR partnership was facilitated by input from H. Philip Stahl at NASA/MSFC, the manager of the Advanced Optics SBIR topic. NASA was excited that the proposal would produce a piece of science-quality demonstration hardware that would be flight-tested on a NASA-funded mission, rather than just simulations and/or test pieces as many SBIR programs have historically.

Successful completion of the telescope required clear communication between manufacturing team at Alliance and the science team at Penn. At times this communication was complicated by administrative hurdles and the fact that Vanguard/Alliance officially reported to NASA not Penn. This became especially true when Vanguard was acquired by Alliance, changing their status as a small business, and government confidentiality agreements barred Alliance from discussing the project with the Penn group. Additionally, the manufacturing and science teams often spoke different technical languages, and had different approaches to solving various problems. During

\(^1\)4398 Corporate Center Dr, Los Alamitos, CA 90720
the engineering phase of the project, Vanguard brought in an outside optical engineering consultant who was critical to translating the science requirements to the manufacturing/engineering groups.

3.3 Telescope Requirements

The performance requirements of the telescope are ultimately driven by the science goals of the experiment. The size scales, distance, and brightness of the clouds that BLAST-TNG plans to map place constraints on the minimum angular resolution and sensitivity of the telescope optical system. These optical characteristics in turn determine the resolution and signal-to-noise ratio (SNR) of the maps produced. During pre-flight planning and target selection it is important to have accurate models of the anticipated telescope parameters to ensure that the observing time is properly allocated to make the most of the flight. A poor understanding of the telescope parameters can result in maps with inadequate SNR, or that do not resolve critical astronomical features. In the worst case unanticipated telescope aberrations can render the maps so distorted as to be unusable.
3.3.1 Diffraction-Limited Performance

The primary optical requirement for the BLAST-TNG telescope is that the performance be “diffraction-limited.” This is essentially a requirement that that the optical performance not be limited by the subtleties of the telescope manufacturing process, but rather by the fundamental diffraction pattern of the telescope aperture. A “perfect” optical system, that is, one with no aberrations, will still be affected by diffraction.

The illumination pattern of a optical system can be calculated from Huygen’s principle [61], which says that each point within the aperture of the system will act as a point source for spherical electromagnetic wavefronts. The focus of the optical system is the point for which all rays over the aperture arrive at the same point at the same time. At this point the optical path difference between all rays (OPD) is zero. Rays incident on the aperture from different angles will arrive at the same plane, but will be displaced spatially. For two point sources at infinity separated by an angle $\alpha$, the physical separation, $dx$ at the focal plane for is determined by the focal ratio of the telescope, $f$:

$$dx = f \alpha$$  \hspace{1cm} (3.1)

The illumination pattern at the focal plane is given by the vector sum over the aperture of these wavefronts, which interfere with each other to produce the areas of constructive and destructive interference. This vector sum is equivalent to taking the square of the Fourier transform of the pupil transmittance function. For a circular aperture with pupil diameter $D$, the pupil function can be expressed in normalized
polar coordinates, following the convention in [113], where $\rho = r/D$:

$$P(\rho, \theta) = \begin{cases} 
1 & \text{if } \rho \leq 1.0 \\
0 & \text{if } \rho > 1.0
\end{cases} \quad (3.2)$$

The illumination at the focus can be calculated from the amplitude point spread function, $A'$:

$$A' = \mathcal{F}\{P(\rho, \theta)\} \quad (3.3)$$

Note that in general, the amplitude point spread function is a complex function. The intensity at the image plane is given by taking the complex conjugate, or square, of $A'$:

$$I = A'^* A' = [\mathcal{F}\{P(\rho, \theta)\}]^2 \quad (3.4)$$

This intensity or illumination function is by definition real-valued, and is typically what is meant when people refer to the point spread function, or PSF, of an optical system. I will follow the convention in [113] and refer to $A'$ as the amplitude PSF, and refer to $I$ as the PSF.

For the circular aperture described above, the amplitude PSF is given by:

$$A_{\text{circ}}(\nu) = \frac{2J_1(\nu)}{\nu} \quad (3.5)$$

where $\nu$ is the spatial frequency in dimensionless units at the focal plane from [103], which can be expressed in terms of physical radial distance $r$ or angular distance $\alpha$. 
from the center of the focus:

\[ \nu = \frac{\pi r}{\lambda} F = \frac{\pi D\alpha}{\lambda} \quad (3.6) \]

where \( F = f/D \) is the focal ratio of the telescope, and \( \lambda \) is the wavelength of light.

Any real optical system will deviate from the “perfect” optical prescription. These deviations introduce OPD between wavefronts arriving at the focus known as wavefront error or WFE. Deviations from the reference optical prescription are typically classified by the spatial size scales on which they affect the transmission. These spatial scales are often expressed in generalized wavelength units based on either the wavelength of observation or the size of the aperture in “cycles per radius.” [113].

Low-frequency (large-spatial-scale) errors, on the order of 1-5 cycles per radius, describe errors in the mirror figure. For the telescope optics these can include tip/tilt/defocus errors, and deviations from the reference prescription radius of curvature or conic constant. These errors can be mitigated by re-positioning the secondary mirror. Low frequency errors also include large-scale aberrations like coma, astigmatism, and trefoil which can cause serious deformation of the beam.

Mid-frequency (middle-spatial-scale) errors generally describe those on spatial scales smaller than 5 cycles per radius, and up to 100\( \lambda \). This broad range covers ripples in the optical surface of the mirrors from polishing defects, lay patterns from machining, and large-scale roughness of the optics. The general affect of these errors is to remove light from the central peak of the PSF and scatter it out to higher angular scales (higher-order Airy rings). The exact nature of this scattering depends strongly on the exact spatial scales of the errors, the randomness/periodicity of the
error distribution.

High-frequency (small-spatial-scale) errors describe surface microroughness on the order of $100\lambda$ and smaller size scales. Like the mid-frequency errors, this roughness dims the central peak and tends to uniformly distribute the power to higher-order angles.

For a generalized system with wavefront error, the pupil transmission depends on the phase of the incoming radiation. In this case the transmission is described by the complex pupil function, $\mathcal{P}(\rho, \theta)$, where $(\rho, \theta)$ describe the pupil in polar coordinates. Continuing to follow the convention in [113], the complex pupil function is given by:

$$
\mathcal{P}(\rho, \theta) = P(\rho, \theta)e^{i2\pi w(\rho, \theta)} \tag{3.7}
$$

where $w(\rho, \theta)$ describes the position-dependent wavefront error of the pupil transmittance.

### 3.3.2 Statistical Models of Optical Performance

The wavefront error is often measured and modeled statistically, based on measured deviations from the reference optical prescription. The WFE can be described by the RMS deviations from the reference optical surface. These deviations can be calculated on different spatial scales, which are fully expressed by the power spectral density (PSD) as a function of spatial frequency. The spatial scales of surface errors on the optical surface can be modeled statistically by calculating the normalized autocorrelation function of the surface residuals:
\[ C(x, y) = \frac{1}{w^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} w(x + x', y + y')w(x - x', y - y')dx'dy' \] (3.8)

This autocorrelation is often modeled as a Gaussian random distribution, which can be described by a correlation length, \( \ell \), which describes the mean spatial scale of the deviation. Assuming the autocorrelation integral is radially symmetric:

\[ C(\rho) = e^{-\rho^2/\ell^2} \] (3.9)

The total RMS WFE on all size scales is a useful measure for the total deviation. While this does not describe all the information about the nature of the deviations, it is a useful statistic, especially for “near-perfect” optical systems without dramatic aberrations [103]. For optical surface, the RMS surface error, \( \sigma \), can be calculated from measured surface deviations from the best fit conic, \( \delta_{z,i} \):

\[ \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (\delta_{z,i})^2 \] (3.10)

The WFE for reflective surface is twice the surface error, since the OPD is traversed by both the incident and reflected ray. Thus the RMS WFE, \( w \), is simply:

\[ w = 2\sigma \] (3.11)

The net effect of the wavefront errors on the telescope PSF is often quantified by the Strehl ratio, \( S \), which describes the dimming of the central peak of the Airy disk. The Strehl ratio is taken to be the ratio of the peak intensity of the “real” optical system, \( I(0) \), to that of an equivalent “perfect” optical system, \( I_p(0) \):
In the case of an obscured aperture, as in the case of the BLAST-TNG optical system, which has a central obscuration and secondary mirror supports which block the aperture, the Strehl ratio is normalized by the pupil transmittance function, $\tau_p$, which is the ratio of the unobscured area to the total area of the pupil [113]:

$$\tau_p = 1 - \frac{A_{obs}}{\pi(D/2)^2}$$  \hfill (3.13)

$$S = \frac{I(0)}{\tau_p I_p(0)}$$  \hfill (3.14)

For an optical surface with random distributions of wavefront errors, and low levels of total distortion, the Strehl ratio is well-approximated by the Ruze formula [101]:

$$S \approx e^{-(2\pi w/\lambda)^2}$$  \hfill (3.15)

which is also found in the literature by applying a further Taylor expansion [103; 113]

$$S \approx 1 - (2\pi w/\lambda)^2$$  \hfill (3.16)

For reasonably small WFE, reduction in Strehl is independent of the correlation length, providing that most of the error is on scales significantly smaller than the aperture [101]. Equations 3.15 and 3.16 are plotted in Figure 3.3. Equation 3.15 is
also plotted in Figure 3.4 where the colored areas describe the wavebands for each of
the BLAST-TNG arrays, centered at 250, 350, and 500 \( \mu m \).

\[
S = e^{-\left(\frac{2\pi w}{\lambda}\right)^2}
\]

\[
S = 1 - \left(\frac{2\pi w}{\lambda}\right)^2
\]

Figure 3.3: Estimated Strehl Ratio from Ruze Formula in Normalized Wavelength
Units
Diffraction-limited performance is not an exact specification, but there are several general rules which quantify the maximum allowable reduction in Strehl before the PSF shows clear degradation compared with a perfect system. The most common definition of diffraction-limited performance is the Maréchal Condition that the Strehl ratio must be greater than or equal to 80%. This is a similar condition to the Rayleigh quarter-wave criterion that the RMS WFE be less than or equal to $\lambda/4$ [16]. For WFE greater than this range, the statistical arguments in the Ruze formula begin to break down, and the approximation quickly becomes a poor representation of the
PSF. Combining the Ruze formula and the Maréchal condition gives:

\[
w_{D,L} \lesssim 0.075\lambda \lesssim \lambda/14 \quad (3.17)
\]

### 3.3.3 Telescope Optical Requirements

The BLAST-TNG telescope must maintain diffraction-limited performance under all combined stresses and loading conditions throughout the anticipated 28-day LDB flight. The telescope must be operational on the ground for pre-flight integration and characterization, and must operate in flight over a broad range of temperatures and pointing angles.

To ensure diffraction-limited performance the driving requirement for the telescope design was that the total wavefront error (WFE) of the telescope be no greater than 10 μm rms under all combined loading conditions. This requirement would ensure that the telescope Strehl ratio be no less than \( \approx 90\% \) across all wavebands. A summary of the telescope performance specifications is given in Table 3.2.

There are three major loads that the telescope was designed to operate under. These loads were studied extensively with finite element modeling (FEM) trade studies which ultimately drove the final design of the telescope optics and support system:

1. **Gravity Sag**

   Gravity-induced sag is the dominant loading stress for the BLAST-TNG telescope. Ground-based telescopes do not have strict limitations on the mass of telescope support structures, and space-borne missions which have extremely demanding mass limits are not affected by gravity sag at all. Sub-orbital
flights occupy the worst of both worlds – having both gravitational stresses and mass constraints.

2. Thermal Soak/Gradients During the flight, the telescope will operate with a thermal shroud or sunshield which should help control the thermal environment and block direct solar illumination. Even so, we anticipate large thermal gradients across the structure, in particular between the primary and secondary mirrors. These gradients were measured to be up to 15-20°C during the 2010 and 2012 BLAST-Pol flights. To account for this, the ability to refocus the telescope in flight is critical.

3. Hygroscopic Strain The resin in CFRP composites exhibits temperature-dependent absorption of water vapor. The amount of water vapor absorbed by the composite depends on the relative humidity (RH) of the environment. The rate at which the moisture content of the composite changes is inversely proportional to the environment temperature [8]. As the mirror absorbs (desorbs) water it will grow (shrink) changing the radius of curvature and the conic constant similar to a change in temperature.
Table 3.2: BLAST-TNG Telescope Performance Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope Wavefront Error</td>
<td>$\leq 10 , \mu m$ rms</td>
</tr>
<tr>
<td></td>
<td>$\leq 7 , \mu m$ rms on 50-250 cm scales</td>
</tr>
<tr>
<td>Primary Mirror Surface Error</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\leq 4 , \mu m$ rms on 5-50 cm scales</td>
</tr>
<tr>
<td></td>
<td>$\leq 2 , \mu m$ rms on 0-5 cm scales</td>
</tr>
<tr>
<td>Secondary Mirror Surface Error</td>
<td>$\leq 1 , \mu m$ RMS</td>
</tr>
<tr>
<td>Operational Elevation Range</td>
<td>$0^\circ$ to $60^\circ$</td>
</tr>
<tr>
<td>Change in Pointing Error from $20^\circ$ to $60^\circ$</td>
<td>$&lt;10$ arcseconds</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>$-20 \pm 15 , ^\circ C$</td>
</tr>
<tr>
<td>Temperature Difference Between Primary and Secondary Mirrors</td>
<td>$&lt;20^\circ$ C</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>$3$ mbar</td>
</tr>
<tr>
<td>Secondary Mirror In-Flight Positioning</td>
<td>$\delta Z_{\text{min}} = 10 , \mu m$</td>
</tr>
<tr>
<td>Total Mass</td>
<td>$&lt;150$ kg</td>
</tr>
<tr>
<td>First Natural Frequency</td>
<td>$&lt;35$ Hz</td>
</tr>
<tr>
<td>Strut Obscuration Ratio</td>
<td>$&lt;3$</td>
</tr>
</tbody>
</table>
Figure 3.5: Preliminary WFE budget for the BLAST-TNG telescope from [21]. All contributions to the WFE are assumed to be statistically independent, and are added in quadrature. This assumption is not necessarily valid for each contribution, but the approach is useful to estimate the WFE requirements for various aspects of the manufacture, assembly, integration, and testing of the telescope. This optimistic WFE budget approximately satisfies the <10µm RMS WFE goal for the telescope.
Figure 3.6: Preliminary WFE budget for the BLAST-TNG telescope from [22]. All contributions to the WFE are assumed to be statistically independent, and are added in quadrature. This WFE is driven by more realistic assumptions about the WFE of M1 (see Section 3.5.1).

### 3.4 Telescope Design and Fabrication

The BLAST-TNG telescope design is comprised of three major components: the primary and secondary mirrors which form the telescope beam, and a sturdy optical bench. The design of each of these components is detailed in the sections below. The final design of each component is the result of exhaustive finite element modeling, trade studies, and incorporates lessons learned from previous mirror designs. The design team had experience building and designing previous generations of BLAST [88] as well as composite optics and reflectors for NASA space missions including *Herschel* [23], WMAP space telescope [86], and MAVEN [27]. The main elements of the telescope are detailed in Figure 3.7.
Figure 3.7: The completed BLAST-TNG telescope during assembly at Alliance Spacesystems, showing the primary and secondary mirrors, the CFRP struts and optical bench, and secondary mirror actuators. The aluminum flexures mount to the aluminum gondola inner frame.

### 3.4.1 Optical Bench and Support Structures

The optical bench, or reaction structure, supports the primary mirror, the secondary mirror struts, and mounts to the balloon gondola. It is responsible for holding the mirrors in a low-stress, kinematic configuration to maintain precise alignment between the mirrors and the cryogenic receiver while not transmitting bending stresses to the optical surfaces. The optical bench is built of flat composite laminates bonded together in a rigid, box-like structure with internal webbing. The laminates are layers of uni-directional tape where all the fibers are oriented in a single direction, as opposed
to woven material. To achieve nearly isotropic stiffness and thermal expansion in the plane of the laminate, the orientation of each layer of the laminate is rotated by 45 degrees from the previous layer. The layers are then vacuum-pressed together and heat-cured. The bench itself is roughly 15 cm thick. The strength and rigidity of the bench is proportional to the thickness. In order to increase the thickness of the bench without altering the location of the primary mirror surface, the front facesheet has a cutout so that the rear surface of the primary mirror sits below the front of the bench. A photograph of bench during assembly is shown in Figure 3.8 showing the inner supports and the cutout on the front facesheet.

![Figure 3.8: Photo showing the assembly of the optics bench. The bean bags keep pressure on the assembly during bonding.](image)

The primary mirror is supported by a pseudo-kinematic mount comprised of three
bipods. Each bipod is made of two composite tubes, referred to as the “M1 Struts.” The tubes have an inner diameter of 1.75 in, a wall thickness of 0.25 in, and are roughly 12 in long. The tubes are bonded to aluminum fittings on each end. On one end these fittings bolt to aluminum fittings on the side of the optics bench, and on the other are bolted to Invar fittings bonded to the interior webbing of the primary mirror. The struts and metallic fittings are shown during assembly in Figure 3.9. FEM showed that making the metallic fittings bonded to the primary mirror out of invar was critical for managing the deformation of the primary under thermal stresses. Invar, like CFRP composites, has a low CTE. Bonding higher CTE materials like aluminum directly to the primary mirror caused significant thermal deformation around the bond sites. FEM showed that using Invar, rather than aluminum, under a -20 °C uniform soak, rms surface error from 51.9 to 11.1 µm, and the peak-to-valley (PV) surface error from 3.4 to 0.6 µm.
Bipod struts fit, brackets bonded to the bench, brackets bolted to M1.

Figure 3.9: Photo showing the primary mirror struts which support the mirror (upper part of the picture) on the optics bench (lower part of the picture). The two struts shown form one of the three bipods that support the mirror. The yellow fittings are anodized aluminum. Photo taken during initial alignment and assembly at Alliance Spacesystems.

The optical bench also supports three long struts which support the secondary mirror assembly. Like the primary mirror struts, the secondary mirror struts are made from all-composite tubes bonded to aluminum end fittings. The strut tubes have a rectangular cross section, with their long sides oriented radially outward from the optical axis. This cross-section provides sufficient stiffness while reducing the obscuration of the primary mirror. The far end of the struts is bolted to an aluminum triangular structure, known as the “push-plate” which supports the secondary mirror and the focusing actuators. The secondary mirror assembly is shown in Figure 3.10.
Figure 3.10: CAD Render of the secondary mirror assembly and support system. The aluminum secondary mirror is shown as a copper color. The push plate (yellow) is the aluminum mirror support which is bolted to the secondary struts (grey). The three focusing actuators are shown in teal. The actuators are mounted to the push plate, and actuate the mirror by pushing against a v-groove block with a ball-end. The mirror is pulled against the ball/groove fittings by the six extension springs shown.

### 3.4.2 Primary Mirror

The BLAST-TNG composite primary mirror features a monolithic front facesheet which is coated with a thin layer of vapor-deposited aluminum (VDA). The mirror’s structural strength comes from an interior CFRP core. The core is formed by a honeycomb-like composite modules with flat laminate strips forming triangular voids. This isogrid structure provides a high bending modulus while maintaining low mass, both of which minimize the effect of gravitational sag. Additional stiffness is provided by a segmented rear facesheet which helps distribute bending stresses across the core. The material selected for all the structural components was a woven prepreg combining
K63712\textsuperscript{2} graphite fiber and BT250E low-temperature-cure (121 °C) epoxy prepreg.\textsuperscript{3}

This roughly 60%/40% fiber/resin composite provides low CTE and high modulus. The design of the primary mirror is shown schematically in Figure 3.11.

The modulus of the isogrid core is a strong function of the core thickness. FEM studies led to increasing the core thickness as much as possible given the fixed positions of the primary mirror surface and the gondola mount surface. At its thickest point, roughly half the radius from the optical axis, the core is roughly 30 cm thick. At its thinnest, around the central hole and at outer edge of the mirror, the core is only 6 cm thick. This tapered shape maximizes the strength at the areas of highest bending stress, while reducing mass where the stresses are low.

\textsuperscript{2}Mitsubishi Chemical Carbon Fiber and Composites, Inc.
\textsuperscript{3}TenCate Advanced Composites
Figure 3.11: Photo showing the primary mirror struts which support the mirror (upper part of the picture) on the optics bench (lower part of the picture). The two struts shown form one of the three bipods that support the mirror. The yellow fittings are anodized aluminum. Photo taken during initial alignment and assembly at Alliance Spacesystems.

The optical surface of the primary mirror was made by laying up multiple layers of prepreg onto a positive graphite mold. The mold was rough-machined from graphite using a CNC mill and then hand polished to the final figure. Further details of the
mold polishing process are given in 3.5.1, and 3.4.4. After the front facesheet was laid up on the mold it was cured in an autoclave while vacuum pressed against the mold. After curing the facesheet was pulled off the mold and inspected. Once inspected the optical surface was placed back on the mold, and the isogrid was built up in small modular sections. The assembly flow for the primary mirror is shown in Figure 3.13.

3.4.3 Secondary Mirror

The comparatively small size of the secondary mirror (Ø 573 mm) greatly reduced the complexity of the engineering and manufacturing. Lightweight ~0.5 m infrared and submillimeter optics are widely manufactured, and as such we could rely on existing capabilities of different vendors throughout the process. Corning NetOptix Inc.\(^4\) developed a stiff, aggressively light-weighted design based on preliminary designs by Alliance Spacesystems, and provided two rough-machined mirror blanks. The blanks were shipped to Penn where they were both surveyed (see section 3.5.2). Both mirrors showed signs of damage during shipping/handling, including dents and scratches. After surveying both, we determined that the both blanks had similar figures, were both close enough to the reference prescription to be able to be diamond-turned. The “spare” mirror had less shipping damage and a lower degree of surface figure error, and was diamond-turned by NiPro Optics Inc.\(^5\). The progression of the diamond-turning is shown in Figure 3.14.

---

\(^4\) 69 Island Street, Keene, NH 03431
\(^5\) 7 Marconi, Irvine, CA 92618
Figure 3.13: Primary Mirror Manufacturing Process
Figure 3.12: Photograph of the two secondary mirror blanks designed and machined by Corning NetOptix Inc, showing the front side (left) of one blank, and the light-weighted rear side (right). Both mirrors were analyzed and the one with lowest figure error was selected for final machining. Note the six tabs around the perimeter of each mirror which were used to pin the blank in place during rough machining, and were machined away before diamond-turning.
3.4.4 Unsuccessful Manufacturing R&D Efforts

Early in the development the hope was to use prefabricated COTS honeycomb core, like those made by Hexcel.⁶ These honeycomb panels are available with aluminum, graphite, or aramid-paper cores. VST had produced smaller radio-frequency reflectors with less demanding surface error requirements using honeycomb cores, and carried out an extensive series of FEM studies in the engineering phase of the project. The honeycomb core studies did not yield a high enough modulus and analysis of the models indicated that the gravitational-induced bending yielded unacceptable surface deformations. Time constraints required VST to fall back on the isogrid-based design. The isogrid core is a much more mature technology that has flight history

⁶Hexcel Corporation, Stamford, CT 06901
not only on the *Herschel* SPIRE prototype composite mirror built by Composite Optics Incorporated (COI) that flew on BLAST '05 [24], but on many other projects developed by VST.

The initial contract from the SBIR Phase I was to produce a new granite mold. Combined with the COTS honeycomb core, this initial proposal would have significantly reduced the cost to produce the primary mirror. Samples of two potential granite stones, Impala Black, and American Black, were obtained for early tests from Rock of Ages\(^7\) \(^8\). These samples were CNC polished, coated with a sealant, and surveyed with a laser tracker. While the samples showed that they could be polished flat with high precision, they exhibited “pitting” and small fissures from the machining/polishing process. A suitable sealant was not found to seal these pits, which could be quite deep. These findings, combined with difficulties in sourcing large enough stones for the final mold, and time constraints again necessitated reverting to a more mature process with significant heritage at VST.

\(^7\)558 Graniteville Road, Graniteville, Vermont 05654
\(^8\)I promise I did not make that address up.
3.5 Metrology

Complete characterization of the full BLAST-TNG telescope optical system is only possible during the flight. In-band absorption from water vapor prevents ground-based observations of far-field sources with the flight receiver. To evaluate the focus for the BLAST-Pol experiment, the telescope was refocused to image near-field sources up to a few hundred yards away. While this approach is useful for testing focus routines, the WFE introduced by moving the focus, and the atmospheric absorption make meaningful evaluation of the telescope beam impractical. To characterize the expected telescope performance for BLAST-TNG, we rely mainly on analytical performance models and finite element analysis. Extensive FEM under all loading conditions was performed at Alliance Spacesystems, with optical analysis performed throughout the design process to ensure that the 10 $\mu$m RMS WFE condition was met under all gravitational, thermal, and hygroscopic stresses expected during operation.

The accuracy of the final primary mirror surface figure presented the largest uncertainty throughout the design process. Because the surface accuracy and size scale of the primary mirror are unprecedented for a composite mirror, there is little heritage for predicting the surface figure errors of the finished surface, and large-scale deviations from the mold surface. Additionally, limited metrology data was available during the intermediate stages of the manufacture and for the final product. Traditional evaluation techniques for large-aperture infrared and submillimeter telescope optics such as infrared interferometry [23], wavefront sensing [71], and coordinate measuring machine (CMM) profilometry were all cost-prohibitive given the size of the primary mirror.
3.5.1 Primary Mirror and Mold Metrology

Accurate metrology at each stage of the primary mirror fabrication is critical to achieving the performance goals of the telescope. Metrology data of the graphite mold was recorded at each critical stage in the mirror development including:

1. After rough machining of the graphite mold
2. After initial polishing steps and sealer application
3. During/throughout final hand polishing
4. After final polishing

The primary mirror itself was surveyed several times after bonding the full primary mirror assembly together:

1. After releasing finished primary mirror assembly from mold
2. After thermal cycling primary mirror
3. Repeated measurement a month later to verify surface

The mold surface and the primary mirror surface metrology data were analyzed using the same approach. Metrology data for the primary mirror manufacture was taken using a FARO laser tracker. Laser trackers have been shown to achieve micron-level surface measurements [18] and were used to survey the BLAST and BLASTPol optics. The laser tracker was mounted approximately 10-15 feet above the target in a metal frame and as near to the center of the mirror as possible in order to

---

9FARO Global Headquarters, 250 Technology Park Lake Mary, FL 32746, USA
reduce systematic errors in the measurements. The measurements were made using a 1.5 inch diameter spherical mirrored retroreflector (SMR) held by hand against the target surface, and sampled on a 2 inch by 2 inch square grid. The surface data were compared with a 3D CAD model of the target.

The laser tracker recorded both the deviations from the reference optics prescription from the CAD model, as well as the (x, y, z) position data. These data points were compensated for the size of the SMR target using the laser tracker software. During the hand-polishing of the graphite mirror, Vanguard relied on the deviations from the CAD model to guide the polishing.

The position data from the laser tracker were used to determine the best-fit conic section of the optical surface. The data was fit using the equation for a generic conic section sitting on top of an angled plane to model any tip in the mirror mounting:

\[
H^2 = S_x(x - x_c)^2 + S_y(y - y_c)^2 \tag{3.18}
\]

\[
z = z_c + \frac{CH^2}{1 + \sqrt{1 - (1 + K)C^2H^2}} \tag{3.19}
\]

where \((x_c, y_c, z_c)\) specify the center of the conic section, \(S_x\) and \(S_y\) specify the tip/tilt, \(C = 1/R\) where \(R\) is the radius of curvature, and \(K\) is the conic section. This fitting was done iteratively, using progressively more complex models of the surface to estimate the initial parameters, using the following process:

1. Subtract the z value of the highest point from all data to remove the rough vertical offset

2. Fit \((x_c, y_c, z_c)\) with fixed \(S_x = S_y = 0\), using the reference prescription
for $K$ and $C$

3. Using the center of the conic from the last step as initial conditions, fit $(x_c, y_c, z_c)$, $S_x$ and $S_y$, using the reference prescription for $K$ and $C$.

4. Using the center of the conic and the slope in x and y from the last step, fit the full conic section using Equation 3.19.

The results of the primary mirror mold metrology are shown in Figure 3.15.

Figure 3.15: Measured surface error of the primary mirror mold after final polishing. Measurements made with FARO laser tracker mounted in frame above reflector. Top: Residuals after refitting and removing a new conic section to the data. Bottom: Residuals compared to nominal conic section.
Results of the M1 metrology are shown in Figures 3.16 through 3.18. Note that the data are not shown with the mirror in the same orientation in each figure. The coordinate system is aligned to SMR pin nests which serve as fiducial reference points located at eight locations around the perimeter of the primary mirror. These nests are bonded to the backside of the front facesheet of the mirror.

![Primary Mirror Surface Data from 01/25/17](image)

**Primary Mirror Surface Data from 01/25/17**

Residuals from Best Fit Conic Section

Residuals from Reference Prescription

Figure 3.16: Measured surface error of the primary mirror taken after releasing mirror from the mold. Measurements made with FARO laser tracker mounted in frame above reflector. **Top:** Residuals after refitting and removing a new conic section to the data. **Bottom:** Residuals compared to nominal conic section.
Figure 3.17: Initial measurements of surface error of the primary mirror after stress-relieving thermal soak. Measurements made with FARO laser tracker mounted in frame above reflector. **Top:** Residuals after refitting and removing a new conic section to the data. **Bottom:** Residuals compared to nominal conic section.
Figure 3.18: Re-measured surface error of the primary mirror taken after stress-relieving thermal soak. Measurements made with FARO laser tracker mounted in frame above reflector. **Top:** Residuals after refitting and removing a new conic section to the data. **Bottom:** Residuals compared to nominal conic section.

Each of the three surface scans are qualitatively different. The large high and low areas which appear in each scan are not especially well-correlated between scans. A high ridge-like region that goes diagonally from top left to bottom right appears in both the pre-thermal soak data from October 25, 2016 (Figure 3.16) and in the final measurement on March 4, 2017 (Figure 3.18), but in both cases this feature is especially well-aligned with the pattern of data collection. The comparison of these
three surface data sets suggests that the RMS surface error is at or below the level of the measurement error.

The rms surface error describes the mean deviation from the best fit surface, but does not provide any information about the size and shape of the deviations. To understand the surface error on different size scales one must compute the power spectrum of the surface error. The power spectral density (PSD) describes the relative amplitude of surface deviations at different size scales. From the laser tracker data we can calculate the PSD for scales as big as the aperture of the primary mirror (2.5 m), to the spacing between the data points (≈ 5 cm). Surface errors on the largest size scales are the most problematic, as these can cause aberrations which cause deformations of the beam. The PSD can also reveal power on intermediate size scales which might be representative of systematic fabrication problems such as misalignment of the isogrid modules, or deformations induced by the mirror mount.

![Figure 3.19](image.png)

**Figure 3.19:** **Left:** Power spectral density (PSD) of the measured deviations from the best-fit conic section. **Right:** The cumulative integral of the surface PSD at different size scales. The integral of the PSD from zero to infinity is equal to the RMS surface error.
The PSD from each of the primary mirror surface measurements as well as the finished graphite mold are shown in Figure 3.19. The mold data exhibits the flattest power spectrum with the lowest amount of power at low spatial frequencies. The surface accuracy of the mirror surface can be no better than that of the mold on which it is formed, so it is not surprising that the mold has lower surface error on large scales. Any deformations or “potato-chipping” of the primary mirror surface after being removed from the mold would appear as large-scale surface errors. The measurements of the primary mirror surface show varying amounts of power at low frequencies, and roll off at different spatial scales. This suggests that the mirror surface changes shape between measurement sets due to gravitational or thermal stresses, or that are instabilities in the laser tracker measurements. The primary mirror itself is much lighter and less sturdy than the >1,000 lb graphite mold and is much more susceptible to mounting instabilities and measurement induced movement or bending.

3.5.2 Secondary Mirror Metrology

The secondary mirror blanks were surveyed at Penn, as noted in 3.4.3, using a FARO Laser Tracker X\textsuperscript{10}. The metrology setup is shown in Figure 3.20. The blank was secured to a precision granite surface plate with hot glue, and four fiducial reference points were secured around the edge of the surface plate to establish a reproducible coordinate system for the laser tracker. The tracker operated in Absolute Distance Measurement (ADM) mode, which measures a distance from the target to the tracker using the measured laser time-of-flight and the tracker head rotary encoders. The

\textsuperscript{10}290 National Rd, Exton, PA 19341
surface plate was placed on the ground and the laser tracker was mounted on a tripod as close to and as high above the mirror as allowed by the equipment. The geometry of the setup is not optimal for eliminating angular errors and systematics [18], but was determined to be sufficient for verification of the mirror blanks.

Figure 3.20: Photograph of the metrology setup used to survey the two mirror blanks in order to select the mirror with lowest figure error for final machining. The left figure shows the setup. The mirror was fixed to a granite surface plate using hot glue to reduce wobble while taking measurements. Placing the heavy surface plate on the floor also reduced vibration-induced measurement error. The laser tracker viewed the mirror from the side, a few feet above the mirror surface. The right image shows a close-up of the mirror surface. A green laser was used to project a regular grid onto the surface, and which was then drawn on the mirror surface with marker. Taking measurements at regular intervals ensured uniform density of surface measurements to reduce systematic error in the analysis.

The data was collected on a regular 1.4 in square grid. To mark the measurement
positions of the SMR, a 2 in square grid was projected onto the mirror using a laser
diffraction grid, and the corners of the grid were drawn onto the mirror with marker.
The position of the SMR was recorded at each corner and center of the grid dots.

Rather than comparing the surface data to a CAD model, the data was collected
in raw position (x,y,z). This required compensating the data for the SMR radius, and
for the angular difference between the laser direction and the surface normal. This
compensation was performed using the following approach.

1. Fit the conic section, ROC, and tip/tilt of the uncompensated data
   (x,y,z) the same way as outlined in 3.5.1. These parameters define
   a conic surface that passes through the center of the SMR at every
   position on the surface

2. Remove any tip/tilt/decenter from the data based on the fit

3. Convert the cartesian position data to cylindrical coordinates (ρ,z)

4. Calculate the tangent slope in the rho,z plane at each point

5. Calculate the surface normal by rotating the tangent vector by 90°

6. Calculate the corrections to rho and z by moving each data point
   a distance equal to the SMR radius, in the direction of the surface
   normal

7. Convert the new corrected positions back to cartesian coordinates

8. Re-fit the conic section, ROC, and tip/tilt of the compensated data
The residuals after fitting the compensated data are plotted for both mirror blanks in Fig. 3.21. The residuals from both the reference optics prescription (Fig. 3.22) and the best-fit conic section (Fig. 3.23). The deviation from the nominal conic section is relevant to determine the amount of material that must be removed during diamond-turning. The deviation from the best-fit conic section is useful for understanding the shape of the blank and identifying aberrations. Note that the “FLIGHT” and “SPARE” labels used on the plots are those given from Corning NetOptix. The Corning “SPARE” mirror was selected to be diamond-turned and used as the BLAST-TNG flight secondary. Both mirrors showed similar maximum peak-to-valley (PV) deviations from the reference optics prescription. NiPro Optics Inc. required that the PV deviation from the nominal conic section be no more than \( \sim 380 \mu m \). The measured PV was slightly higher than this specification, but was determined to be within allowable limits.

The “SPARE” blank was selected because there appeared to be no correlation between the residuals from the best-fit conic section and radial distance (Figure 3.23. This suggests that while the rough-cut figure does not match the reference prescription, there are no additional large-scale aberrations in the surface. The “FLIGHT” blank, on the other hand, showed that there was clear correlation between the residuals and the distance. The residuals showed a clear potato-chip bend in the surface. The “FLIGHT” blank also had more denting and had clearly been handled roughly during shipping or storage at some point. We worried that a large-scale bend in the mirror might remain even after the final machining, and introduce significant coma or other aberrations into the telescope beam, and decided to reject the “FLIGHT” blank.
Figure 3.21: Laser tracker surface measurements of secondary mirror blanks. The equations for the reference prescription and best fit conic section in each instance are displayed on the plot. The “FLIGHT” mirror blank shows more pronounced potato-chip-like low-frequency deformation. If real, this deformation would could induce significant coma if not removed in the final diamond-turning step. The “SPARE” mirror was selected to use in flight.
Figure 3.22: Radial dependence from the reference optics prescription. Both blanks show similar PV surface error. The “SPARE” mirror blank was selected to use in flight.
In order to protect the optical surface, no full-aperture metrology was performed on the secondary mirror after the final machining step. For a mirror of this size and surface finish, non-contact surface verification could be done using a Twyman-Green interferometer or a wavefront-sensing camera [103], but these tools were not available to the group. Using a profilometer mounted on the diamond-turning lathe, NiPro Optics was able to measure the surface profile of a small section of the mirror, and saw <2 μm of surface error, with no probe compensation or error correction. Before cutting the mirror, NiPro cut a spherical curve into a sample piece using the same
setup. An interferometer mounted on the lathe measured the curve surface error to be 0.119 \( \mu m \) PV. From these measurements and the typical machining tolerances of the diamond-turning lathe, we anticipate that the secondary mirror satisfies the \(<1 \mu m \) rms WFE, and is an insignificant contributor to the total WFE of the telescope.

### 3.6 Expected Performance

The available metrology data were incorporated into a model of the system optical response based on the nominal optics design and the measured feedhorn beam pattern. The model uses the Zemax model for the full optical system as the nominal reference prescription, models the feedhorn response as a true Gaussian, and assumes that the primary mirror surface perfectly replicates the mold surface. Although the surface of the mold exhibits a number of high frequency surface errors, the impact to performance is minor due to the wavelength compared to the size of the deformations. Even though we have several (see Figs 3.16, 3.17, 3.18) I will not consider these them in this model. While surface measurements were sufficient for placing an upper limit on the surface figure error, large-spatial-scale surface errors were not repeatably observed between subsequent measurements. We attribute these systematic errors to the relative thermal and mechanical stability of the mirror itself during these measurements, as compared with the mold.

In this model I will also assume that the secondary mirror is refocused to account for deviations from the nominal primary mirror conic section. The following sections present a model for the system PSF.
3.6.1 Lyot Stop Pupil

The Lyot underfills the primary mirror, and serves as the limiting aperture of the optical system. The image of the Lyot stop pupil is calculated from ray tracing in Zemax. While the full extent of the primary mirror is 2.5 m, the Lyot only illuminates 2.33 m, reducing the angular resolution (broadening the FWHM of the PSF), but reducing spillover around the edge of the primary mirror.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter of Lyot Stop</td>
<td>6.96 cm</td>
</tr>
<tr>
<td>Inner Diameter of Lyot Stop</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Outer Diameter of Lyot on Primary</td>
<td>233 cm</td>
</tr>
<tr>
<td>Inner Diameter of Lyot on Primary</td>
<td>72 cm</td>
</tr>
</tbody>
</table>

3.6.2 Feedhorn Beam Pattern

As noted in Section 3.1, the feedhorns are designed to taper the illumination on the Lyot stop. The feedhorn angular response was measured in an anechoic chamber at Cardiff University, and is shown in Fig. 3.24. The response is well-approximated by a Gaussian beam, which is shown in the red fit to the raw data in Fig. 3.24. Once the data is fit, the response can be normalized such that the integral over all angles is unity. The normalized feedhorn response, $G_{feed}(\theta)$, is shown in Fig. 3.25, and can be modeled as:
\[ G_{\text{feed}}(\theta) = \frac{1}{\sqrt{2\pi \sigma_{\text{feed, } \theta}^2}} \exp\left( -\frac{\theta^2}{2\sigma_{\text{feed, } \theta}^2} \right) \]  

(3.20)

where \( \sigma_{\text{feed, } \theta} = 3.93^\circ \) is angular width of the Gaussian.

Figure 3.24: Measured feedhorn response for ASU Blast Prototype Horn #1. Filter 28-35cm-1 BP 1K Bolo. Polariser Wires Horizontal.

To calculate the illumination of the feedhorns in the pupil plane, we convert the angular width of the feedhorn beam to a physical size on the Lyot stop. The cold optics illuminate the feedhorns at a focal ratio or F/# of \( F = 5 \). We can use this focal ratio to calculate the numerical aperture \( NA \), or angular extent of the beam at the Lyot stop:
Figure 3.25: Normalized Gaussian fit to feedhorn response. Light blue area is the angular extent of the F/5 feedhorn beam on the Lyot stop (M4).

\[ NA_{rad} = \frac{1}{2F} \] (3.21)

\[ NA_{deg} = \frac{1}{2F} \frac{180^\circ}{\pi} \] (3.22)

The numerical aperture can then be used to scale the beamwidth by the diameter of the image of the Lyot on the primary mirror, \( D_{\text{Lyot,M1}} \), and calculate the physical width of the beam on the primary mirror, \( \sigma_{\text{feed,M1}} \):

\[ \sigma_{\text{feed,M1}} = \sigma_{\text{feed,\theta}} \frac{D_{\text{Lyot,M1}}}{NA_{\text{deg}}} \] (3.23)
Which can be written in terms of the Focal ratio, $F$:

\[
\sigma_{\text{feed},M1} = 2\pi F D_{\text{lyot},M1} \left( \frac{\sigma_{\text{feed},\theta}}{180^\circ} \right) \tag{3.24}
\]

### 3.6.3 System Pupil Function

We model the system PSF by recalling from Section 3.3.1 that the image intensity PSF of the system, $I_{\text{sys}}$, is given by squaring the complex amplitude PSF, $\mathcal{A}_{\text{sys}}$:

\[
I_{\text{sys}}(\theta_x, \theta_y) = \mathcal{A}_{\text{sys}}^*(\theta_x, \theta_y) \mathcal{A}_{\text{sys}}(\theta_x, \theta_y) \tag{3.25}
\]

where $(x, y)$ are spatial coordinates at the system pupil, and $(\theta_x, \theta_y)$ are angular coordinates at the image plane. The image intensity can also be described in coordinates of spatial coordinates at the focal plane, or as spatial frequency response. Doing these calculations in terms of angular response at the image plane will be useful for estimating the FWHM of the PSF.

The amplitude PSF is the Fourier transform of the system complex pupil function, $\mathcal{P}_{\text{sys}}$:

\[
\mathcal{A}_{\text{sys}}(\theta_x, \theta_y) = \mathcal{F}[\mathcal{P}_{\text{sys}}(x, y)] \tag{3.26}
\]

The complex pupil function is described by two real-valued functions, the pupil transmission function, $P_{\text{sys}}$ and the WFE function $w_{\text{sys}}$, as in Eqn.3.7:

\[
\mathcal{P}_{\text{sys}}(x, y) = P_{\text{sys}}(x, y) e^{-i2\pi w_{\text{sys}}(x,y)} \tag{3.27}
\]
The system pupil transmission function $P_{sys}(x, y)$ describes the illumination of the system pupil. This illumination pattern depends on the primary mirror pupil, the obscuration of the primary mirror from the secondary mirror and struts, the image of the Lyot stop on the primary mirror, and the beam pattern of the feedhorns. The effective system pupil is calculated by multiplying the pupil functions of each of these optical elements, and weighting the illumination by the feedhorn beam pattern on the primary mirror:

$$P_{sys}(x, y) = P_{M1}(x, y) \times P_{obs}(x, y) \times P_{Lyot,M1}(x, y) \times G_{feeds}(x, y)$$ (3.28)

Where $P_{M1}$ is the pupil function of the primary mirror, $P_{obs}$ is the obscuration of the primary, and $P_{Lyot,M1}$ is the image of the Lyot stop on the primary mirror. These pupil functions describe the illumination of the system pupil, and are set to 1 for illuminated areas, and 0 for regions that are obscured. $G_{feeds}$ is a weighting function which describes the feedhorn beam pattern on the primary mirror.

We expect the WFE due to manufacturing errors of the cold optical system and the secondary mirror to be subdominant to that of the primary mirror. Thus I will assume that the secondary mirror, the Lyot stop, and the rest of the cold optics perfectly match the nominal optics design. However, even in this case, we expect some degree of WFE due in the nominal optics design based on the Zemax model. This WFE arises from small amounts of coma, astigmatism, defocus, and other aberrations in the nominal optics design, as a result of compromises made in the design. For instance, to relax the machining and alignment tolerances of the cold optics, the relay mirrors...
Figure 3.26: Diagrams of the telescope pupil including obscuration from the struts and secondary mirror, the image of the Lyot stop on the primary mirror, the near-Gaussian illumination of the primary mirror by the Feedhorns. The illumination of the effective system pupil is shown at right.

are spherical, rather than more complicated conic sections, which introduces spherical aberration at the edge of the field of view. In order to simplify the beam model, I will model this WFE inherent to the design by a Gaussian blur, \( G_{\text{blur}}(x, y) \) in the pupil plane which yields the same Strehl ratio for the nominal optics design reported by Zemax: \( S_{\text{nom}} = 0.956 \).

We define the blur as a one parameter, radially symmetric, normalized 2D Gaussian:

\[
G_{\text{blur}}(x, y) = \frac{1}{2\pi\sigma_{\text{blur}}} \exp \left[ \frac{x^2 + y^2}{2\sigma_{\text{blur}}} \right] \tag{3.29}
\]

We define this Gaussian blur width \( \sigma_{\text{blur}} \) such that:

\[
S_{\text{nom}} = \frac{\text{PSF} [P_{\text{Lyot}}(x, y) \times G_{\text{blur}}(x, y)]}{\text{PSF} [P_{\text{Lyot}}(x, y)]} \bigg|_{x,y=0} \tag{3.30}
\]

Including the blur in the weighting of the illumination of the pupil transmission
function we find:

\[ P_{\text{sys}}(x,y) = P_{M1}(x,y) \times P_{\text{obs}}(x,y) \times P_{\text{Lyot,M1}}(x,y) \times G_{\text{feeds}}(x,y) \times G_{\text{blur}}(x,y) \] (3.31)

To evaluate the effect of WFE from manufacturing errors in the primary mirror, I will consider the surface deformations of the primary mirror mold, as shown in Fig. 3.15, and 3.27. The WFE at each position within the pupil plane can be calculated from the surface errors in the mold after removing the best fit conic section, along with any tip, tilt, and decenter, \( \delta(x,y) \). Because incoming light traverses the optical path difference due to this surface error twice (as incoming and reflected light) the WFE is simply:

\[ w(x,y) = \frac{2\delta(x,y)}{\lambda} \] (3.32)

where \( \lambda \) is the wavelength of incoming light.

Figure 3.27: Surface error of the primary mirror graphite mold after final polishing measured using a commercial laser tracker. Deviations shown are calculated after subtracting the best-fit conic section and tip/tilt.
3.6.4 PSF Normalization

We can now calculate the PSF of the system. Plugging Equations 3.24, 3.29, 3.31, and 3.32 into 3.7, and calculate the PSF using 3.25. In order to normalize the PSF so that the peak intensity give the Strehl ratio, we normalize the response to a perfect optical system with no WFE, and with the same geometry. For the full system this means normalizing to the PSF to that of a simplified system just including the Lyot stop and the feedhorns:

\[
\text{PSF}_{\text{norm}}(\theta_x, \theta_y) = \frac{\mathcal{F} \left[ P_{M1}(x,y)P_{\text{obs}}(x,y)P_{Lytot,M1}(x,y)G_{\text{feeds}}(x,y)G_{\text{blur}}(x,y)e^{-2i\pi \delta(x,y)/\lambda} \right]^2}{\mathcal{F} \left[ P_{\text{Lytot,M1}}(x,y)G_{\text{feeds}}(x,y) \right]_{x=0,y=0}^2}
\]  

(3.33)

3.6.5 Results

The predicted point-spread functions (PSF) of the system at 250 and 500 µm are plotted in Fig. 3.28. Because the Lyot stop underilluminates the primary mirror, the resolution is set by the image of the stop on the primary mirror. The predicted Strehl ratio of the system exceeds the 80% convention for the diffraction limit based on the Maréchal condition across all but the shortest wavelengths. The anticipated WFE of the system is low enough that despite a reduction of power in the main beam, the resolution is not degraded beyond the diffraction limit. A summary of the expected optical performance is given in Table 3.4.
Figure 3.28: Modeled point-spread function for the BLAST-TNG optical system at 250 and 500 µm, based on reference optical prescription (“Nominal Optics”), the telescope obscuration (“Nominal + Struts”), and the measured surface error of the primary mirror mold (“Nominal + Struts + Mold”). The model includes the measured response of the Gaussian illumination of the Lyot stop by the feedhorns.

Table 3.4: Expected Telescope Performance Summary

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Beam FWHM</th>
<th>Strehl Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 µm</td>
<td>30″</td>
<td>0.79</td>
</tr>
<tr>
<td>350 µm</td>
<td>41″</td>
<td>0.84</td>
</tr>
<tr>
<td>500 µm</td>
<td>59″</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Chapter 4

The Balloon-Borne Platform

The gondola is the mechanical structure that houses the science payload and attaches to the balloon. This structure must support and provide precise, stable alignment between the telescope and the receiver under changing mechanical and thermal stresses throughout the balloon flight. The gondola comprises two major mechanical systems: an outer frame which allows the telescope to rotate in azimuth, and an inner frame that can be precisely pointed in elevation with respect to the outer frame by way of a direct-drive motor. An overview of the entire balloon payload showing the gondola, telescope, receiver, suspension elements, Sun shields, and various electronic components is shown in Fig. 4.1. These components are discussed in turn in the sections below.
4.1 Mechanical Requirements

The balloon-borne platform presents a distinct set of constraints and requirements, combining the gravitational stresses of a ground-based telescope, and the mass constraints and extreme thermal environment of a space telescope. For a given size balloon, the altitude of the balloon during flight is determined by the buoyancy of the helium in the balloon and the mass of the payload. To reach the required altitudes
with the 34 million cubic feet balloon used by BLAST-TNG, this places an absolute maximum mass requirement of 8,000 lbs. Reducing the mass as much as possible below this maximum reduces both the structural demands on the gondola and suspension elements and the torque output from the pointing motors. For BLAST-TNG an upper limit of 7,000 lbs was set on the total payload mass, though we expect the actual mass of the payload to be closer to 6,000 lbs. A detailed estimate of the mass of various structural components is given in Fig. 4.2.

The flight trajectory and the conditions during launch, ascent, and descent are largely unpredictable, and can vary widely between different launches. As such it is necessary to design the gondola platform to handle a wide range conditions and stresses. The Columbia Scientific Ballooning Facility, the NASA agency which manages the balloon certification and launch, provides guidelines for “worst-case” conditions and events that the gondola must be able to handle. The mechanical components were designed to survive each of the scenarios described in the CSBF Structural Requirements and Recommendations for Balloon Gondola Design manual. For components that have not already been flight-proven on previous generations of BLAST, the component performance was modeled using SolidWorks finite element analysis tools.

The gondola experiences the largest mechanical shocks when it is released from the launch vehicle, and when the parachute is deployed after the termination of the flight. Before launch the gondola is suspended from a pin on the launch vehicle while the balloon is inflated. The the balloon is released once fully inflated and allowed to rise. Once the balloon is overhead, the pin holding the gondola is released. Depending
### 4.1.1 Expected Mass Budget

**TOTAL MASS = 5129 lbs**

<table>
<thead>
<tr>
<th>Item</th>
<th>Weighed</th>
<th>Estimate</th>
<th>Number</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>409</td>
<td>1</td>
<td>409</td>
<td>409</td>
</tr>
<tr>
<td>Telescope</td>
<td>400</td>
<td>1</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>30</td>
<td></td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>Solar Panel/Supports</td>
<td></td>
<td></td>
<td>65</td>
<td>0</td>
</tr>
<tr>
<td>Swivel</td>
<td>2</td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cables/Other Electronics</td>
<td>20</td>
<td></td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Cables/Other Electronics</td>
<td>60</td>
<td></td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Flywheel and Cover</td>
<td>250</td>
<td>1</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Star Camera</td>
<td>36</td>
<td>2</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Star Camera Mount</td>
<td>23</td>
<td>1</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>P-Box</td>
<td>16</td>
<td>1</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>E-Box</td>
<td>15</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Cables/Other Electronics</td>
<td>30</td>
<td></td>
<td>1</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Weighed</th>
<th>Estimate</th>
<th>Number</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swivel</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1/2&quot; Cable/ft</td>
<td>0.04647785</td>
<td>1034</td>
<td>48.0580969</td>
<td></td>
</tr>
<tr>
<td>3/4&quot; Cable/ft</td>
<td>0.09855545</td>
<td>56</td>
<td>5.5191052</td>
<td></td>
</tr>
<tr>
<td>1/2&quot; Cable Turnbuckle</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>(10)</td>
</tr>
<tr>
<td>3/4&quot; Open Speaker</td>
<td>4.25</td>
<td>2</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>3/4&quot; Closed Speaker</td>
<td>1.5</td>
<td>6</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Swivel</td>
<td>15</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Motor Yoke</td>
<td>30</td>
<td>1</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Gear Frames</td>
<td>402</td>
<td>1</td>
<td>402</td>
<td></td>
</tr>
<tr>
<td>Base Frame</td>
<td>15</td>
<td>4</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Base Frame Lugs</td>
<td>25</td>
<td>1</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Spreader Bar Ends</td>
<td>25</td>
<td>1</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Pivot</td>
<td>95</td>
<td>1</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1</td>
<td>700</td>
<td>2</td>
<td>1180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Weighed</th>
<th>Estimate</th>
<th>Number</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Panel/Supports</td>
<td>65</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Gear Frames</td>
<td>402</td>
<td>1</td>
<td>402</td>
<td></td>
</tr>
<tr>
<td>Base Frame Lugs</td>
<td>15</td>
<td>4</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Spreader Bar Ends</td>
<td>25</td>
<td>1</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Pivot</td>
<td>95</td>
<td>1</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>1</td>
<td>700</td>
<td>2</td>
<td>1180</td>
</tr>
</tbody>
</table>

Confidence Level on Value:

- **Confident**
- **Some Uncertainty**
- **Poor Estimate**

Figure 4.2: Table of expected mass of various payload components.
on the wind and the timing of this operation, the gondola may jerk sharply as it falls before the flight train takes up the slack, and/or swing back and forth. At this time, CSBF mandates that the gondola may experience:

A load five times the weight of the payload applied at the suspension point and 45 degrees to the vertical. This load factor must be accounted for in the direction perpendicular to the gondola’s short side, perpendicular to the gondola’s long side, and in the direction of the major rigid support members at the top of the gondola structure. If flexible cable suspension systems are used, they must be able to withstand uneven loading caused by cable buckling.

Buckling is accounted for by ensuring that each cable can support the full extent of the launch stresses on its own: in particular that each suspension element satisfies the ‘5g Cable Pull Rule’ and has: “an ultimate strength greater than five times the weight of the payload divided by the sine of the angle that the cable makes with horizontal... in a normal flight configuration.” As detailed further in Chapter 4.5, this is the most stringent requirement on the suspension cables and their attachment points on the pivot motor housing. Furthermore, all structural elements must also survive a sideways acceleration of up to 5g.

For most of the structural elements of the gondola, the highest mechanical stresses occur during the termination of the flight, when the parachute is deployed. As the parachute suddenly fills with air it jerks the gondola sharply. While the parachute cord is bundled up in a rip-stitch which is designed to attenuate the acceleration of the gondola during this “parachute shock” (or simply, “chute-shock”), the payload can still experience high stresses [40]. Images of the gondola recoil are shown in Figure 4.3. CSBF requires that the gondola withstand, “A load 10 times the weight of the payload applied vertically at the suspension point” without ultimate failure of any
Figure 4.3: Gondola recoil following termination and parachute deployment [48].
elements.

To be certified for flight, all structural components must exhibit a factor of safety (FOS) greater than 1.0 for all loads. The FOS is determined by the maximum stress experienced by the part/parts during simulated loading divided by the ultimate tensile strength. Any structures made of materials which exhibit an elongation at break of less than 10%, are considered to be brittle by CSBF. Brittle materials must maintain an additional 50% increase in the FOS to 1.5 for the 10g vertical and 5g horizontal and angled load cases.

The size and dimensions of the payload are constrained by the launch vehicles and the dimensions of the CSBF integration facilities in Palestine, TX and McMurdo Station, Antarctica. In particular, the gondola must be less than 18 feet wide in order to fit through the front door of the high bays, must be no taller than 25 feet, and must not stick out past an imaginary plane extending from the tallest point of the payload towards the rear of the gondola at an angle of 20° with respect to the horizontal. This stay-out zone is shown in Fig. 4.4.

4.2 Finite Element Modeling

4.2.1 Modeling Parameters

Mechanical simulations for all structural components, even those which flew on BLAST-Pol, were carried out using the SolidWorks 2016 Simulation package. The material properties used for the mechanical FEM are listed in Table 4.1. Except for the gondola inner frame and the pivot motor housing, the mill test report (MTR) was
Figure 4.4: Rendering of the BLAST-TNG payload on the CSBF launch vehicle. Telescope baffle which extends out the front of the payload around the telescope mirror is not shown.

not obtained at the time of manufacture.

For the aluminum 6061 and 7075 components, the material properties used for the simulations were worst-case properties obtained from the Granta Mil-Spec online materials database [67]. For the heat-treated steel components (pivot housing, u-joint cross, pivot rotor shaft), the Rockwell C hardness was measured in the heat treated state, and used to determine the elastic modulus and ultimate tensile strength from published literature. Where possible, assemblies were modeled together so that
interfaces and contacts could be modeled more realistically without the need for unrealistic constraints. Where needed, bolts and pins were modeled as rigid members. The pivot motor bearings were simulated as solid collars with the same geometry as the actual bearings, though the balls/needle bearings themselves were not explicitly modeled. The bearings are made from through-hardened carbon chromium steel (100Cr6), which was used for the simulated bearings.

The details of the individual FEM simulations are given in the following sections.
The results of the simulations are summarized in Table 4.2.

<table>
<thead>
<tr>
<th>Suspension Element</th>
<th>References</th>
<th>Hardness (Rockwell C)</th>
<th>Poisson Ratio (-)</th>
<th>Elastic Modulus (MPa)</th>
<th>Ultimate Tensile Strength (KSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 6061-T6</td>
<td>[67]</td>
<td>-</td>
<td>0.33</td>
<td>69</td>
<td>10.008</td>
</tr>
<tr>
<td>Aluminum 7075-T6</td>
<td>[67]</td>
<td>-</td>
<td>0.33</td>
<td>72</td>
<td>10.443</td>
</tr>
<tr>
<td>Heat Treated 4340 Steel</td>
<td>[15; 20]</td>
<td>44.5</td>
<td>0.32</td>
<td>210</td>
<td>30.458</td>
</tr>
<tr>
<td>Heat Treated 4340 Steel</td>
<td>[15; 20]</td>
<td>50</td>
<td>0.32</td>
<td>210</td>
<td>30.458</td>
</tr>
<tr>
<td>Carbon Chromium Steel (100Cr6)</td>
<td>[9; 1]</td>
<td>60</td>
<td>0.285</td>
<td>200</td>
<td>29088</td>
</tr>
</tbody>
</table>

Table 4.1: Material properties used for FEM simulations of the suspension elements.

### 4.2.2 Summary of FEM Simulations

An updated (as of this revision) table summarizing the results from FEM simulations of all the structural elements of the gondola and flight suspension system are given in Table 4.2. The FOS listed are calculated from ultimate tensile strength values for the material properties of each element, as summarized in Table 4.1. The lists all the simulated load cases, based on structural requirements from [48]. The filename of the SolidWorks part or assembly file used in the simulation is also listed in the table. The model assumptions of the payload mass at which each component is certified based on the simulation results are also given in the table. For example, based on the material properties in Table 4.1, all components of the flight suspension system, except the spreader bar end fittings, meet the CSBF structural requirements up to a maximum payload mass of 7,000 lbs. The spreader bar end fittings meet the structural requirements for the 5g cable pull only up to a maximum payload mass of 6,000 lbs. As this document is updated based on improved estimates of the payload mass and the material properties of the structural components, this table will continue to be updated to accurately reflect the structural properties of the BLAST-TNG mechanical
Table 4.2: Summary of Mechanical Element Simulation Results

<table>
<thead>
<tr>
<th>Element</th>
<th>Acceleration Case</th>
<th>Simulation Filename</th>
<th>Simulated Load</th>
<th>Material</th>
<th>Min FOS</th>
<th>Simulation Updated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Frame Assy</td>
<td>10g Vert</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>2.1</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g Horizontal</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>1.6</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Front</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>1.7</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Side</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>2.3</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Back</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>1.7</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Front Corner</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>1.8</td>
<td>4/25/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Back Corner</td>
<td>Outer_Frame_v18.SLDASM</td>
<td>2500 lbs (IF Mass)</td>
<td>AL 6061-T6</td>
<td>1.6</td>
<td>4/25/18</td>
</tr>
<tr>
<td>Inner Frame Asy</td>
<td>10g Vert</td>
<td>Inner Frame FEA_As Built.SLDASM</td>
<td>1000 lb cryo + 370 lb telescope</td>
<td>AL 6061-T6</td>
<td>2.3</td>
<td>4/28/18</td>
</tr>
<tr>
<td></td>
<td>5g Hor</td>
<td>Inner Frame FEA_As Built.SLDASM</td>
<td>1000 lb cryo + 370 lb telescope</td>
<td>AL 6061-T6</td>
<td>8</td>
<td>4/28/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg Front</td>
<td>Inner Frame FEA_As Built.SLDASM</td>
<td>1000 lb cryo + 370 lb telescope</td>
<td>AL 6061-T6</td>
<td>5.5</td>
<td>4/28/18</td>
</tr>
<tr>
<td>Pivot Housing</td>
<td>5g Pull - Front Ear</td>
<td>Spreader Bar Pivot Assembly.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 44.5</td>
<td>1.1</td>
<td>4/27/18</td>
</tr>
<tr>
<td></td>
<td>5g Pull - Rear Rear</td>
<td>Spreader Bar Pivot Assembly.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 44.5</td>
<td>1.4</td>
<td>4/28/18</td>
</tr>
<tr>
<td></td>
<td>10g Pull - All Ears</td>
<td>Spreader Bar Pivot Assembly.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 44.5</td>
<td>1.8</td>
<td>4/27/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg - All Ears</td>
<td>Spreader Bar Pivot Assembly.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 44.5</td>
<td>5.5</td>
<td>4/28/18</td>
</tr>
<tr>
<td>Pivot Shaft</td>
<td>10g Vert</td>
<td>Rotor_Shift_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>2.5</td>
<td>5/23/18</td>
</tr>
<tr>
<td></td>
<td>5g Hor</td>
<td>Rotor_Shift_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>1.7</td>
<td>5/23/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45deg</td>
<td>Rotor_Shift_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>31</td>
<td>5/23/18</td>
</tr>
<tr>
<td>Spreader Bar End Fitting</td>
<td>5g Pull</td>
<td>Spreader_Bar_End_Fitting.SLDPRT</td>
<td>6000 lbs (Payload Mass)</td>
<td>AL 7075-T6</td>
<td>1.1</td>
<td>5/25/18</td>
</tr>
<tr>
<td>U-Joint Ends</td>
<td>10g Vert</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>2.4</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g Hor</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>5/29/18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Front</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>3.1</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Side</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>3.1</td>
<td>5/29/18</td>
</tr>
<tr>
<td>U-Joint Cross</td>
<td>10g Vert</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>2.3</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Front</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>4.1</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Side</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>2.1</td>
<td>5/29/18</td>
</tr>
<tr>
<td>U-Joint Shackle Block</td>
<td>10g Vert</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>2.5</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Front</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>4.4</td>
<td>5/29/18</td>
</tr>
<tr>
<td></td>
<td>5g @ 45 Deg Side</td>
<td>U-Joint_FEM.SLDASM</td>
<td>7000 lbs (Payload Mass)</td>
<td>4340 Steel HRC 50</td>
<td>4.1</td>
<td>5/29/18</td>
</tr>
</tbody>
</table>
4.3 Outer Frame

The outer frame of the gondola serves as the interface between the inner frame where the main scientific components reside, and the balloon flight train. The outer frame connects to the balloon through four steel wire rope suspension cables. The inner frame is supported by two elevation mounts which allow the inner frame to rotate in elevation. One of these elevation mounts supports the elevation motor, and the other holds a fixed bearing which connects to the inner frame.

4.3.1 Modifications to Existing Hardware

In order to reduce construction time and costs, we decided to reuse the gondola outer frame from one of the previous BLAST flights. Using flight-tested and pre-qualified hardware also reduced the risk of failure during flight. The outer frames from both the 2010 and 2012 BLAST-Pol flights arrived at Penn in April of 2013. Both frames were carefully inspected for damage, and it was determined that while the 2012 frame had a number of cracked welds and bent structural members, the 2010 frame had sustained only cosmetic damage, and was suitable for reuse.

Modifications to the outer frame were necessary to accommodate the new compact inner frame and the large primary mirror. The elevation mounts in BLAST-Pol each formed a square-base pyramid made from four structural beams, as shown in Figure 4.18. The pyramidal structure of these mounts would interfere both with the back of the new 2.5 m primary mirror, and the sides of the new inner frame. New ladder-like
Figure 4.6: The completed outer frame at GSM Industrial Inc after modifications and construction of the new elevation mounts.
elevation mounts were designed which allowed free rotation of the inner frame, inspired by the elevation mounts from the EBEX balloon gondola. The front of the mounts are comprised of two standard (4” wide x 6” tall x 0.19” web) structural aluminum I-beams which are welded to a standard structural aluminum c-channel (12” wide x 4” tall x 0.29” wall). Plates are welded into the c-channel so that it serves as a stepladder for climbing up to access components on the inner frame. The angle between the front and back of the “stepladder” was made as large as possible to balance the load from the inner frame between the front and back members, while not interfering with the primary mirror. Not interfering with the mirror meant that the front of the elevation mount could not bolt to the front of the base frame, and a cross beam had to be added to the frame to support it, as shown in Figure 4.7. The narrow support for the inner frame necessitated the addition of lateral stiffeners to account for side and cornering loads.
Figure 4.7: Render of the base frame showing the required additions in color, and the existing hardware in white. The blue cross members are where the elevation mounts bolt, and the green support tubes add structural support beneath the front of the mount and spread the weight of the inner frame.
4.3.2 Structural Analysis

Structural Analysis

Detailed FEM of all outer frame structural components was carried out to ensure that they met the CSBF requirements in all relevant cases. These simulations were all calculated assuming a maximum inner frame assembly mass of 2,500 lbs, and a maximum total payload mass of 7,000 lbs. The inner frame was modeled as a rigid element attaching the two elevation mounts. A global bonded contact was used. The cable attachments were not explicitly modeled. The cable attachment points on the gondola were modeled, and a fixed hinge condition fixture was used at each of the cable attachment points, to allow rotation and flexion around the suspension cable.
attachment points. The only simplifications made to the outer frame itself was to remove all bolt holes to reduce mesh complexity. The results of these simulations are shown in the following figures.

Figure 4.9: Outer frame simulation parameters and mesh used for analysis.
Figure 4.10: Outer frame under 10g vertical acceleration.
Figure 4.11: Outer frame under 5g vertical acceleration.
Figure 4.12: Outer frame under 5g acceleration at 45° from vertical, oriented towards the rear of the gondola.
Figure 4.13: Outer frame under 5g acceleration at 45° from vertical, oriented towards the rear of the gondola.
Figure 4.14: Outer frame under 5g acceleration at 45° from vertical, oriented towards the side of the gondola.
Figure 4.15: Outer frame under 5g acceleration at 45° from vertical, oriented towards the front corner of the gondola.
Figure 4.16: Outer frame under 5g acceleration at 45° from vertical, oriented towards the back corner of the gondola.

### 4.4 Inner Frame

The main mechanical requirement of the inner frame is that it maintain precise alignment between the telescope, the receiver, and the star cameras. Any relative motion of the telescope with respect to the receiver will cause spurious blurring and streaking of the images. Equally important is that the telescope beam not move with respect to the star cameras, as this would cause an elevation-dependent systematic
pointing offset in the maps and jitter during elevation turnarounds. The absolute offset angle between the star camera beam and the telescope beam is not critical, as long as they are roughly aligned such that the star cameras have a clear view of the sky at all elevation angles. This means the star cameras must be aligned to the telescope bore sight to within a few degrees. Misalignment between the telescope and the receiver shifts the center of the beam on the focal planes, leading to under-illumination of the pixels at the edge of the array. To achieve the necessary rigidity of the inner frame, we required that the relative pointing misalignment between the telescope and the receiver due to deformation of the mounting structure be less than half the FWHM of the beam at the smallest wavelength of observation over the full range of observed elevations between 20 and 60 degrees. A photo of the inner frame assembly showing the cryostat mounted in the inner frame with the star cameras mounted can be found in Fig. 4.17.

4.4.1 Design Philosophy

The driving philosophy for the design of the inner frame was to keep the frame itself as compact as possible, minimize the distance between distributed loads and the elevation axis, and utilize the inherent strength of the cryostat. The cryostat itself is extremely stiff, and dominates the mass of everything mounted on the inner frame (see table in Fig. 4.2). The inner frame was meant to be an interface to couple the cryostat itself the elevation motors, and couple the mirror to the cryostat. Additionally, the frame was to be designed such that deformations induced by the cryostat were decoupled from the telescope mount, so that these bending stresses would not be
Figure 4.17: Photograph of the BLAST-TNG gondola, showing the telescope mounting surface on the front of the inner frame, the cryogenic receiver (painted red), and the two autonomous daytime star cameras mounted above the receiver. Each star camera has a long baffle to reject stray light and reflections off of the telescope baffle. For flight, both baffles will be painted white to reduce their thermal emissivity.
transferred into the aberrations in mirrors.

This philosophy is in contrast with that behind the inner frame flown on the BLAST and BLAST-Pol experiments (the “BLAST inner frame”). The BLAST frame was cage-like truss structure made of welded aluminum box beams. As shown in Figure 4.18, the receiver (painted blue) was held at its top and bottom and bolted to the top and bottom of the inner frame. The primary mirror mounted to a triangular mount welded to the perimeter of the frame. The primary mirror mount was welded to the center of the perimeter box beams rather than their joints, causing significant deflection of the simply supported box beams. Additionally, as the inner frame was
pointed up in elevation, the gravitational forces on the cryostat causing the entire frame, including the primary mirror mount, to flex. The primary mirror was directly bolted to this frame, so any deformations of this mount were transferred directly to the optical surface.

4.4.2 Inner Frame Design and Fabrication

To keep the BLAST-TNG inner frame stiff and compact, while separating the bending stresses from the telescope optics, the frame is composed of two joined sections: a ring of aluminum c-channel which attaches around the waist of the cryostat, and a welded monocoque structure of thin aluminum sheets which forms a broad flat surface for the telescope to mount at the front of the frame (see Figure 4.20). A 12” x 24” cut-out in this front plate allows the telescope beam to pass through the inner frame, and affords access to the cryostat front window. Below the rear section of the frame hangs a welded frame of 3” x 3” box beams which allow the cryostat read-out electronics to be mounted securely.

Aluminum 6061-T6 was selected for the frame material because it is easily machined, welded, relatively inexpensive, and there are many readily available standard structural beams and other elements that can be incorporated into the design. Because aluminum is also a good thermal conductor, the frame can be used as a heat sink for the flight electronics.

The monocoque structure contains four internal ribs, thin vertical sheets of metal, in addition to thick sidewalls which make it very stiff along the direction of the optical axis to minimize sag from the weight of the telescope. The internal webbing structure
is shown in Figure 4.21. To reduce mass, most panels include oval cut-outs where their presence would not unacceptably reduce the structural strength or interfere with the mounting locations of the mirror, motors, or electronics. A series of 0.5”-thick pads were welded to the front facesheet, six for mounting the flight telescope, and three for mounting the BLAST-Pol 2012 primary mirror in the event that something prevented us from using the carbon fiber mirror, or that we wanted to use it as a mass model for pointing tests. Before joining the front and rear frame sections, these pads were machined flat and coplanar after they were welded on in a machine large enough to accommodate the full monocoque assembly. Only after surfacing all these mounts were the bolt holes tapped for the telescope mount. This process ensured that the telescope would mount on a flat surface which would not stress the optics. The monocoque assembly is shown in Figure 4.19.

The rear section of the frame where the cryostat mounts is made of standard
c-channel that is 10” tall, 2.6” wide, with 0.24” wall thickness. A thick 0.5”-thick plate bolts around the top perimeter, with a circular cutout where the cryostat mounts. Underneath the channel is another thin, 0.125” plate which is stitch-welded in place, with a cut-out for the cryostat as well. These two plates give the rear section extra stiffness against large-scale bending of the frame which puts the top and bottom plates in tension and compression, respectively. The top plate must be thick enough that it can accommodate the cryostat mount bolts as well as prevent rotational motion of the cryostat with respect to the c-channel due to bending of the plate. To further stiffen the plate against this bending, eight 0.5” gussets or webs are welded into the channel and bolt to the top plate.

The top plate was made to be removable to simplify the final integration with the cryostat and the telescope. The circular cut-out in the plate, and the mounting rim of the cryostat were designed such that the cryostat could be moved ±0.5” in any direction. Because it is removable, the bolt patterns could be redrilled, and any vertical misalignment of the cryostat could always be taken care of by either adding shims or machining down the top surface. Initially only a few holes were drilled for fixing the cryostat in place for pointing tests. During final AI&T, the cryostat was positioned using an overhead crane into its best alignment with the telescope, and the final location of the bolt holes was marked. The plate was then removed from the inner frame, the holes drilled, and two alignment pins were inserted to ensure that in subsequent integration the cryostat would go back into the same location repeatably. This is in contrast with the BLAST-Pol integration in which the cryostat would have to be surveyed into position anew each time it was mounted.
Figure 4.20: Solidworks renders of the BLAST-TNG inner frame. **Top Left:** isometric view, **Top Right:** top-down view, showing circular cutout where cryostat mounts, **Bottom Left:** side view showing starboard side. The rectangular panel with the circular bolt pattern is the elevation motor attachment point. A rack made of box beams hangs below the cryostat allowing the cryostat readout electronics to be mounted. **Bottom Right:** Front view showing central cutout where the telescope beam passes through the frame to the receiver. The telescope mounts to pads welded around the perimeter of the front surface.
When joining the front and rear sections of the frame, we required that the cryostat mount plate be perpendicular to the telescope mounting surface to minimize the need for complicated shimming to align the cold and warm optics. The drawings required that the surfaces be flat to 0.005” and perpendicular to within 0.063”. After manufacture, the surfaces were measured to be perpendicular to within 0.1” using a digital protractor. Achieving this high tolerance required the addition of shims between the front and rear sections, which made the center of the cryostat mount hole come out ∼0.4” too far back, which was compensated for when the final mount holes were drilled. The rear section is welded to the rear facesheet and the thick 0.5”-thick side panels of the monocoque. To increase the strength of the joint, as well as to provide a flat surface for the elevation drive bearings to attach, a 0.5”-thick panel was welded to both the 0.24”-thick rear C-channel and the 0.5”-thick side panels of the monocoque. These stiffening panels were machined flat after welding to ensure the motor-mount locations were flat and parallel.

There were a few unanticipated problems during the assembly of the inner frame. During assembly of the monocoque, it was determined that it would not be possible to weld the internal webs to the rear facesheets of the structure, only to the front. Subsequent FEM modeling determined that this would have little effect on the stiffness of the structure. In several locations, the heat from the welding caused significant bending and deformation of the panels, especially where panels of dissimilar thickness were joined. Welding the 0.125”-thick internal webs to the 0.25”-thick front face of the monocoque caused the webs to come out “wavy.” The 0.125”-thick rear facesheet of the monocoque experienced deformation around the interface with the rear channel.
of the frame. Both of these problems could have been avoided by using 0.25”-thick panels for the entire monocoque, which would further increase stiffness, minimize unwanted deformation, though at the cost of significant increased mass. The bottom panel of the rear section was significantly deformed when welding on the mounts for the electronics rack. This could have been easily avoided by bolting these pads on rather than welding them.

Figure 4.21: Render of the inner frame with the front facesheet removed showing the internal ribbing of the monocoque.

4.4.3 Structural and Frequency Analysis

In order to size the structural members of the inner frame, a detailed finite element model (FEM) was developed and a series of trade studies performed to achieve the desired stiffness of the frame at as low mass as possible. A number of parameters were
varied in these studies, including the monocoque web thickness, the height and web thickness of the rear c-channel, the thickness of the top (cryostat mount) and bottom rear plates, the cryostat support gussets, geometry of the front and rear sections, and mesh size. From these trade studies a few lessons were learned:

1. The internal webs or ribs of the monocoque provide significant stiffness, even when made of thin material (see Figure 4.22).

2. If the width of the frame is as close as possible to the cryostat diameter, the mass of most components can be minimized. The frame should tightly “hug” the cryostat.

3. The height of the rear c-channel is not especially important

4. The location and geometry of the monocoque panels is much more important in stiffening the structure than the plate thickness.

5. The most important factor in how much the frame bends in the simulations are the thickness of the sidewall where the elevation motor mounts. This can be seen to be the area of highest stress in Figure 4.28.

6. The cryostat has the biggest effect on pointing misalignment by bending/buckling the rear top plate. The thickness of the rear top plate can be significantly reduced by adding gussets.

7. The stiffness requirements for normal operation/pointing were much more stringent in terms of design than the launch/termination load-
ing requirements from CSBF (section 4.1) Also see 10g load case in Figure 4.24.

The FEM trade studies were calculated using the SolidWorks 2014 simulation package. The FEM mesh was created using the curvature-based mesh tool, and the maximum mesh element size was varied to balance accuracy with run time. To aid in meshing the frame, all bolt holes were suppressed in the parts. For the simulations, a simplified version of the telescope was created which would faithfully represent the mass of the telescope assembly and act as a distributed load on the frame, but did not include the details of the actual mirror assembly/mounting hardware. As such, the bending of the telescope struts and mirror tip shown in the simulations like Figure 4.28 is not representative.

The simulations were run on a computer running Windows7, with a 4 core Intel i7-3770K CPU@3.50GHz, with 32Gb of RAM. For the full inner frame/telescope/cryostat assembly, the computer could run the FEM with a max mesh size of 1-2” in about 10-20 minutes. For meshes of 2-3” the computer could run the model in 5-10 minutes. Meshes below 1” for the full assembly were found not to converge. By varying the mesh size for a given model, it was found that meshes below 2” generally returned the same answer, and further increasing the mesh density did not show higher returns. However, as explained further in section 4.4.4, the most important metric in most of the simulations was the differential pointing offset calculated between high and low elevations. Though the absolute pointing offset would vary between smaller and larger mesh sizes, the differential pointing offset was relatively insensitive to the mesh size, so most pointing calculations were done using a 2” max mesh size.
Figure 4.22: Results of a trade study of the internal web or rib thickness of the monocoque, on an early model of the inner frame. In the study all webs were set to be the same thickness, as seen in the cutaway render in the lower left. Shown in the plots are the maximum displacement, maximum predicted stress, and total inner frame mass given 1-g gravitational loading from the cryostat and telescope. The max stress flattens out around 1000 PSI for webs thicker than 0.125”, while the max displacement seems to change slope around 0.1875”. Based on these plots the four innermost internal ribs were set to 0.125” thick, which was deemed the thinnest possible plate that could be reasonably welded in place. The outermost ribs were made thicker as note in section 4.4.2.
The inner frame was modeled together with the cryostat vacuum shell, and schematic models for the elevation axis bearings. The vacuum shell of the cryostat was explicitly modeled because it provides structural stability for the entire frame. The mass of the cryostat was modeled as a distributed mass over the full vacuum jacket. The telescope was modeled as a remote load with the same approximate mass and moment of inertia tensor as the actual telescope. The results for the simulations are shown below. The inner frame was modeled at an elevation of 35deg, the locked position during launch and descent after the flight termination.

![Figure 4.23: Inner frame assembly simulation parameters.](image_url)
Figure 4.24: Inner frame stress under 10g vertical acceleration.
Figure 4.25: Inner frame stress under 5g horizontal acceleration.
4.4.4 Modeling Pointing Misalignment

To evaluate the results of the FEM simulations of the inner frame assembly, the pointing offset between the receiver and the telescope optics was estimated for each simulation. The method for making this estimate is shown in Figure 4.27. The x, y, and z coordinates of five finite elements was tracked before and after running the simulations. Two elements at the front and back of the cryostat top plate were used to define the cryostat boresight vector, \( \vec{V}_{\text{cryo}} \). Three elements on the telescope
Figure 4.27: Cartoon of pointing offset calculation shown over finite element model mesh of inner frame, telescope, and cryostat.

optics bench, at the rear of the three secondary mirror struts, were used to define a plane perpendicular to the optical axis of the telescope. The normal vector to this optics bench plane, \( \vec{N}_{OB} \) points along the telescope optical axis. The pointing offset, \( \theta \), was defined as angle between these two vectors:

\[
\cos(\theta) = \vec{N}_{OB} \cdot \vec{V}_{cryo}
\]

Because this bending-induced pointing offset changes with elevation, the FEM simulation was run at 20° and 60°, the upper and lower elevation limits during flight, and the differential pointing offset, \( \Delta \theta \), between these angles was calculated.

Because the simulations were meant to evaluate the stiffness of the inner frame
itself, not all elements in the assembly were modeled. Only the exterior of the cryostat was included, and the internal components were not modeled. The star cameras and their mount were not included in these simulations, as we required the star camera mount be stiff enough that any bending would be subdominant to the bending of the inner frame. Details of this mount are given in section [pointing sensors]. The aluminum flexures that attach the telescope optics bench to the front of the inner frame were modeled as perfectly rigid elements as the details of their design were still being developed at Vanguard. This assumption means that the simulations likely over-estimate the bending of the front facesheet of the inner frame. The Figure 4.28 shows the deformation of the front facesheet of the monocoque from the simulations at the upper and lower limits of the elevation range. The magnitude of the deformation across the full face is less than 10 µm. The mean offset in z was calculated for each of the six telescope mount points at each elevation, and these offsets were put into the detailed telescope FE model at Vanguard. The displacements of the mount points had no observed effect on the primary mirror bending or WFE.

The results of the FEM simulations of the as-built inner frame are shown in Figure 4.28. At an elevation of 20°, the pointing offset is 28 arcseconds, and at an elevation of 60°, the pointing offset is 19 arcseconds, giving a differential pointing offset over range of observing elevations of 9 arcseconds. This is less than half the beam FWHM at the shortest observed wavelength. This offset is of roughly the same order as the anticipated differential pointing offset due to bending of the telescope optics alone. Even if the bending of the telescope optics causes the beam to move in the same direction as the bending of the inner frame, we expect the elevation-dependent pointing
offset from bending/motion of the telescope optics, inner frame, and cryostat to be less than the size of the beam at 250 µm.

Figure 4.28: Results of finite element modeling of bending of the inner frame under 1-g gravitational loading at different elevation angles. Figures A and C show the calculated bending in z-direction of the front facesheet of the inner frame monocoque. The six rectangles around the perimeter are the telescope mount points. The four vertical dashed lines show the location of the internal ribs of the monocoque. As expected most of the bending occurs between the ribs. Figures B and C show the total displacement from bending of the inner frame, cryostat, and simplified telescope. The deformation scale is exaggerated by several hundred times in order to make the direction of the bending more clear. The largest displacement in the model is the cryostat, and is only 200 µm.
4.5 Suspension System

The suspension system is a critical structural component of the gondola which comprises all mechanical elements which attach the outer frame to the balloon flight train. The gondola attaches to the balloon flight train through a universal joint, allowing the gondola to rotate in all directions about the base of the flight train, which is essential during launch when the gondola is suspended from the launch vehicle and the balloon is inflated while draped across the ground. The universal joint is attached to a hardened steel shaft which rotates inside the pivot motor housing, supported by a load-supporting thrust bearing and a centering bearing which ensures proper alignment. The exterior of the pivot motor housing has four machined tabs where the suspension cables attach via open pin-anchored shackles (Spelter sockets). The rear two suspension cables run directly from the pivot housing to similar anchoring tabs welded on the back corners of the gondola. The front two cables are attached to a carbon fiber spreader bar which routes the suspension cables away from the telescope mirrors, allowing the inner frame to be pointed up to 55° in elevation.

The details of each critical element in the suspension system are given in the sections below.
### Table 4.3: Suspension cable geometry and forces experienced under critical load cases.

<table>
<thead>
<tr>
<th>Suspension Element</th>
<th>Angle with Horizontal (°)</th>
<th>Rated Capacity (lbf)</th>
<th>Ultimate Tensile Strength (lbf)</th>
<th>10 G Force (lbf)</th>
<th>5 G Cable Pull Force (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Front Suspension Cables</td>
<td>33.68</td>
<td>90,400</td>
<td>452,000</td>
<td>31.557</td>
<td>63.114</td>
</tr>
<tr>
<td>Lower Front Suspension Cables</td>
<td>75.22</td>
<td>40,800</td>
<td>204,000</td>
<td>18,099</td>
<td>36,198</td>
</tr>
<tr>
<td>Rear Suspension Cables</td>
<td>70.70</td>
<td>40,800</td>
<td>204,000</td>
<td>18,542</td>
<td>37,084</td>
</tr>
</tbody>
</table>

### Table 4.4: Summary of the suspension cable and spreader bar design summary.

<table>
<thead>
<tr>
<th>Suspension Element</th>
<th>Material</th>
<th>Manufacturer</th>
<th>10 G Min FOS</th>
<th>5 G Cable Pull Min FOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Front Suspension Cables</td>
<td>ø18 mm CASAR Betalift Steel Wire Rope</td>
<td>WireCo</td>
<td>14.5</td>
<td>7</td>
</tr>
<tr>
<td>Lower Front Suspension Cables</td>
<td>ø13 mm CASAR Betalift Steel Wire Rope</td>
<td>WireCo</td>
<td>11.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Rear Suspension Cables</td>
<td>ø13 mm CASAR Betalift Steel Wire Rope</td>
<td>WireCo</td>
<td>11</td>
<td>5.5</td>
</tr>
<tr>
<td>Spreader Bar</td>
<td>Filament-Wound Carbon Fiber Tube</td>
<td>CST Composites</td>
<td>2.6</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.29: The BLAST-TNG suspension cables. **A:** schematic cross-section of the CASAR Betalift steel wire rope showing the many strands. **B:** render of the upper front cable assembly showing the open (left) and closed (right) spelter sockets molded on to the cable. **C:** close-up image of the upper front cable assembly pinned to the pivot motor housing. **D:** the BLAST-TNG gondola hanging in the Penn highbay suspended from the hoist using the suspension system.
4.5.1 Suspension Cables

The BLAST-TNG suspension cables are made from CASAR Betalift multistranded lubricated steel wire rope. These ropes were turned into cable assemblies by WireCo World Group,\(^1\) by using molten zinc to mold shackle-like fittings known as Spelter sockets on each end. The \(\varphi 18\) mm and \(\varphi 13\) mm wire rope assemblies have breaking strengths gaurenteed by WireCo to be 45.2 US Tons (90,400 lbf) and 20.4 US Tons (40,800 lbf) respectively. The diameter of the rope is sized to ensure positive safety margins during the 5 G cable pull load case from CSBF as detailed in [48], which is the most stringent requirement on the suspension cables and their attachment points on the pivot motor housing:

Each cable, cable termination and cable attachment must have an ultimate strength greater than five times the weight of the payload divided by the sine of the angle that the cable makes with horizontal, which should be larger than 30\(^\circ\), in a normal flight configuration.

The factor of safety (FOS) for each suspension cable was calculated for each cable assembly based on the manufacturer’s guarantee of the breaking strength, and assuming a nominal mass of 7,000 lbs for the full payload. We anticipate a payload mass of <6,000 lbs, so certifying the suspension system for a 7,000 lbs payload will likely add an additional FOS of 1.16 to all stated FOS. The 5 G cable pull FOS is computed from:

\[
F_{5G} = \frac{5 \times M_{payload}}{\sin \theta_H}
\]  
(4.2)

\[
FOS_{5G} = \frac{F_{5G}}{F_{breaking}}
\]  
(4.3)

\(^1\)2400 W 75th Street Prairie Village,KS 66208 USA
Where \( F_{5G} \) is the force on the cable experienced in a 5G pull, \( M_{\text{payload}} \) is the total payload mass, \( \theta_H \) is the cable angle with respect to the horizontal, and \( F_{\text{breaking}} \) is the breaking strength of the cable assembly. The cable angles, thicknesses and forces experienced are listed in Table 4.3, and the resultant FOS are given in 4.4.

Figure 4.30: Force diagram showing the cable angles and forces on the spreader bar. As the angle of the cables with the vertical direction increases, the strength requirements on the cables and fittings increases due to the 5g cable pull rule.

### 4.5.2 Spreader Bar

The spreader bar allows the front suspension cables to be routed in such a way that they do not interfere with BLAST-TNG’s large 2.5 m diameter primary mirror. Previous generations of BLAST, with smaller primary mirrors did not require any spreader bar. BLAST-TNG reaches is upper elevation limit when the inner frame sun shield or “scoop” hits the lower-front suspension cables. While increasing the length
of the spreader bar would allow the inner frame to point higher in elevation, it would also make the angle above the horizontal of the upper-front suspension cables flatter. As this angle gets flatter, the upper cables must be made stronger to satisfy the 5 G cable pull rule. For BLAST-TNG, the spreader bar was made as short as possible while still allowing the inner frame to point to a minimum of 55° in elevation.

The BLAST-TNG spreader bar is based on the design of the spreader bar that was successfully flown on the SPIDER 2012 payload [107]. The spreader bar consists of a 1400 mm-long filament-wound carbon fiber reinforced polymer (CFRP) tube with an inner diameter of 80.4 mm, a wall thickness of 1.5 mm. Two 7075 aluminum attachment fittings are bonded into each end with 3M Scotch-Weld 2166 A/B two-part epoxy. Because the spreader bar is oriented horizontally, it cancels out the horizontal components of the tension in the suspension cables. In this orientation the primary failure mode is Euler buckling which can occur in structural members under high compressive loading. The equation for the critical force at which failure occurs is given by [107]:

$$F_{crit} = \frac{\pi^2 (EI)}{(\kappa L)^2}, \quad (4.4)$$

where $L$ is the length of the member, $EI$ is the flexural rigidity, a product of the modulus of elasticity and $I$, the moment of inertia, and $\kappa$ is a constant which depends on the geometry of the loading. The flexural rigidity is hard to derive for an anisotropic material like CFRP, but is guaranteed by the manufacturer\(^2\) to be >25 kN m\(^2\). In the worst loading case of the structural member under compression with

\(^2\)CST Composites. Caringbah NSW 1495, Australia
both ends fixed, $\kappa = 0.5$. The critical force under Euler buckling is $F_C = 113,203$ lbf. The driving load for the spreader bar is the 5G pull on a single cable, during which the compressive force experienced by the spreader bar is the vector sum of the force from the upper-front suspension cable, $\vec{F}_{UF}$ and the lower-front cable, $\vec{F}_{LF}$

$$\vec{F}_{\text{compressive}} = \vec{F}_{UF} + \vec{F}_{LF},$$

which is determined by the payload mass, $M$, and the each cable’s angle with respect to the horizontal as shown in Figure 4.31:

$$F_{\text{compressive}} = 5M\left(\cot(\theta_{UF}) - \cot(\theta_{LF})\right)$$

Figure 4.31: Force diagram showing the cable angles and forces on the spreader bar.
For the BLAST-TNG suspension system, based on the angles and tension forces listed in Table 4.3, the max compressive force on the spreader bar in a 5 G cable pull is 43,290 lbf, giving a FOS of 2.6, which exceeds the 1.5 FOS minimum for brittle elements.

### 4.5.3 Spreader Bar End Fitting

The spreader bar end fittings were machined out of a single block of 7075 aluminum. Minimum FOS for the fittings was determined through SolidWorks FEM analysis. In the simulations the load from the suspension cables was modeled as a sinusoidally-distributed bearing load applied to the bolt holes, while the insert into the tube was fixed. The compressive force of the bolts was simulated by applying roller/slider fixtures to the front and rear faces which forced them to stay parallel to each other. The simulation loads and fixtures are shown in Figure 4.32. The results of the simulation are shown in the stress plot in Figure 4.32. Based on the material properties from [67] and the angles of the suspension cables, the spreader bar end fittings are rated for a maximum load of 6,000 lbs.
Figure 4.32: SolidWorks render of the spreader bar end fitting showing location of the applied loads (purple arrows) and fixtures (green arrows).
4.5.4 Pivot Motor Housing

As the primary attachment point of the complicated geometry of the suspension cables and the home of the many parts with close tolerances of the pivot motor itself, the pivot motor housing is the most complex and demanding component of the suspension system. All of the internals of the pivot motor, including the bearings, rotor shaft, motor, and electronic components were kept from the BLAST-Pol 2012 flight, thus requiring the internal geometry and height of the motor housing to be maintained from the old design. The pivot motor housing had to be rebuilt to accommodate the new suspension cables. Not only do the BLAST-TNG suspension cables attach at different angles, forcing the attachment points to be moved, the altered geometry
requires stronger attachment points due to the steep attachment angle of the upper-
front cables. The four suspension cables attach to the motor housing with open spelter 
sockets which are pinned to four attachment points or “ears” which protrude from the 
housing as shown in Figure 4.50.

To reduce discrepancies between the as-modeled and as-manufactured parts, and 
to best utilize the institutional experience at Penn, the pivot motor was machined 
in-house at the Penn machine shop from a single piece of steel. In both the BLAST-Pol 
and SPIDER pivot housing, which was based on a similar design [107], the cable 
attachment ears were made from plate stock, and welded onto the body of the housing 
which was machined separately. For BLAST-TNG, simulations showed that the stress 
on the ears was very demanding, and indicated that uncertainties in the size, geometry, 
and strength of the weld bead could threaten failure of the weld under the 5 G cable 
pull scenario. We were wary about our ability to properly specify and model the welds 
and validate their design to ensure they achieved the strength necessary. We decided 
we would best be able to ensure the machined part matched the SolidWorks model 
if we machined the entire monolithic housing out of a single piece of aluminum. A 
single 13” x 14.5” x 6” AISI 4340 (E4340) per AMS 6359 aircraft-quality hot-rolled, 
annealed plate was purchased from Benedict-Miller LLC,\(^3\) and machined by Jeffrey 
Hancock at the University of Pennsylvania machine shop using a 5-axis CNC mill. 
The progression of the machining process is shown in Figure 4.34.

The pivot housing had to be heat-treated in order to achieve the high tensile 
strength necessary to withstand the worst-case forces on the cable attachment ears. 
We wanted to achieve the highest tensile strength possible for the part without over-

---

\(^3\)123 North 8th Street, Kenilworth, NJ 07033
Figure 4.34: Images showing the pivot motor housing in different stages of the manufacture. **A:** Roughing out the shape of the housing from the annealed 4340 plate stock, **B:** Initial machining complete, with extra material left on critical surfaces, **C:** The part after heat-treating, **D:** Interior bearing surfaces are remachined to tolerances, **E:** Part is cleaned, painted, and interior surfaces wiped down with a light oil to prevent rust.
hardening the steel into a brittle condition. After consulting with several companies, it was decided that the part would be heat-treated at ACME Heat Treating Co.\textsuperscript{4} according to the following approach:

1. Machine all surfaces, leaving at least $1/16$” extra material on internal bearing surfaces and cable attachment holes in ears. Drill all bolt holes.

2. Give part a salt bath hang in and out at $1200^\circ$ F to stress relieve

3. Austenitize (heat treat) the part $1450^\circ$ - $1550^\circ$ F

4. Oil quench

5. Temper the part at $<830^\circ$ F

6. Remachine all holes in ears and internal bearing surfaces

After heat-treating, the Rockwell C hardness was measured on two spots on the front ears. Due to the geometry of the part these were the only locations that fit into the hardness gauge. The Rockwell C hardness was measured to be between 44 and 45. The final hardness and the ultimate tensile strength of the heat-treated part directly depends on the temperature of the final temper, as shown in Figure 4.35. The relationship between Rockwell C hardness and tensile strength is shown in Figure 4.36, based on data from [15; 20; 105]. Based on these data and the measured hardness, we anticipate that the ultimate tensile strength of the BLAST-TNG pivot is 198,412 PSI (1,368 MPa), as listed in Table 4.1.

\textsuperscript{4}4626 Hedge St, Philadelphia, PA 19124
Figure 4.35: Plot from [15] showing the dependence of final material properties of 4340 steel hardened at 840°C (1544°F), oil quenched and tempered at different temperatures. The BLAST-TNG pivot housing was tempered at the lower end of the plot at 443°C (830°F).
Figure 4.36: Ultimate tensile strength for 4340 steel heat-treated to different hardness values from three different references [20; 15; 105]. The Rockwell C hardness of the BLAST-TNG pivot housing was measured in two locations after heat treating and was determined to be between 44 and 45, giving an estimated ultimate tensile strength of between 1335-1403 MPa depending on the reference. For FEM simulations a tensile strength of 1368 MPa was used, the average of the three predicted values from the above references of the tensile strength for a Rockwell C hardness of 44.5.
FEM simulations of the pivot housing were re-run using the measured values for the tensile strength and parameters listed in 4.1. Three simulations were run, modeling a 10 G load distributed evenly on all four cables, and a 5 G load applied in turn to a single front and rear ear. The forces applied are listed in Table 4.3, and were applied as bearing loads to the interior face of the ear at the location of the spelter socket pin and along the direction of the suspension cables. The worst-case scenario of the 5 G cable pull was modeled where the load is applied while the pivot is in its nominal position with the motor axis oriented vertically, with no tipping of the gondola allowed. Two fixtures were used in the model: a fixed-condition was applied to the face where the thrust bearing sits, and a fixed-hinge condition at the location of the centering bearing. The fixed-hinge models the behavior of this bearing and allows vertical motion about the motor axis, but prohibits radial squishing or stretching. The location of the fixtures and loads are shown in Figure 4.37. The final results of the simulations are listed in Table 4.4.
Figure 4.37: Pivot motor housing FEM parameters.
Figure 4.38: Pivot motor housing FEM parameters.
Figure 4.39: Pivot motor housing FEM parameters.
Figure 4.40: Pivot motor housing ear FEM parameters used for the 5g cable pull simulations.
Figure 4.41: 5g cable pull on front ear of pivot housing.
4.5.5 Pivot Bearing and Rotor Shaft

A cross-section of the pivot motor enclosure is shown in Figure 4.43. The two critical structural components within the pivot motor enclosure are the thrust bearing which supports the pivot housing off of the rotor shaft, and the rotor shaft itself which attaches through the universal joint to the balloon flight train. Both of these components will be reused for BLAST-TNG after being successfully flown on the the BLAST-Pol 2010 and 2012 flights. The SPIDER 2012 flight successfully flew the same
rotor shaft design [107]. The critical load case for both of these parts is the 10 G chute-shock case.

Figure 4.43: Cutaway render of the BLAST-TNG pivot motor enclosure showing critical structural components like the upper pivot housing, thrust bearing, and rotor shaft.

The thrust bearing is an SKF\textsuperscript{5} 51218 single-direction thrust ball bearing with a basic static load limit (lower than the ultimate failure rating) of 65,195 lbf (290 kN). These bearings typically have a design factor of 5, which gives a FOS = 5.5 at 10 G.

The rotor shaft, like the pivot motor housing, is made of 4340 oil-quench-hardened heat-treated steel. The bearing was flown previously on the BLAST-Pol 2010 and 2012 flights, and was manufactured at the University of Toronto. The hardness was

\textsuperscript{5}SKF USA Inc. - North American Headquarters 890 Forty Foot Rd. Lansdale, PA
measured at Acme Heat Treating in Philadelphia, PA in March, 2018 to be between 50 and 51 on the Rockwell C scale, corresponding to a minimum UTS of 198.4 KSI (1368 MPa) based on the data shown in Fig. 4.36.

The rotor shaft was modeled in an assembly with the pivot motor housing, and simplified models of the thrust and needle bearings which support the pivot rotor shaft. The simplified bearings were simulated as carbon chromium steel solid elements; the details of the ball/needle bearings were not explicitly modeled. The bearings are press fit into the pivot housing, which was modeled by using bonded contacts between the pivot motor housing and the simplified bearings in the FEM. Fixed, rigid elements were used to represent the suspension cable spelter socket attachment points. The acceleration loads were modeled as an equivalent force (assuming 7,000 lb payload mass) applied to the lower section of the universal joint in the direction of the acceleration. For the purposes of modeling the loading on the rotor shaft, the universal joint was modeled as a rigid element. The universal joint strength was assessed in a separate FEM, as discussed in section 4.5.6. The details of the mesh and the FEM for the rotor shaft are shown in Fig. 4.45.
Figure 4.44: Cross-section view of the pivot rotor shaft FEM assembly showing the components modeled.
Figure 4.45: FEM model of the pivot rotor shaft assembly, showing the mesh, and model parameters.
Figure 4.46: FEM of stress on the pivot motor housing and rotor shaft during a 10g vertical acceleration.
Figure 4.47: FEM of stress on the pivot motor housing and rotor shaft during a 10g vertical acceleration, showing only the stresses on the shaft. The model used is the same as shown in Fig. 4.46, but with other components hidden for clarity.
Figure 4.48: FEM of stress on the pivot motor housing and rotor shaft during a 5g acceleration at 45° from vertical, showing only the stresses on the shaft. The model used is the same as shown in Fig. 4.46, but with other components hidden for clarity.
Figure 4.49: FEM of stress on the pivot motor housing and rotor shaft during a 5g horizontal acceleration, showing only the stresses on the shaft. The model used is the same as shown in Fig. 4.46, but with other components hidden for clarity.

4.5.6 The Universal Joint

The BLAST-TNG universal joint is based on the same design which on the BLAST-Pol 2012 payload, which is a reproduction of the universal joints which suspended all prior BLAST flights (BLAST 2003, BLAST 2005, BLAST-Pol 2010), and the SPIDER 2012 [107]. The joint was originally designed by AMEC Dynamic Structures,\textsuperscript{6} and

\textsuperscript{6}1515 Kingsway Avenue, Port Coquitlam, British Columbia V3C 1S2 Canada
consists of a monolithic hardened 4340 steel core, with four machined shafts which form a cross. A split yoke rotates about each pair of steel shafts. Each yoke is formed by two machined blocks bolted together with hardened steel shoulder bolts. The upper yoke couples to the balloon flight train, while the lower yoke bolts to the pivot motor shaft as shown in Figure 4.50. The yokes are retained on the steel cross by steel snap rings. This design allows up to 135° rotation in each direction.

For BLAST-TNG the yokes have been remade out of hardened 4340 steel, heat-treated to 50 HRC. This provides higher tensile strength than the 7075 aluminum construction used in BLAST-Pol. Under the 10g chute-shock load case, the steel cross and the yokes have FOS of 2.3 and 2.4, respectively.

The details of the FEM are shown in Fig. 4.51. Besides the 10g vertical load, the load was modeled based on a 5g pull at 45° to the vertical towards both of the possible directions of rotation of the universal joint, as shown in Fig. 4.52. The hardened steel bolts in the joint assembly, and the shackle which attaches to the flight train, were modeled as rigid elements (shown in orange in Figs. 4.51 and 4.52). No penetration global bonds were used for all attachments to the rigid pins. The clamping force from these fasteners was modeled by using bonded contacts between the upper yokes and the shackle block, and by using roller/slider fixtures for the inner face of the lower yokes that attach to the pivot rotor shaft. For the 5g pull at 45° from vertical towards the side, an additional bonded contact between the cross and the lower yokes was necessary to simulate the retaining force of the spring clips which prevent the yokes from sliding back and forth along the cross. To keep the load force pulling in the correct direction without unrealistic twisting in the FEM, a roller/slider fixture was
applied to the end faces of the shackle pin. The results of the simulations are given in the following figures.

Figure 4.51: Details of the FEM of the universal joint for the 10g vertical acceleration load case.
Figure 4.50: Detail of the BLAST-TNG universal joint parts and attachment points between the pivot motor and the balloon flight train. Note in this photo the pivot motor itself has been removed from the upper motor housing.
Figure 4.52: Details of the FEM of the universal joint for the 10g vertical acceleration, and the 5g acceleration at 45° from vertical. The angled loads were modeled based on a pull towards the “side” (middle figure), and the “front” (right figure), the two allowed rotations of the joint.
Figure 4.53: FEM of stress on the universal joint during a 10g vertical acceleration.
Figure 4.54: FEM of stress on the universal joint during a 5g acceleration at 45° from vertical, oriented towards the side of the joint.
Figure 4.55: FEM of stress on the universal joint during a 5g acceleration at 45° from vertical, oriented towards the front of the joint.

4.6 Pointing Control

4.6.1 Pointing Motors and Electronics

The pointing of the BLAST-TNG gondola is controlled by three motors. The elevation of the inner frame is controlled by a direct-drive, brushless DC servo motor.\textsuperscript{7} The elevation motor is attached to the outer frame elevation mount and turns a

\textsuperscript{7}Kollmorgen Cartridge DDR C053A
steel shaft which is bolted directly to the side of the inner frame. To ensure smooth operation of the elevation drive without over-torquing the motor, the inner frame must be well-balanced. The inner frame will be balanced by hand before flight by strapping lead bricks to various points on the frame. However, as the 250 L (∼70 lbs) of liquid helium in the cryostat boils off over the course of the flight, the inner frame center of mass will systematically move towards the elevation axis. To account for this change in balance, we implemented active balance system consisting of a 1 m long belt drive, mounted at an angle of ∼48° off of the optical axis, which moves a 25 kg mass away from the elevation axis if the elevation motor current begins to exceed a desired threshold. This belt-drive balance system replaces the balance system flown in previous generations of BLAST in which liquid coolant was actively pumped between two reservoirs mounted on opposite sides of the elevation axis to adjust the inner frame center of mass. The liquid coolant system was successful, but exceedingly messy, leaky, and ran the risk of failure from freezing or clogging.

The azimuth of the gondola is controlled by two motors. Fine pointing is provided by a high moment of inertia 76 kg reaction wheel spun by a direct-drive brushless DC motor. Changes to the angular velocity of the reaction wheel provides torque to the outer frame. The reaction wheel motor can be used to impart precise control of the angular velocity of the gondola but saturates if large slews or fast azimuth scans are required. To provide the extra torque needed for these scan operations, a second azimuth motor known as the pivot motor sits above the gondola at the attachment point between the suspension cables and the balloon flight train. The pivot motor

---

8Macron Dynamics Inc MSA-R15-B-AB-AM1-1000 1000 mm stroke actuator with Thoomson Linear XT060-100-0-RM060-1 100:1 Gearbox and Danaher Motion NEMA 23 2-Stack Stepper Motor
9Kollmorgen D062M
servos directly off of the reaction wheel velocity and typically is set to maintain to the reaction wheel velocity below 20 rpm.

Like the other pointing motors, the pivot motor is a brushless direct drive motor.\textsuperscript{10} The pivot motor stator is glued to the interior of a hardened steel housing which has attachment points for the four steel wire ropes which suspend the gondola outer frame. The rotor of the motor is glued to a hardened steel shaft which is suspended by a thrust bearing inside the housing. The rotor attaches through a universal joint to the balloon flight train, allowing the gondola to rotate in all directions about the base of the flight train. The structural and mechanical design of the pivot motor, housing, and flight suspension are detailed in chapter 4.5.

Each of the three pointing motors is controlled by an external motor controller, mounted in an enclosure next to or below the motor. These motor controllers take in velocity commands from the flight computers and take care of the motor commutation to drive the motor at the desired speed. The controllers can be programmed to change the PID parameters for the servo loops to adjust how the motors respond to the incoming commands. These parameters must be tuned after changing the moment of inertia of the load when, for example, pointing with or without the cryostat mounted. For consistency, all three motor controllers were all purchased from the same company. The reaction wheel and elevation drive both use sine encoders for their commutation feedback, and used the same model motor controller,\textsuperscript{11} while the pivot motor uses a slightly different model that can handle the commutation feedback from a use mounted below the motor.\textsuperscript{12}

\textsuperscript{10}Bayside K1782008Y1
\textsuperscript{11}AccelnetPlus EtherCAT AEP-090-30
\textsuperscript{12}AccelnetPlus EtherCAT BEL-090-30-R
Communications with the flight computers are handled along a EtherCAT communications daisy chain, shown in Figure 4.56. EtherCAT is an ethernet servo drive communications protocol typically used for multi-axis CNC computer aided manufacturing (CAM) tools. Because the EtherCAT communications must be sent along a daisy chain, the ethernet cables between each motor are a single point of failure. To reduce the risk of damage to these cables, heavy-duty shielded UV-damage-resistant cables were used for ethernet cables that must move in flight (ie, those that pass from the inner to outer frame). Conventional off-the shelf ethernet cables were used elsewhere. The RJ45 jacks on the motor controller enclosures were replaced by more rugged milspec metal circular connectors. Further details of the pointing motors, their construction and operation can be found in [45].
4.6.2 Pointing Sensors

A suite of pointing sensors are used to continuously measure the attitude, geographic location, and trajectory of the payload and are read in by the flight computers to calculate the real-time telescope pointing solution in right ascension (RA) and declination (DEC). These sensors are able to compute the solution to $<5'$ rms during flight, and to $<5''$ rms after post-flight pointing reconstruction [52]. The flight code produces a separate pointing solution from the input of each sensor. These separate solutions are then combined into a single in-flight pointing solution by weighting each sensor by its systematic variance [52]. This in-flight solution is then used to calculate the pointing motor velocities needed to complete the programmed scan pattern of the telescope.

The absolute pointing information of the telescope is primarily provided by two autonomous daytime-operating star cameras, mounted above the cryostat pointed parallel to the optical axis. These cameras contain a high-resolution integrating CCD camera controlled by a single-board computer, both mounted in an aluminum pressure vessel. The camera observes a $2^\circ$ by $2.5^\circ$ area, and the exposure time, aperture, and focus can be controlled by the single-board computer and stepper motors mounted to the camera lens [99]. The control computer runs a attitude-determination program called Star Tracking Attitude Reconstruction Software (STARS), developed for the EBEX experiment [31; 26]. STARS locates “blobs” in the star camera images, and then matches the pattern of the brightest blobs against a catalog of known stars to determine the RA and DEC of the camera field of view. With a good initial guess of the pointing solution to reduce the size of the search space in the catalog, STARS
can provide a new solution within a few seconds. With no initial guess, the software implements a “lost-in-space” algorithm which systematically checks the blob pattern against the entire star catalog. The two star cameras operate simultaneously, both providing pointing solutions to provide degeneracy in the event that one camera is damaged.

The input from coarse pointing sensors is crucial to providing accurate initial guesses to STARS and ensuring fast star camera solutions. BLAST-TNG flies a suit of coarse sensors which use totally different methods of measuring various aspects of the payload attitude. An array of eight pinhole-sun-sensors (PSS), shown in Figure 4.57, measure the elevation and azimuth of the Sun with respect to the gondola which can be used to compute the telescope RA and DEC [73; 52]. The eight sensors are arranged in a semicircle to ensure observation of the Sun over an azimuth range >180°. Each sensor has a 40° FOV, and are mounted at an angle of 22.5° apart in azimuth, so that within the FOV of the PSS array, the Sun should be visible in at least two sensors at any given time. Each sensor is mounted at 25° from horizontal, to allow observation of the Sun in the event that the balloon drifts ±10° from its expected latitude (see Figure 4.58). A three-axis magnetometer13 is connected to each flight computer and mounted at the furthest forward part of the outer frame (on the “chin” of the outer frame sun shield) determines azimuth pointing by measuring the direction of Earth’s magnetic field, although its accuracy is limited in such close proximity to the magnetic pole. Two alcohol-bubble biaxial inclinometers 14 measure the tip/tilt of the inner and outer frame.

13Honeywell Honeywell HMR2300  
14Applied Geomagnetics Model 904-TH
The timing of the star camera image capture is dictated by the scan pattern of the gondola. The exposure time to achieve an adequate SNR for attitude determination is on the order of a second. However, the typical scan speed for BLAST-TNG is around $0.5 \, ^\circ/s$ for BLAST-TNG, meaning that to avoid blurring of the images, the star cameras can only capture images at the turnarounds of the scans, which are in practice a few seconds apart. Two three-axis fiber-optic gyroscope units $^{15}$ mounted on opposite sides of the inner frame are used to precisely measure the angular velocity of the inner frame and interpolate the telescope pointing in between star camera solutions. During flight, readout from an absolute encoder in the elevation motor also provides precise elevation information. In post-flight pointing reconstruction, only the star camera solutions and the gyroscope readings are used to create the post-flight pointing solution [52; 31].

$^{15}$KVH Industries DSP-1760
Figure 4.58: The elevation of the Sun on December 22, 2017 at Antarctic latitudes. The blue curve shows the Sun elevation at the latitude of the balloon when launched from McMurdo. Over the course of the flight we expect drifts in the payload due to changing winds, which typically carry the balloon no more than \( \pm 10^\circ \) north or south, though certainly can exceed this in rare events.
4.7 Sun Shields

The BLAST-TNG payload thermal environment is controlled by extensive baffling and Sun shields. The thermal environment of the telescope and the payload must be carefully controlled to avoid direct solar illumination of the optical system, and to ensure all components operate within allowable temperature ranges. The flight trajectory and the conditions during launch, ascent, and descent are largely unpredictable, and can vary widely between different launches. As such, it is necessary to design the gondola platform to handle a wide range conditions and stresses.

The Sun shield design follows the approach from the BLAST-Pol experiment, detailed in Soler et. al., 2014 [108]. A 6.5 m long aluminized mylar baffle surrounds the telescope optics. The baffle is formed around a truss of carbon fiber tubes\textsuperscript{16} bonded to aluminum fittings, incorporating design elements from the X-Calibur gondola [72]. An outer Sun shield built from welded aluminum pipe\textsuperscript{17} encloses the entire payload and acts as a ground screen protecting the entire instrument from both direct and reflected solar illumination.

4.8 Thermal Model

An accurate thermal model of the payload during flight is critical to the design of the Sun shields, as well as the surface treatments, location, and shielding of individual electronic components around the gondola. A detailed model was used to determine the placement of the reflective panels and predict the operating temperatures of the

\textsuperscript{16}CST Composites
\textsuperscript{17}GSM Industrial Inc.
Figure 4.59: Photographs of the outer frame Sun shield (left), and the inner frame telescope Sun shield/telescope baffle (right). The outer frame Sun shield is shown with the front section which serves as a ground screen protecting the telescope from Earth shine. The outer frame Sun shield is composed of welded aluminum sections which bolt together and are lifted on together. The inner frame baffle is made of machined aluminum fittings and hubs which form the anchors of a CFRP truss. The baffle is assembled in layers and bolted to the frame while suspended from a hoist. Neither Sun shield has its Mylar paneling installed, which will not happen until the integration in Antarctica.
major systems and electronic components. This model is designed and simulated with ThermalDesktop\textsuperscript{18}. ThermalDesktop creates a node and conduction network from an AutoCAD model, and interfaces with a built-in differential equation solver, SINDA/FLUINT, which solves the heat transfer equations, and interprets and displays the results. The Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA/FLUINT) is the NASA standard for computationally simulating heat transfer and fluid flow networks. This suite of software is able to calculate the radiative and conductive heat transfer for the full gondola model, based on solar heating rates during simulated flights from any latitude, trajectory, and launch date. A series of simulated flights along anticipated flight paths components based on a range of launch dates are used to verify the thermal management plan for the whole payload, and ensure all components operate within rated temperatures at all times.

The most uncertain aspect of this thermal modeling approach is the thermal links between various components. Thermal loads and connections must be input by hand. Improper accounting for the conduction across bolted, clamped, or glued joints can lead to unrealistic results and mask problems that may arise during flight. The details of conductive paths between the gondola and internal components of the computers, hard drives, and other electronics are particularly difficult to estimate. As such, the details of the connections must be calibrated by making laboratory measurements in near-flight conditions.

\textsuperscript{18}Cullimore & Ring
4.8.1 Case Study: ROACH Enclosure Thermal Model

An example of a thermal model component calibration is shown in Fig. 4.61 for the ROACH-2 detector readout enclosure, known as the ROACH Motel. The ROACH Motel is the most demanding component on the payload in terms of thermal management. The enclosure is bolted to the inner frame, and contains five readout cards, each composed of dozens of small electronic radio-frequency modulation components and computer chips. Each readout card generates a static heat load of 25-30 W, most of which is generated by two components: an onboard field-programmable gate array (FPGA), and a single board computer known as the Power PC (PPC). The details of
the components and initial testing can be found in [56]. The stages in each numbered picture of Fig. 4.61 are described in the corresponding numbered paragraphs below:

0. **Hand Calculations:** In the earliest stages, a series of hand calculations were used to estimate the thermal link between the FPGA and PPC and the gondola inner frame that would be required to pull sufficient heat away to the gondola frame. The gondola inner frame has a large amount of surface area which acts as an efficient radiator to radiate the power out to the sky. Based on these early hand calculations, a set of heat pipes were installed and glued to the FPGA and PPC and connecting them to the enclosure.

1. **Vacuum Chamber Test:** The hardware was then tested in a vacuum chamber at the University of Pennsylvania. The side panels of the enclosure were cooled with a liquid-water heat exchangers. The steady state temperatures of the enclosure and sensitive components were recorded

2. **Thermal CAD Model Creation:** Steady state temperatures from the vacuum chamber test were used to build a ThermalDesktop model of the test chamber and water-cooling system. By tuning the thermal links in the model to reproduce the measured temperatures, the thermal conductivity of the connections were determined empirically.

3. **Thermal Vacuum Chamber Test:** After building an accurate thermal model of the internal components, it was necessary to determine the allowed operating temperature of the enclosure, and calibrate the thermal link between the ROACH Motel and the inner frame. Because the inner frame could not
be run in the thermal vacuum chamber at CSBF, a large aluminum plate was used as a proxy. This plate was not able to radiate away as much heat as the inner frame, but was useful for measuring the conductivity of the bolted contact between the enclosure and its mount.

4. Refining/Tuning Thermal CAD Model: Based on the temperatures of the ROACH Motel components and the mount plate recorded in the thermal vacuum chamber, the ThermalDesktop model was again tuned to reproduce the observed results. In this way the thermal conduction between the both the internal components and the enclosure, and the enclosure to the inner frame could be calibrated.

5. Hand Calculations: With the ROACH Motel model now fully calibrated with accurate thermal links, the ROACH Motel was added to the full working model of the payload, and temperatures were simulated during the flight path.

6. Final Integration: Once the thermal performance of the model was verified, the ROACH Motel was reinstalled in its flight configuration.

This thermal modeling approach is being applied to all electronic components, and the full model is still under development, and will be updated during the pre-flight integration in Palestine, TX to reflect the final flight configuration of the payload.
Figure 4.61: Schematic of the approach to building the thermal model of the payload and various components. A detailed explanation can be found in the list on the preceding pages.
Chapter 5

The Cryogenic MKID Receiver

Success of all of BLAST-TNG’s observational goals relies on making sensitive and stable observations of many different molecular clouds, and a varied sample of regions of the ISM with different densities and radiative environments. This is enabled primarily through by the high-sensitivity MKID detector arrays, careful control of polarization systematics, and crucially, a cryogenic receiver that will operate autonomously for the full 28-day flight.

5.1 Cold Optics

The cryogenic receiver encloses a series of cold re-imaging optics arranged in a modified Offner relay configuration. A similar configuration was flown in the BLAST/BLASTPol optics box. The design features a cold Lyot stop at the image of the primary mirror which significantly reduces the optical loading on the detectors from stray light. The optics bench, shown in Fig. 5.1, cools the 4K reimageing optics,
and supports the band-defining filters which split the telescope beam to the three focal plane arrays. Details of the optical design can be found in Lourie, et. al[79], and in [51; 33].

Figure 5.1: Photograph of the BLAST-TNG 4 K reimaging optics with critical components labeled.

5.2 Cryostat Design

To simplify the mechanical design and minimize the number of pressure vessels, the cryostat is based on liquid helium-only system. A 250-L liquid helium tank cools the optics and cold electronics to 4 K, and backs the operation of the sub-Kelvin refrigeration system, described in further detail in Section 5.3, and in Galitzki, et. al. [51].
The 4 K cold plate is integrated into the tank, and forms the lower cap of the liquid helium dewar as shown in Fig. 5.2. The cold plate has a domed center to maximize structural rigidity while reducing mass. The optics bench is bolted to the thick rim of the tank and located with precision alignment features machined around the perimeter. By mounting the optics to the perimeter, the optics are isolated from pressure-induced bowing at the center of plate. The 4 K optics cavity is enclosed by an 1100-series aluminum shroud. The interior of this shroud is coated with an absorptive coating made from Stycast 2850-MT/Cat 23LV\(^1\) mixed with 10\% by mass of powdered charcoal\(^2\) to absorb stray in-band light as well infrared radiation to prevent indirect loading of the sub-Kelvin components [89].

All housekeeping electronics are accessed via the top lid of the cryostat. A series of six pass-through pipes is welded into the liquid tank to allow wiring, coaxial connections from the detector focal plane readout, and axles from the cryogenic actuators to be passed directly from the cold-plate to the top of the cryostat. These pass-throughs can be accessed by removing the top lids of the vacuum shell and vapor-cooled shields, so that making changes to the wiring harnesses does not require disassembly or removal of all of the cryostat shells.

Two intermediate thermal shrouds made of 1100-series aluminum enclose the 4 K volume to reduce the conductive and radiative loading on the liquid helium bath. As the liquid helium boils, the vapor is forced through two copper spiral heat exchangers [49], one bolted to each of these intermediate vapor-cooled stages (VCS), cooling the first intermediate stage (VCS1) to 40 K and the second stage (VCS2) to 140 K. The

\(^1\)Henkel Adhesives, North America
\(^2\)General Pencil Company, Inc. Redwood City, CA
entrance and exit apertures of the spiral heat exchangers sit within the helium fill port, which is the only port attached to the helium tank. Two spring-loaded PTFE plugs seal the fill port at each VCS stage, allowing vapor pressure in the tank to build to 25 mbar above atmospheric pressure and force the cold helium gas from the cryogen boil-off through the heat exchangers[49]. These plugs are removed during cryogen transfers. A TAVCO\textsuperscript{3} 1-atm absolute pressure valve regulates the pressure at the outlet of the VCS2 heat exchanger. The 4, 40, 140, and 300 K stages are separated.

\textsuperscript{3}TAVCO Sales & Service Company, Inc. Gilbert, AZ
by G10 fiberglass cylinders with wall thicknesses of 0.018, 0.040, and 0.063 inches respectively. The G10 cylinders are assembled from epoxy-coated woven fiberglass, and are assembled such that the warp of the G10 fibers is oriented circumferentially around the cylinders which reduces the effective thermal conductivity of the supports [81]. The VCS stages are a highly coupled system, and the cooling power of the heat exchangers is proportional to the boiloff rate of the helium bath, providing negative thermal feedback to the 4 K stage. The VCS typically reach +/- 5 K of their equilibrium temperatures within 48 hours of the initial liquid helium transfer and reach equilibrium temperatures stable to <1 K within 4 days.

If not properly controlled, infrared loading through the cryostat window can dominate the loading at each stage. A series of metal-mesh band-defining and thermal/infrared blocking filters, and low-pass band-defining filters reflects infrared light back out of the cryostat, while passing submillimeter wavelengths through to the cold optics and FPAs. The filter arrangement at each temperature stage has been adjusted between “light runs” with the window installed, in order to optimize the infrared rejection and maximize in-band transmission. The radiative load on the 4 K stage is particularly sensitive to the filter arrangement at the two VCS. The low-pass filters reject out-of-band submillimeter radiation, but are extremely absorptive in the infrared, which must be filtered out earlier in the filter stack. Where allowed by space constraints, the filters are tipped at opposing angles to reduce Fabry-Perot resonances and multiple reflections.
5.3 Sub-Kelvin Refrigeration System

The BLAST-TNG focal plane arrays are cooled to $\sim 275$ mK via a closed-cycle $^3$He sorption refrigerator, backed by a $\sim 1$ K superfluid, pumped $^4$He volume (the “pumped pot”), which draws liquid helium from the main liquid helium tank. The $^3$He refrigerator is a copy of that flown on the BLASTPol and BLAST experiments[88], and built for the MUSTANG instrument on the Green Bank Telescope[29].

Figure 5.3: Cross-section of render of the BLAST-TNG cryostat with critical components labeled.

The geometry of the BLAST-TNG superfluid system is designed to minimize the consumption of liquid helium during operation, and run as cold as possible to reduce loading on the FPAs. The flow of liquid helium into the pumped pot is regulated by a 0.25 mm diameter rate-limiting capillary, and can be turned on and off by a cryogenic
This is contrasted by similar systems in the BLAST-Pol and SPIDER cryostats in which the pumped-superfluid pot is continually filled by a smaller capillary [88; 59]. While introducing a cryogenic valve increases the complexity and risk of in-flight valve failure, it greatly reduces the consumption of liquid helium over the course of the flight and minimizes chances of clogs or ice-plugs in the capillary. Additionally, stopping the flow of liquid helium into the pot lowers the base temperature of the system, since the pot will operate at a lower vapor pressure for a given pumping speed. During flight, the pot is pumped to the ambient pressure at ∼35 km float altitude through a 19 mm diameter pump tube. We expect in-flight operation below 1.3 K, an improvement from the 1.8 K BLAST-Pol system [5]. The 4 K valve is actuated via a G10 fiberglass shaft, through a ferrofluidic feed-through5, driven by a geared stepper motor mounted outside the vacuum shell on the top of the cryostat.

The diameter of the capillary was chosen such that the 200 mL pumped-pot can be completely filled in less than half an hour. While filling, some amount of helium entering the pot will be pumped directly through the pot and into the pump tube rather than collecting. By measuring the flow rate of helium gas through the pump with the 4 K valve open and closed, we find the flow rate of liquid helium through the capillary to be 13.3 mL/min, which collects in the pot at a rate of 8.3 mL/min, a filling efficiency of ∼60%. With the valve open, the pot temperature rises above 2 K. The capillary diameter is such that if the pot valve were to be stuck in its open position due to a mechanical failure, the flight maximum flight time would be reduced to 13 days before the full helium tank is depleted.

4Swagelok Solon, OH
5FerroTec Corporation, Santa Clara, CA
The helium consumption of the pumped pot during operation can be quantified by calculating an average equivalent thermal load which would consume the same volume of liquid helium over the course of the flight. The pot is sized such that the $^3$He refrigerator can be recycled without refilling, and in practice must be refilled every $\sim 3$ days. By turning off the flow of helium into the pumped-pot when it is full, we reduce the equivalent thermal load compared to BLAST-Pol by nearly 85%, from 23 mW to 3.5 mW, even while increasing the capillary diameter from 0.038 to 0.25 mm.

The cryostat and the sub-Kelvin system must be able to operate entirely autonomously. While commanding and communications from the ground will be available during the flight, the telemetry bandwidth is limited and equipment failures could cause contact to be lost completely. Housekeeping thermometry is continuously read out via a combination of custom thermometry bias/demodulation electronics and commercial off-the shelf data acquisition hardware.\(^6\) Any time the array temperatures exceed threshold values, the flight computer triggers the pot valve to open and recycle the $^3$He sorption refrigerator. The thermal loading is low enough that lab testing indicates that the sorption refrigerator will have to be cycled only once every 4-5 days.

\section*{5.4 Receiver Performance}

The cryostat, designed at the University of Pennsylvania\cite{50} and built by Precision Cryogenic Systems\(^1\), first arrived at the University of Pennsylvania in October, 2015.

\begin{footnotesize}\footnote{\textsuperscript{6}LabJack Corporation, Lakewood, CO} \footnote{\textsuperscript{1}Precision Cryogenic Systems, Indianapolis, IN}\end{footnotesize}
Preliminary testing indicated the presence of excess loading on each of the thermal stages. During dark tests with the windows covered at each thermal stage, VCS1/2 ran at 65 K and 165 K respectively, and the loading on the liquid helium bath was $\sim 40\%$ larger than modeled, corresponding to a shortened 22.5 day hold time. The excess loading was attributed to un-modeled radiative loads from light leaks between thermal stages and inadequate multilayer insulation (MLI) around feedthroughs and fixtures [51].

In June, 2017 the cryostat experienced a catastrophic cryogenic failure during a pre-cooling procedure with liquid nitrogen, when an ice plug on the fill port caused an over-pressurization of the liquid cryogen tank rupturing the tank welds. The rupture caused liquid nitrogen to spill into the cavity between the tank and VCS1 where it flash-boiled. The ensuing pressure wave destroyed most of the VCS and 4 K shrouds, the magnetic shielding around the optics box, the focal plane mounts, the plumbing for the sub-Kelvin refrigeration system and the housekeeping wiring. Crucially, however, the cold optics, the cold plate, $^3$He refrigerator, the heat exchangers, and the vacuum vessel were determined to be undamaged. The cryostat was rebuilt and assembled, and underwent its first dark test in December, 2017.

The rebuilt BLAST-TNG cryogenic receiver performance has been validated during extensive laboratory testing and has benefited from key redesigns from its initial conception. Rather than hand-cutting and wrapping single layers of polyester-fiber-backed aluminized mylar to form MLI blankets, custom-designed laser-cut 10-layer blankets of Coolcat 2 NW$^1$ were purchased. Layering these blankets provided 10, 20, and 30 layers of aluminized mylar at the around the 4 K, 40 K, and 140 K stages.

---

$^1$RUAG Space GmbH, Vienna, Austria
The laser-cut slits for the various housekeeping components, along with the addition of metallic baffles around the motor axle shafts significantly reduced the light leaks between stages. Dark testing indicates that the excess loading at each stage has been reduced, and the performance matches the modeled 28 day hold time.

5.5 MKID Detector Arrays

The BLAST-TNG detectors are based on arrays of Microwave Kinetic Inductance Detectors (MKIDS). MKIDs are superconducting, lumped element LC circuits with a resonant frequency and quality factor that is sensitive to changes in incident radiation. Absorbed radiation with enough energy to break Cooper pairs in the circuit causes a change in the kinetic inductance of the device, changing the impedance of the device and causing a shift in the resonant frequency\[28\]. MKIDs can be highly multiplexed, and arrays can be formed by capacitively coupling multiple resonators to a single transmission line. BLAST-TNG achieves multiplexing factors up to \(\sim1000\) (see Table 5.1) using a ‘tile-and-trim’ approach in which arrays of resonators with identical inductive absorbers and capacitive elements of multilayer TiN/Ti/TiN films are laid out on a silicon substrate, before trimming the capacitors with a deep-reactive-ion-etch to uniquely tune the resonant frequency of each resonator [84]. Fabrication errors and wafer non-uniformity can cause displacement of the resonances from their designed frequencies, leading to an ambiguity in the mapping between resonant frequency and physical location on the array. Collisions or overlap between resonances can lead to unusable detectors and reduced yield. The physical location of each resonator was mapped at NIST-Boulder using an custom array of optical LEDs designed for each
The three BLAST-TNG detector arrays are shown in Fig. 5.4. The 350 and 500 µm arrays are both read out on a single transmission line, while the 250 µm array is split into three identical rhombus-shaped subarrays, each with its own transmission line. By using the long, thin inductive element of the MKID as the absorber itself, each resonator is sensitive to single linear polarization. Dual-polarization pixels are formed by coupling two single-polarization-sensitive detectors to a single feedhorn, in a crossoverless configuration which achieves less than 3% cross-polar coupling [32]. Single-pixel testing with a temperature-controlled blackbody load indicate that the detectors are photon-noise-limited for at their 275 mK operating temperature and 15 pW expected optical loading [65; 84].

<table>
<thead>
<tr>
<th>Array Band Center</th>
<th>Number of Feedhorns</th>
<th>Number of MKIDs</th>
<th>Multiplexing Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 µm</td>
<td>918</td>
<td>1836</td>
<td>612</td>
</tr>
<tr>
<td>350 µm</td>
<td>469</td>
<td>938</td>
<td>938</td>
</tr>
<tr>
<td>500 µm</td>
<td>272</td>
<td>544</td>
<td>544</td>
</tr>
</tbody>
</table>

The BLAST-TNG detector arrays are read out using a highly multiplexed, FPGA-based digital spectrometer. This readout is the first of its kind to have been developed for the second generation Reconfigurable Open Architecture Computing Hardware (ROACH-2) board developed by the CASPER collaboration[112]. Each readout module includes a ROACH-2 board, MUSIC [55] digital-to-analog and analog-to-digital converter boards (DAC/ADC) and a set of analog radio-frequency (RF) components, which are housed in a custom enclosure. Using firmware designed for BLAST-TNG, a single board is capable of simultaneous readout of over 1000 detectors at a rate of 488
Hz, over 512 MHz of RF bandwidth. Each ROACH-2 module generates a baseband carrier waveform containing the resonant frequencies of each detector. The carrier signal, which is multiplexed on a single coaxial cable, is upconverted to RF and passed to the detector array, where its phase is modulated by the sky signal. The carriers are then amplified by a ∼4 K SiGe cryogenic low-noise amplifier (developed at Arizona State University), converted to baseband, and looped back into the ROACH-2, where they are digitized, demodulated, and stored to disk. Five readout modules (three for the 250 μm array, one each for the 350 and 500μm arrays) are mounted in an enclosure mounted on the balloon gondola frame. Details of the readout and pre-flight demonstration are presented in Gordon et al. 2017 [56].

Figure 5.4: Cross-section of render of the BLAST-TNG cryostat with critical components labeled.

5.6 Detector Integration

The first detector tests in the rebuilt BLAST-TNG receiver began in February, 2018. The 350 μm array was installed first and run completely in the dark to characterize
the non-optical thermal loading on the array. Each array is mounted on a rigid carbon
fiber mount which mounts to the 4 K optics box, and supports the array off of a 1.4 K
intercept stage. These mounts conduct less than 1 µW per array of thermal power to
$^3$He refrigerator[33]. During dark tests the array operated successfully at 275 mK. The
cryogenic run with all the windows and filters installed was conducted in April 2017
with both the 250 and 350 µm FPAs installed. The optical loading on the detectors
did not affect the operating temperature, allowing for preliminary optical testing.

As of early May 2018, all three MKID FPAs were mounted in the receiver in flight
configuration. Initial results indicate that all arrays are fully operational, with high
detector yield and expected sensitivity. Vector network analyzer (VNA) sweeps for
each array taken in the flight receiver are shown in Fig.5.5.

\section{5.7 Flight Receiver Optical Testing}

\subsection{5.7.1 Polarization Response}

Understanding the response of the receiver to polarized light is critical to character-
izing the instrument analyzing the maps made during the flight. The detector cross-pol
has been measured at NIST to be less than 3\% [32]. The polarization efficiency and
cross-polar response of the receiver is measured by observing the response to a chopped
liquid nitrogen source which provides a near-square-wave chop between 300 K and
77 K. The source does not fill the receiver beam but provides adequate signal across
most of the array. To ensure the detectors operate when viewing the 300 K blackbody
we place a 4 K 4\% neutral density filter (NDF) at the entrance to the optics box.
Figure 5.5: VNA sweeps for each of the arrays taken in the BLAST-TNG flight receiver. Data has been low-pass filtered to remove ripple and slope from cable attenuation. The sweep from the 250 µm array is for one of the three identical subarrays of MKIDs that make up the full FPA.

A metal-mesh polarizing grid provided by Cardiff University is placed in front of the cryostat and mounted at a 45° angle to the optical axis to reduce Fabry-Perot resonances. Detector time streams are recorded using the flight ROACH-2 readout hardware during chops and the angle of the polarizer grid is stepped to measure the response as a function of polarization angle.

Detector time streams measured during preliminary measurements are shown in Fig. 5.6 for representative X and Y-polarized resonators on the 250 µm array. Further
measurements for each detector array are ongoing. To measure the instrumental polarization we repeat the same chopped measurement with the polarizing grid at a fixed position and step the position of the half wave plate. This characterizes the polarization effects induced by the receiver optics themselves.

The degree of instrumentally-induced polarization signal in the receiver is measured by using the 4 K half wave plate (HWP) in the receiver cold optics. Instrumental polarization is characterized by repeating the same observations of the chopped liquid nitrogen source with the external grid at a fixed angle while stepping the HWP. Repeating these measurements at different grid angles allows polarization effects inherent to the receiver design to be identified and accounted for during data analysis. As of May 2018 the HWP was removed from the system to improve the design of the thermal strapping to mitigate observed drifts in the filter temperature, and will be re-installed during the summer of 2018 to carry out these measurements.

5.7.2 Noise

The BLAST-TNG detector arrays have been demonstrated to be photon-noise-limited at the expected in-flight optical loading [65], and a number of improvements have been made to the receiver RF system to maintain this low-noise performance. In order to minimize the conductive thermal loading on the liquid helium bath and the two VCS, we use thin (0.86 mm diameter) stainless steel coaxial cable \(^1\) between 4 K and 300 K. These cables have sufficiently low thermal conductivity, but have relatively high signal attenuation, contributing to a round-trip signal attenuation of \(~\)

\(^1\)COAX CO. LTD., Kanagawa, Japan
Figure 5.6: Preliminary polarization response demonstration of the 250 µm FPA, showing response to a 300 K/77 K chop viewed through a polarizer grid at different angles. Upper plot shows response of an X-Pol resonator and the lower plot shows a Y-Pol. Response is in arbitrary uncalibrated units read in using the ROACH electronics in flight configuration. Chop time streams are arbitrarily offset along the y-axis for better visibility. Polarizer grid absolute angles are arbitrary and are not referenced to the detector antenna axis.

-30 dBm. Maintaining high signal-to-noise detector operation requires sufficient cold amplification. We require that the noise readout through the full receiver/ROACH readout chain be dominated by the cold amplification stage based on 4 K SiGe low-noise amplifiers designed by Arizona State University. Based on preliminary noise measurements of the 250 µm FPA in the BLAST-TNG receiver, we are experimenting with adding additional SiGe amplifiers at both 4 K and at 300 K in the ROACH enclosure to optimize the readout signal-to-noise, ensure operation within the working range of the ROACH ADCs.
Figure 5.7: Response of three MKIDs on the 250µm array to different beam-filling optical loads, measured through the BLAST-TNG cryogenic receiver with a vector network analyzer. The three curves show a different optical load: a metal plate covering the window of the receiver (blue), a 300 K blackbody (orange), and a 300 K blackbody viewed through a 2.85 % neutral density filter (NDF). The resonator towards the center of the figure is a dark pixel (non-optically-coupled), while the resonators on either side of the figure are feedhorn-coupled to the cold optics. As the optical power is increased, the resonant frequencies and quality factors of the optically-coupled resonators decreases. The dark pixels show no change with the optical load. There is a clear difference in the quality factor and resonator depth between the dark and light pixels, due to the optical loading. We expect the optical loading in flight to be significantly reduced compared to these laboratory tests.

5.7.3 Responsivity

The sensitivity of the receiver is determined by measuring the detector response through the full cold optical system to known optical loads. For these measurements to be accurate, the optical load must fill the entire beam of the receiver. A beam-filling
calibration source was built for these measurements, with a spinning, bow-tie-shaped paddle, which chops between a room temperature blackbody load, and one which can be heated above room temperature. The temperature of the hot load was stepped in 5 K steps from 300 K to 330 K. At each temperature, the resonant frequencies of the MKIDs were determined using the ROACH-2 readout in vector network analyzer (VNA) mode, and the response to a 1 Hz chop between the room temperature and hot blackbody loads was recorded. Additional data was recorded viewing a 300 K blackbody through a room-temperature 2.85% neutral density filter (NDF), and viewing a 77 K liquid nitrogen source. The response of approximately a dozen dark (not-feedhorn-coupled) MKIDs on each array can put limits on the cross-talk between pixels. During these laboratory tests, a 4.0% NDF was placed at the entrance to the 4 K optics box to reduce the optical load and ensure the detectors operated when viewing the 300 K thermal load. The response of several resonators is shown in Fig.5.7. Full characterization of the response of each array is still ongoing.

5.7.4 Spectral Response

The bandpass of each FPA will be measured with a Fourier transform spectrometer (FTS). An FTS, designed to operate at the BLAST-TNG wavebands, has been built at the University of Pennsylvania in collaboration with Cardiff University, and is currently being tested using the BLAST-TNG receiver. These measurements are ongoing, and we expect to finalize the bandpass measurements before summer 2018.
Chapter 6

CMB Foreground Observation

Planning

6.1 Polarized Foreground Removal

Thermal emission from galactic dust is the dominant polarized foreground for observations of the cosmic microwave background (CMB). The Planck satellite has shown that above \( \sim 100 \) GHz the polarized sky signal is dominated by this thermal dust emission [97; 91]. The spectra of the polarized foregrounds and the CMB anisotropy signal are shown in Figure 6.1. The Planck survey has also revealed that not only is the strength of the polarized dust emission greater than previously thought, but that there are no “clean windows” for CMB observations where dust emission can be ignored [95].
Figure 6.1: Polarized CMB foreground spectra from the *Planck* telescope. Image from *Planck* photo archive [92]. The *Planck* frequency bands (labeled in GHz) are highlighted with the grey vertical boxes. Above \( \sim 100 \) GHz the signal is dominated by thermal dust emission. The red band on the dust spectrum represents uncertainty in the dust models, something we hope to address with BLAST-TNG.

The typical approach to making CMB maps is to build a template for the foreground dust emission at CMB frequencies, then cross-correlate and subtract it from the data. This process is referred to as “cleaning” the data at CMB frequencies. Foreground removal templates are built by taking submillimeter-wavelength maps, where the dust signal dominates, and using a model for the dust spectral dependence to extrapolate the emission down to microwave frequencies. The *Planck* data, which span 30 GHz to 353 [91], and the FIRAS/DIRBE data, which extend up to 100 \( \mu \)m (3000 GHz) [43],
can be used to produce robust power-law models for extrapolating the dust emission. For modeling the polarized intensity however, this approach is complicated by the fact that the polarized power depends on both the absolute intensity of the emission, and the degree of polarization.

Results from Planck indicate that a CMB polarization map of a region can only be cleaned by using polarized foreground template that incorporates direct measurements of the polarized intensity in that same region. The Planck intermediate results represent the first all-sky map of the polarized intensity and polarization fraction at dust frequencies [91]. Before the Planck data were published, the typical approach for modeling polarized dust emission to extrapolate total intensity templates to CMB frequencies using the FIRAS/DIRBE model from [43], referred to as FDS Model 8 after the authors Finkbeiner, Davis and Schlegel, and scale it using some fiducial value of the polarization fraction, typically around 5% [87; 39]. This approach was used by the BICEP2 team in their pre-Planck data release to model the contribution of dust in their data taken at a single frequency at 90 GHz [12]. The assumption that the polarized intensity would scale with the total dust intensity also led experiments like BICEP and SPIDER [42] to target the darkest patches of the sky at the southern galactic cap in the hopes that the polarized foregrounds would be nearly negligible.

The Planck data revealed that not only does the degree of polarization vary widely over the sky, but the polarization fraction is significantly higher in more diffuse regions [91], a trend observed in the region around the Vela C molecular cloud by BLASTPol [46]. The Planck maps at 353 GHz reveal that most regions of the sky is more than 5% polarized, and that while polarization greater than 15% is less common, some
areas polarized up to 25% \cite{96}. The Planck data showed that all of the B-mode polarization observed by the BICEP2 experiment in their 2014 data release \cite{12} could be explained by polarized dust emission \cite{13}. However, the Planck dust maps do not have the sensitivity to adequately remove the dust signal to the level necessary for detecting primordial B-modes at the level of \( r < 0.1 \) \cite{13}.

Current generation CMB experiments are limited in their ability to remove polarized foreground emission by a lack of high-sensitivity dust maps at submillimeter wavelengths. To remove polarized foregrounds to the level necessary to measure primordial B-modes at the level of \( r < 0.001 \), CMB experiments will have to include high-sensitivity arrays at several dust frequencies well above 100 GHz, or rely on future high-sensitivity foreground-specific instruments like the proposed BFORE mission \cite{17}, to map large areas of the sky (hundreds to thousands of square degrees) that overlap with current generation CMB instruments at low resolution and high sensitivity \cite{3}. Adequate construction of foreground removal templates will depend not just on having high-sensitivity submillimeter dust maps, but on developing accurate models of the spectral dependence of the polarized dust emission, dust composition, angular power spectrum, and correlations with other tracers of dust foregrounds.

\section{6.2 High-Resolution CMB Foreground Studies}

BLAST-TNG is poised to make the most sensitive measurements of polarized galactic dust emission to date, and can fill a unique role in understanding the physics of polarized foregrounds. BLAST-TNG is designed to make high-resolution maps of degree-scale regions of the sky. The resolution, FOV, and scan strategy make the
telescope impractical for making the low-resolution, large-area dust maps required for cleaning foregrounds from current and next-generation state-of-the-art CMB experiments like BICEP3 [58], Advanced ACTpol [62], SPT-3G [10], CLASS [41], or the Simons Observatory. Instead, BLAST-TNG will be able to make the deepest maps to date of small regions of the diffuse ISM in regions relevant for CMB observation. By penetrating into the small-scale structure of these regions, BLAST-TNG will offer insight into the underlying physics of the diffuse ISM on small scales. These high-resolution submillimeter data is critical to developing accurate models of polarized galactic foregrounds.

Little is known about the structure of the diffuse ISM on scales smaller than a few degrees. The angular power spectrum of dust emission at CMB frequencies has a roughly power-law dependence which decreases with decreasing angular scale, $\theta$ (increasing multipole moment $\ell \sim 180^\circ/\theta$), as shown in Figure 6.2. For this reason the small-scale features of the galactic dust are often assumed to have a negligible effect on the CMB power spectrum at small scales (high-$\ell$). However, the exact behavior of the power spectrum on small scales is not known, and whether there are deviations from the power-law such as a steepening of the slope at higher $\ell$ [19]. The CMB power spectrum is gravitationally lensed on these small angular scales as the CMB radiation interacts with matter in the galaxy. This lensing converts some fraction of the E-mode polarization to B-mode polarization. Understanding the details of the foreground emission at small scales is critical for delensing the polarized signal and removing the lensed B-modes produced by galactic foregrounds from the primordial B-modes. BLAST-TNG can help answer whether the small-scale structure of the foreground
signal contaminates the lensing power spectrum. Measuring diffuse dust polarization at all scales is also important for understanding the physics behind the polarization patterns produced by galactic dust.

Figure 7. Bin-by-bin forecasted tensor constraints for \( r=0.01 \), \( f_{\text{sky}}=0.03 \), and the default detector \( f_{\text{det}} \) (106 detector years). The boxes denote the forecasted CMB-S4 error bars. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: \( r=0.001 \) and \( r=0.01 \). The dashed green line shows the \( \Lambda \)CDM expectation for the B modes induced by gravitational lensing of E modes, with the solid line showing the residual lensing power after delensing. The dashed blue and red lines show the dust and synchrotron (current upper limit) model assumed in the forecasting, at the foreground minimum of 95 GHz. The contribution of dust and synchrotron to the vertical error bars are shown in solid blue and red lines. Since these are calculated from a multi-frequency optimization, the “effective frequency” at which these foreground residuals are defined varies with each bin, allowing the residual lines to go above the input foreground model lines which are defined at a fixed frequency of 95 GHz. Furthermore, due to the low frequency channels having larger beam sizes than the higher frequency ones, in the higher bins, the primordial CMB component will be constrained at a higher “effective” frequency. Defining the foreground residuals at these “effective” frequencies will yield a higher amplitude for the dust residual, and a lower amplitude for the synchrotron residual, resulting in the respective shapes of the solid blue and red lines.

Figure 6.2: Power spectrum of polarized emission from CMB B-modes and galactic foregrounds from the CMB S4 science white paper [3]. The boxes denote the forecasted CMB-S4 error bars. Primordial B-mode spectra (solid black lines) are shown for two representative values of the tensor-to-scalar ratio: \( r=0.001 \) and \( r=0.01 \). The dashed green line shows the \( \Lambda \)CDM expectation for the B modes induced by gravitational lensing of E modes, with the solid line showing the residual lensing power after delensing. The dashed blue and red lines show the dust and synchrotron (current upper limit) model assumed in the forecasting, at the foreground minimum of 95 GHz. The contribution of dust and synchrotron to the vertical error bars are shown in solid blue and red lines.
One of the most surprising results from the Planck dust maps is the asymmetry in the E and B-mode decomposition of the dust polarization. Like the CMB polarization, the dust polarization can be decomposed into E (gradient) and B (curl) modes. The Planck 353 GHz maps reveal that the power in E-mode polarization is roughly twice that in B-modes [93]. This EE/BB \( \approx 2 \) ratio is observed to be nearly scale-invariant over the entire sky. A randomly-oriented polarization pattern should produce equal parts E and B-mode (EE/BB = 1). Similarly, if polarization fluctuations are due to amplitude fluctuations with fixed field orientation, then the E and B-mode powers should be equal [70; 19]. As described in [19], this E-mode preference is inconsistent with current models of magneto-hydrodynamic (MHD) turbulence, but can be explained by correlations between the filamentary structure of the ISM and the orientation of the magnetic field. Though the EE/BB ratio observed by Planck is nearly invariant across the sky, deviations from the average on small scales are expected. Quantifying the relationship between the degree of alignment between structures in the ISM with magnetic field and the variation of the EE/BB ratio on small scales may offer insight into the physical processes which shape the ISM. Observing correlations between small-scale ISM structures and the magnetic field is exactly what BLAST-TNG is designed to do, and the experiment is poised to make important observations for these studies.

6.3 Diffuse Dust and CNM Structures

BLAST-TNG can probe the correlation between dust foregrounds and neutral hydrogen (HI) structures in the cold neutral medium (CNM) phase of the ISM. Planck
dust data and the recent HI4PI [63] joint analysis of full-sky galactic HI measurements from the GASS [69] and EBHIS [114] surveys indicate that most of most of the filamentary dust structures in the diffuse ISM are in the CNM phase of the ISM [54]. The structure of the CNM can be probed by mapping the line emission of HI, which has been shown to display a high degree of alignment between HI structures and the magnetic field inferred from dust polarization [82]. This suggests that HI data traces the same structures that act as dust foregrounds. If this is true, it represents an important alternative for understanding CMB foregrounds, and predicting the foreground emission. Because of its limited sensitivity, Planck is not able measure dust emission in low signal to noise dark regions where most CMB telescopes observe [54]. HI observations are not affected by this limitation, and if a reliable model of dust emission can be produced from HI data it can help guide CMB observations. BLAST-TNG will have the sensitivity to make deep maps of dark regions of the diffuse ISM to further constrain the correlation with HI contours and column density.

6.4 Flight Planning Overview

BLAST-TNG plans to observations of a large number of galactic targets address different science goals. Half of planned 28 day flight is reserved for a survey of giant molecular clouds and their environments. 96 hours (15%) of the balloon flight will be dedicated to mapping dust emission in regions of high galactic latitude overlapping with current-generation state-of-the-art CMB observatories. Another 50 hours (8%) will be used for mapping the Pyxis diffuse cloud, and 40 hours (6%) will be used to map assorted other targets of interest including three nearby galaxies. The remaining
140 hours (21%) will be reserved for shared-risk observations open to proposals from outside observers. A summary of the observing plan is shown in the table in Figure 6.3.

<table>
<thead>
<tr>
<th>Target(s)</th>
<th>Distance (pc)</th>
<th>Total Map Area (deg^2)</th>
<th>Observation Time (hrs.)</th>
<th>Approx. No. of B-vectors expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela Molecular Ridge^b</td>
<td>~700</td>
<td>10</td>
<td>70</td>
<td>30,000</td>
</tr>
<tr>
<td>Lupus Cloud Complex^c</td>
<td>~155</td>
<td>8.7</td>
<td>100</td>
<td>5,000</td>
</tr>
<tr>
<td>Ophiuchus Cloud Complex^c</td>
<td>~140</td>
<td>9.1</td>
<td>60</td>
<td>50,000</td>
</tr>
<tr>
<td>Pipe Nebula^c</td>
<td>~150</td>
<td>3.2</td>
<td>20</td>
<td>17,000</td>
</tr>
<tr>
<td>Pyxis Diffuse Cloud^d</td>
<td>~200</td>
<td>25</td>
<td>50</td>
<td>6,000</td>
</tr>
<tr>
<td>VMR Wide Area Survey^e</td>
<td>~700</td>
<td>30</td>
<td>15</td>
<td>4,000</td>
</tr>
<tr>
<td>Lupus Wide Area Survey^e</td>
<td>~155</td>
<td>30</td>
<td>15</td>
<td>1,000</td>
</tr>
<tr>
<td>Ophiuchus Wide Area Survey^e</td>
<td>~140</td>
<td>30</td>
<td>15</td>
<td>2,500</td>
</tr>
<tr>
<td>The IRDC “Nessie”^f</td>
<td>~3000</td>
<td>4.0</td>
<td>4</td>
<td>1,000</td>
</tr>
<tr>
<td>13 Giant Molecular Clouds^g</td>
<td>1800-7800</td>
<td>41.0</td>
<td>48.5</td>
<td>100,000</td>
</tr>
<tr>
<td>3 nearby galaxies</td>
<td>-</td>
<td>0.8</td>
<td>21</td>
<td>150</td>
</tr>
<tr>
<td>CMB Foreground Survey</td>
<td>-</td>
<td>25</td>
<td>96</td>
<td>30,000</td>
</tr>
<tr>
<td>shared risk targets</td>
<td>-</td>
<td>NA</td>
<td>140</td>
<td>NA</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>186</td>
<td>654</td>
<td>250,000</td>
</tr>
</tbody>
</table>

Figure 6.3: Observation overview, with lengths planned observation for various targets.

### 6.5 BLAST-TNG’s View of the Sky

The visibility of BLAST-TNG is determined by the sky above Antarctica during the austral summer, and the geometry of the telescope payload and Sun shields. The availability of targets throughout the day depends on the launch date and the angle of the Sun. For a given day during the flight, scheduling software developed for BLAST-Pol calculates the number of hours every part of the sky is available for observation, and generates visibility plots. These visibility calculations guide both the target selection and day-to-day observing plan throughout the flight. Example visibility plots are shown in Figs. 6.4 and 6.5.
Figure 6.4: Sample visibility plot for December 22, 2018, superimposed on an image of the Galaxy. Targets of interest are plotted as green boxes, and the path of the Sun throughout the day is shown in the yellow dashed line. The white shading and the purple contours represent the number of hours a region is available for observations.

Figure 6.5: Sample visibility plot for January 21, 2019, superimposed on an image of the Galaxy. Targets of interest are plotted as green boxes, and the path of the Sun throughout the year is shown in the yellow dashed line. The white shading and the purple contours represent the number of hours a region is available for observations. The available area of observation has shifted significantly from the visibility in December. The southern galactic cap is now unavailable for observation, and the Lupus Cloud Complex has gone from being unobservable to available for nearly continuous observation.
We had hoped to overlap our CMB foreground observations with area of the southern galactic cap observed by experiments like BICEP and SPIDER. However, this region is not easily accessed by BLAST-TNG. The BICEP/SPIDER regions are highest in the sky at the beginning of the campaign season in early December and continue to set throughout December making them available for fewer and fewer hours. Many of the GMCs which represent the majority of BLAST-TNG’s observing plan are not available until late December and early January. As shown in Figures 6.4,6.5, the available area of observation has shifted significantly from the visibility in December. The southern galactic cap is now unavailable for observation, and the Lupus Cloud Complex has gone from being unobservable to available for nearly continuous observation. To maximize the observing time and sample size of these GMCs, we plan on launching December 25 at the earliest.

In addition to complications from sky rotation, the BICEP/SPIDER region lies on the opposite side of the Sun from many of the GMCs that BLAST-TNG was designed to observe. Some of the GMCs we hope to observe with BLAST-TNG are quite close to the Sun, and reaching these targets required designing the telescope baffle to allow pointing within 35° in azimuth of the Sun without direct solar illumination of the telescope mirrors. The severe asymmetry of the baffle prevents pointing within ~160 degrees of the Sun in the opposite direction.

The visibility of BLAST-TNG compared with current-generation CMB telescopes is shown in Figures 6.7 and 6.6. Based on visibility constraints we decided that it was impractical to target a region with significant overlap with the BICEP/Keck/SPIDER region. Instead we opted to search for targets with similar optical characteristics to
these diffuse, low-intensity dust regions, which would be available for observation during more of the flight.

Figure 6.6: BLAST-TNG visibility for late (thin blue) and early (thin green) launches. For each of the BLAST-TNG contours, the outermost contour corresponds to an area available only 1h / day (not particularly useful for mapping most sources). The middle contour corresponds to 10h / day, and the innermost contour corresponds to areas available 20h / day. Approximate fields from the PolarBear, BICEP, SPTpol and ACTpol experiments are shown for comparison. Red dots mark galactic sources of interest, some of which were mapped by BLAST-Pol, and/or will be mapped by BLAST-TNG.
Figure 6.7: BLAST-TNG visibility for late (thin blue) and early (thin green) launches. For each of the BLAST-TNG contours, the outer contour corresponds to an area available only 10h / day, and the second smaller contour corresponds to areas available 20h / day. Approximate fields from the PolarBear, BICEP, and ACTpol experiments are shown for comparison. Red dots mark galactic sources of interest, some of which were mapped by BLAST-Pol, and/or will be mapped by BLAST-TNG.
6.6 Foreground Target Selection Goals

In order to select a region for CMB foreground characterization, we sought regions of the sky that satisfied the following criteria:

1. Selected regions should reside in high galactic latitude and probe diffuse, low dust intensity/highly polarized regions typically targeted for CMB observations

2. Targets should be visible by the telescope for a minimum of 10 hours per day to reduce conflicts and complications with scheduling

3. Each target region must have features for which we expect to detect polarized power with a signal to noise ratio (SNR) of 5

4. Target regions should have known HI features to correlate with the dust polarization

5. Targets should be no smaller than $2^\circ \times 2^\circ$ to minimize the amount of time spent during scan turnarounds

To satisfy these observation requirements as best as possible based on an assumed 96 hours of observation time as best as possible, we explored three options for these foreground observations

- **Observation Scenario 0**: scan one $5^\circ \times 5^\circ$ patch for 96 hours

- **Observation Scenario 1**: scan two $2^\circ \times 2^\circ$ patches for 48 hours each, one on each side of the galactic plane
• **Observation Scenario 2:** scan one $1^\circ \times 10^\circ$ patch perpendicular to the galactic plane for 96 hours

To guide the selection of the foreground observation patches, we developed simulated observations based on the *Planck* sky model for each of the observation scenarios based on estimates of the instrument sensitivity at each waveband.

### 6.7 BLAST-TNG Sensitivity

For the purposes of observation planning, the BLAST-TNG sensitivity was estimated by scaling the measured noise level from the 2012 BLAST-Pol maps, scaled to account for differences in detector count and nominal resolution, assuming an 85% detector yield. The estimates do not account for improvements in the detector noise, as the characterization of the receiver is still ongoing. The details of the sensitivity calculation is given in [44]. The noise characteristics of the estimates used for the observation planning are given in Table 6.1. The table gives the map noise per beam, $N_f$, accounting for all $N_d$ detectors operating at 30% bandwidth with the given beam FWHM and beam solid angle, $\Omega_B$.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (µm)</th>
<th>$N_d$ (\text{-})</th>
<th>$N_f$ (MJy/sr $\sqrt{s}$)</th>
<th>$N_f$ ($\mu K_{CMB} \cdot \sqrt{s}$)</th>
<th>Beam FWHM (\arcmin)</th>
<th>$\Omega_B$ (\arcmin $\times$ \arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>250</td>
<td>1836</td>
<td>0.3856</td>
<td>29.43</td>
<td>25</td>
<td>5.45E-05</td>
</tr>
<tr>
<td>860</td>
<td>350</td>
<td>950</td>
<td>0.2873</td>
<td>0.209</td>
<td>35</td>
<td>1.07E-04</td>
</tr>
<tr>
<td>600</td>
<td>500</td>
<td>360</td>
<td>0.1547</td>
<td>4.86E-03</td>
<td>50</td>
<td>2.18E-04</td>
</tr>
</tbody>
</table>

Following the approach in [30], we calculate the signal to noise in our maps. The SNR in the map improves as we integrate for longer periods of time. To calculate the
SNR, we calculate the we use the per-beam sensitivity, or the noise in the map from a single beam, $S_{\text{beam}}$ integrated over a time $t_{\text{beam}}$:

$$S_{\text{beam}} = N_f \frac{1}{\sqrt{t_{\text{beam}}}}$$  \hspace{1cm} (6.1)

The integration time is typically stated for the integration over a full map of some angular size, $A_{\text{map}}$, which we can relate to the integration time per pixel using the ratio of the map size to the pixel size:

$$t_{\text{beam}} = t_{\text{map}} \times \frac{A_{\text{map}}}{A_{\text{beam}}} = t_{\text{map}} \times \frac{A_{\text{beam}}}{\Omega_B}$$  \hspace{1cm} (6.2)

Which gives combining Equations 6.1 and 6.2:

$$S_{\text{beam}} = N_f \sqrt{\frac{A_{\text{map}}}{\Omega_B}} \frac{1}{\sqrt{t_{\text{map}}}}$$  \hspace{1cm} (6.3)

The SNR of the maps can also be improved by smoothing them to a larger pixel size. Smoothing the pixel size from the diffraction-limited solid angle $\Omega_B$ to a large area $A_{\text{pix}}$ gives a sensitivity of:

$$S_{\text{pix}} = S_{\text{beam}} \sqrt{\frac{\Omega_B}{A_{\text{pix}}}}$$  \hspace{1cm} (6.4)

$$S_{\text{pix}} = N_f \sqrt{\frac{A_{\text{map}}}{A_{\text{pix}}}} \frac{1}{\sqrt{t_{\text{map}}}}$$  \hspace{1cm} (6.5)

The resolution of the map is less important than the map depth for these studies, and reasonable SNR can be achieved at resolutions of a few arcseconds, which still represent a dramatic increase in resolution over Planck’s 353GHz channel. For our
observation models we used HEALPix [57] map coordinates with Nside = 2048, giving a pixel area of 2.95 square arcminutes, or approximately 1.7′ x 1.7′ pixels.

6.8 Foreground Simulations

Simulations of the polarized dust emission in the three BLAST-TNG bands were done using the PySM sky model [111]. The model uses the Planck sky model for dust emission and models of synchrotron, free-free emission and other foreground contaminants based on available observational data.

For the wavelength at the center of each of the three BLAST-TNG bands, PySM was used to compute a map of each of the Stokes I, Q, and U parameters. The polarized power or polarized intensity at each wavelength, $P_\lambda$ is computed from:

$$P_\lambda = \sqrt{Q_\lambda^2 + U_\lambda^2}$$

(6.6)

and the polarization fraction, $p_\lambda$ is simply the ratio of the polarized to unpolarized emission:

$$p_\lambda = \frac{P_\lambda}{I_\lambda} = \frac{\sqrt{Q_\lambda^2 + U_\lambda^2}}{I_\lambda}$$

(6.7)

BLAST-TNG is unable to measure the absolute degree of polarization, and is only sensitive to relative measurements, or contrast in the polarized power. To account for this in our simulations we subtract off the mean value of $Q_\lambda$ and $U_\lambda$ from each prospective patch to calculate the polarization power contrast, $P_{c,\lambda}$:
\[ P_{c,\lambda} = \sqrt{(Q_{\lambda} - \langle Q_{\lambda} \rangle)^2 + (U_{\lambda} - \langle U_{\lambda} \rangle)^2} \] (6.8)

To calculate the SNR for each pixel in our smoothed maps, we divide the this polarization power contrast by the smoothed pixel sensitivity:

\[ \text{SNR} = \frac{P_{c,\lambda}}{S_{\text{pix}}} \] (6.9)

All-sky maps from the PySM dust model are shown in Figures 6.8, 6.9, 6.10, showing the unpolarized intensity, the polarization fraction, the polarized power, and the SNR focused on the BLAST-TNG region. These maps are of the absolute polarization power, not the polarization power contrast since they are plotted over the entire sky. These maps were used to identify regions by eye that might be suitable for each of the observation scenarios.
Figure 6.8: All-sky dust simulations at 250 µm from PySM.
Figure 6.9: All-sky dust simulations at 350 µm from PySM.
Figure 6.10: All-sky dust simulations at 500 μm from PySM.
6.9 Patch Evaluation for Different Observational Scenarios

A series of test patches selected for analysis were based on the observation requirements, the three observation scenarios, and the dust simulations. Because the emission in the 500 µm channel is the dimmest, the dust simulations for the 500 µm channel were used for evaluation of the patch suitability. The patches selected for further analysis are shown in Figure 6.11. The patch numbers correspond to the scenario numbers. The patches show varying degrees of contrast in the SNR plots. The simulations are extremely limited, however, by the lack of observational polarization data at small angular scales - precisely the problem we hope to address with BLAST-TNG. As is evident in the plots, the intensity data is much higher resolution than the polarization data, which is effectively smoothed to $\sim 10\arcmin$. 

Figure 6.11: Patches selected for further analysis as targets for the CMB foreground studies, overlaid on the 500µm intensity plot. The green contours outline the patches. The yellow contour represents the 10 hour per day visibility region on December 22, 2018.
Figure 6.12: Foreground observation Scenario 0: 96 hour map of 5° x 5° region. The patch, Patch 0, is centered on Galactic (lon, lat) = (-106.41°, 10.631°).

Figure 6.13: Foreground observation Scenario 1: two 48 hour maps of 2° x 2° regions located on opposite sides of the galactic plane. Left figures show simulations of Patch 1a, centered on Galactic (lon, lat) = (-119.424°, -22.331°), and right figures show simulations of Patch 1b, centered on Galactic (lon, lat) = (-46.996°, 31.454°).
In order to further evaluate the interstellar environment towards the patches under study, the CNM structures in these patches were plotted using HI data from the HI4PI survey [63]. These plots are shown in Figs. 6.15 - 6.18. These plots show the gas velocity of CNM structures. Each plot shows the intensity of a different velocity component, together giving a picture of the shape and motion of these structures.
Figure 6.15: HI velocity data from the HI4PI [63] survey, towards Patch 0, centered on Galactic (lon, lat) = (-106.41°, 10.631°).
Patch 1a: zoom on 2x2 deg region

Figure 6.16: HI velocity data from the HI4PI [63] survey, tracing the CNM structure towards Patch 1a, centered on Galactic (lon, lat) = (-119.424°, -22.331°).
Figure 6.17: HI velocity data from the HI4PI [63] survey, tracing the CNM structure towards Patch 1b, centered on Galactic (lon, lat) = (-46.996°, 31.454°).
6.10 Final Patch Selection

The dust simulations and the HI data are a critical tool for selecting a region for in-flight observation. While no quantitative comparison was done to compare the HI data with the PySM model, it is clear that all of the selected patches contain complicated HI structures, indicating the presence of CNM filaments in these regions. Even though the simulations indicate that some patches may yield low SNR for dust polarization measurements with BLAST-TNG, we feel confident that BLAST-TNG
will reveal previously unresolved small-scale structure in the regions, or place a new upper bound on the strength of the dust foregrounds in these dark, diffuse regions.

These simulations were prepared in the lead-up to the planned December, 2017 launch that was canceled when the cryostat experienced the explosion in June, 2017. Based on this analysis, the collaboration opted to pursue Observation Scenario 1, to split the planned 96 hours of CMB foreground observation time between two $2^\circ \times 2^\circ$ patches, Patch 1a, and Patch 1b. Since then our understanding of the optical performance of the telescope, receiver, and FPAs have come a long way. The receiver is in the midst of full optical characterization, and we expect direct measurements of the receiver sensitivity before the integration in Palestine, TX in July, 2018. When updated numbers for the sensitivity and noise performance of the full system become available, I plan to update these simulations so we can reevaluate the patch selection and final observation plan.
Chapter 7

Conclusion

BLAST-TNG will be the most sensitive submillimeter polarimeter to date, and will build on the observing techniques developed for BLAST-Pol to make deeper maps of more science targets at higher resolution. The BLAST-TNG experiment features one of the most technologically ambitious telescopes ever flown on a balloon experiment. With a 2.5 m diameter carbon fiber composite primary mirror, BLAST-TNG will be able to map the submillimeter polarized thermal emission from interstellar dust at sub-arcminute resolution, probing the magnetic field structure of molecular clouds and the diffuse interstellar medium on previously unexplored angular scales.

The cryogenic receiver, MKID arrays, and ROACH-2-based readout are operating in flight configuration. Array-level optical characterization data is still being analyzed, but initial results indicate the detector arrays in the flight receiver will maintain the photon-noise-limited performance demonstrated during single-pixel testing. The telescope has been completed and will be integrated with the balloon gondola and cryogenic receiver during pre-flight systems integration at the NASA Columbia Scientific Ballooning
Facility in Palestine, TX, in preparation for a planned 28-day stratospheric balloon flight from McMurdo Station, Antarctica during the winter of 2018/2019.

I will be continuing on with the BLAST team following my thesis defense, and will be part of the team integrating the payload in Palestine, TX, during the summer of 2018. Should we pass certification and be selected for launch, I will deploy the instrument in Antarctica, help to guide the experiment from the ground during flight, and recover the hard drives and essential components after landing.
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter.</td>
</tr>
<tr>
<td>ADM</td>
<td>Absolute Distance Measurement.</td>
</tr>
<tr>
<td>BLAST</td>
<td>Balloon-borne Large Aperture Submillimeter Telescope.</td>
</tr>
<tr>
<td>BLAST-TNG</td>
<td>Balloon-borne Large Aperture Submillimeter Telescope - The Next Generation.</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Assisted Design.</td>
</tr>
<tr>
<td>CASPER</td>
<td>Collaboration for Astronomy Signal Processing and Electronics Research.</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Composite.</td>
</tr>
<tr>
<td>CMB</td>
<td>Cosmic Microwave Background.</td>
</tr>
<tr>
<td>CNM</td>
<td>Cold Neutral Medium.</td>
</tr>
<tr>
<td>CSBF</td>
<td>Columbia Scientific Ballooning Facility.</td>
</tr>
</tbody>
</table>
DAC Digital to Analog Converter.
DEC Declination.
FEM Finite Element Model.
FFT Fast Fourier Transform.
FIR Far-Infrared.
FOV Field of View.
FPGA Field Programmable Gate Array.
FTS Fourier Transform Spectrometer.
FWHM Full Width at Half-Max.
GMC Giant Molecular Cloud.
HRO Histograms of Relative Orientations.
HWP Half Wave Plate.
HWPR Half Wave Plate Rotator.
IR Infrared.
ISM Interstellar Medium.
LNA Low-Noise Amplifier.
LO Local Oscillator.
LPE Low-Pass Edge Filter.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Primary Mirror.</td>
</tr>
<tr>
<td>M2</td>
<td>Secondary Mirror.</td>
</tr>
<tr>
<td>M4</td>
<td>Lyot Stop.</td>
</tr>
<tr>
<td>MKID</td>
<td>Microwave Kinetic Inductance Detector.</td>
</tr>
<tr>
<td>MLI</td>
<td>Multi-Layer Insulation.</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture.</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration.</td>
</tr>
<tr>
<td>NDF</td>
<td>Neutral Density Filter.</td>
</tr>
<tr>
<td>NIR</td>
<td>Near-Infrared.</td>
</tr>
<tr>
<td>OFHC</td>
<td>Oxygen Free High Conductivity.</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic Aromatic Hydrocarbon.</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density.</td>
</tr>
<tr>
<td>PySM</td>
<td>Python Sky Model.</td>
</tr>
<tr>
<td>RA</td>
<td>Right Ascension.</td>
</tr>
<tr>
<td>ROACH-2</td>
<td>Reconfigurable Open Architecture Computing Hardware 2nd Generation.</td>
</tr>
<tr>
<td>ROC</td>
<td>Radius of Curvature.</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>SBIR</td>
<td>Small Business Innovation and Research.</td>
</tr>
<tr>
<td>SMR</td>
<td>Spherical Mirrored Retroreflector.</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio.</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet.</td>
</tr>
<tr>
<td>VCS</td>
<td>Vapor-Cooled Shield.</td>
</tr>
<tr>
<td>VST</td>
<td>Vanguard Space Technologies.</td>
</tr>
<tr>
<td>WNM</td>
<td>Warm Neutral Medium.</td>
</tr>
</tbody>
</table>


