Mapping Submillimetre Polarization with BLASTPol

by

Steven James Benton

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Physics
University of Toronto

© Copyright 2015 by Steven James Benton
Abstract

Mapping Submillimetre Polarization with BLASTPol

Steven James Benton
Doctor of Philosophy
Graduate Department of Physics
University of Toronto
2015

The Balloon-borne Large Aperture Submillimetre Telescope for Polarimetry (BLASTPol) observes the linearly polarized emission from interstellar dust. Dust polarization traces magnetic fields, and submillimetre wavelengths can see into the dense molecular clouds in which stars are born. With this measurement, BLASTPol can help resolve long-standing questions about the role of magnetic fields in the beginning of star formation.

BLASTPol is a 1.8 m telescope with 288 Herschel/SPIRE-heritage bolometric detectors at 250 µm, 350 µm, and 500 µm. Polarimetric capability was added with photolithographed grids and a stepped half-wave plate. This work outlines the instrument, with a focus on the BLASTbus electronics system for detector readout, telescope attitude control, and cryogenic housekeeping.

In December 2010 and in December 2012, BLASTPol had two long duration balloon flights. An improved map making procedure has been used for reducing the 2012 dataset to maps of the polarized sky. The overall data analysis procedure is described, along with details of the map maker characterization. Finally, maps are presented for the seven targets observed during the 2012 flight. The 14 square degree map of the Vela C giant molecular cloud is of particularly high quality and will be used in several upcoming studies of dust physics and star formation.
Acknowledgements

I am very fortunate to have had an advisor with ceaseless enthusiasm, amazing intuition, and constant availability. Thank you, Barth.

BLASTPol and SPIDER are large projects, in which numerous people have invested their time and energy. Thank you all. Thank you to the field teams for sharing the long struggles, the silliness, the occasional successes, and many great times. Special thanks to my local companions on both teams: Laura, Juan, Natalie, and Jamil. And to Tristan, for adventuring with me.

The staff of the Physics Electronics Resource Center, especially Rob, have allowed me to accomplish much more than I could alone. The Columbia Scientific Balloon Facility team do their job so well that the risky business of ballooning seems like a reasonable choice. Computations were performed on the GPC supercomputer at the SciNet HPC Consortium.

Thank you to my roommates for being there, to my friends and family who will never read this, and to my mom who will try.
3.8 Cryogenic Housekeeping .............................................. 41
3.9 Status and Future of the BLASTbus .............................. 44

4 Map Making Theory .................................................. 45
  4.1 Polarization Overview ............................................ 45
    4.1.1 Stokes Parameters ........................................ 45
    4.1.2 Mueller Matrices .......................................... 47
  4.2 Polarimeter Data Model ......................................... 48
    4.2.1 Simple Polarimeter ....................................... 48
    4.2.2 Polarization Efficiency and Half-Wave Plates ......... 49
    4.2.3 Instrumental Polarization ................................ 51
    4.2.4 Non-ideal Half-Wave Plates ............................... 52
  4.3 Map Maker Formalism ........................................... 53
    4.3.1 Linear Model ............................................... 53
    4.3.2 Solving for the Map ....................................... 54
    4.3.3 Naive Map Making ......................................... 56
    4.3.4 Generalized Least Squares (GLS) Noise Model ....... 58
    4.3.5 Iterative Map Making ..................................... 59
    4.3.6 Preconditioned Conjugate Gradient Method ......... 60

5 BLASTPol 2012 Data Analysis .................................... 64
  5.1 Pre-Flight Calibrations .......................................... 65
    5.1.1 Polarization Calibrations .................................. 65
  5.2 Merging Datasets and Defining Chunks ......................... 66
  5.3 Pointing Solution ............................................... 67
  5.4 Detector Cleaning ............................................... 68
    5.4.1 Despiking .................................................. 68
    5.4.2 Deconvolution ............................................. 70
    5.4.3 TDRSS Pickup ............................................. 70
    5.4.4 Preprocessing ............................................. 73
  5.5 Pointing Offsets ................................................ 73
  5.6 Detector Gain Adjustment ...................................... 74
  5.7 Telescope Non-Idealities ...................................... 79
    5.7.1 Beam Shape ............................................... 79
    5.7.2 Instrumental Polarization ................................ 81

6 BLASTPol Map Making .............................................. 84
  6.1 BLASTPol Map Making Software ................................ 84
  6.2 Noise Model .................................................... 85
    6.2.1 Initial Estimate .......................................... 86
    6.2.2 PSD Parametrization ..................................... 86
    6.2.3 Noise Stationarity, Improved Estimate ............... 88
    6.2.4 Correlated Noise Between Detectors ................. 91
  6.3 TOAST Characterization ....................................... 94
    6.3.1 Transfer Function ........................................ 94
6.3.2 Comparison to Planck .......................... 96
6.3.3 Polarization Angle Comparison with SPARO .......................... 96
6.3.4 Effects of Detector Correlated Noise ................................................. 104
6.3.5 Calibrating the Covariance Estimate ................................................. 104
6.3.6 Computational Performance ......................................................... 106
6.4 Future Work ......................................................... 108
  6.4.1 Asymmetric Beam Correction .................................................. 108
  6.4.2 SPIDER Map Making ..................................................... 109

7 BLASTPol Maps ..................................................... 110
  7.1 Calculating Polarization Pseudo-Vectors ...................................... 110
    7.1.1 Reference Regions .................................................. 110
    7.1.2 Zero-point Correction with Planck HFI .................................. 113
    7.1.3 Error Bars ..................................................... 113
    7.1.4 Smoothing Maps and Covariances ......................................... 115
    7.1.5 Noise Bias ..................................................... 115
    7.1.6 Data Cuts ..................................................... 116
  7.2 Null Tests ......................................................... 117
    7.2.1 Grid Angle H–V .................................................. 119
    7.2.2 Array Top–Bottom .................................................. 120
    7.2.3 Array Left–Right .................................................. 120
    7.2.4 IP High–Low ..................................................... 131
    7.2.5 Time Early–Late .................................................. 131
    7.2.6 Time Interleaved .................................................. 137
    7.2.7 Null Test Conclusions .................................................. 137
  7.3 Maps ............................................................... 138
    7.3.1 Vela C ......................................................... 138
    7.3.2 Lupus I ......................................................... 140
    7.3.3 Puppis ......................................................... 145
    7.3.4 Carina Nebula .................................................. 145
    7.3.5 G331.5–0.1 ..................................................... 149
    7.3.6 IRAS 08470-4243 .................................................. 149
    7.3.7 VY Canis Majoris .................................................. 149

8 BLASTPol Science ..................................................... 153
  8.1 Understanding Polarization as a Tracer ...................................... 153
    8.1.1 Temperature and Column Density ......................................... 153
    8.1.2 Polarization Correlations .................................................. 154
  8.2 Orientations of Polarization and Structures .................................. 157
  8.3 Polarization Spectrum ..................................................... 158
  8.4 Comparison to Near-Infrared Polarization ..................................... 159
  8.5 Conclusion and Future Work .................................................. 164

Bibliography ........................................................... 167
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Pointing Sensors</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>BLASTPol 2012 observations</td>
<td>23</td>
</tr>
<tr>
<td>3.1</td>
<td>Breakdown of BLASTbus word</td>
<td>26</td>
</tr>
<tr>
<td>3.2</td>
<td>An example BLASTbus superframe with multiplexing</td>
<td>28</td>
</tr>
<tr>
<td>4.1</td>
<td>Preconditioned conjugate gradient algorithm</td>
<td>63</td>
</tr>
<tr>
<td>5.1</td>
<td>Polarization calibrations</td>
<td>66</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Dust polarization mechanisms ........................................ 3
1.2 Submillimetre transmission of the atmosphere at various altitudes ....................... 5

2.1 BLASTPol telescope .................................................. 8
2.2 BLASTPol optics ..................................................... 10
2.3 Detector bandpass response ......................................... 11
2.4 Photograph of detector array and closeup of bolometer ...................... 11
2.5 Polarization analyzer (grid) and HWP ................................ 12
2.6 HWP modulation efficiency .......................................... 13
2.7 Diagram of gondola and major systems ................................ 14
2.8 Flight computer system .............................................. 17
2.9 Scan strategy .......................................................... 19
2.10 2012 flight path ..................................................... 21

3.1 BLASTbus serial waveforms ......................................... 25
3.2 BLASTbus PCI controller ............................................. 27
3.3 Photograph of BLASTbus motherboard, with daughterboards ............... 30
3.4 BLASTPol DAS crate .................................................. 31
3.5 ADC daughterboards ................................................ 33
3.6 ADC schematic ....................................................... 34
3.7 Digital daughterboard ................................................ 35
3.8 Digital I/O schematic ................................................. 36
3.9 Analog output (DAC) boards ........................................ 36
3.10 DAC board schematic ............................................... 37
3.11 NTD-Ge bolometer readout schematic ................................ 38
3.12 BLASTbus digital filter response ................................... 39
3.13 BLASTPol bolometer noise .......................................... 40
3.14 Noise levels of cryogenic thermometers ................................ 43
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Kalman filtered pointing between star camera solutions</td>
<td>68</td>
</tr>
<tr>
<td>5.2</td>
<td>BLASTPol timestream processing</td>
<td>69</td>
</tr>
<tr>
<td>5.3</td>
<td>BLASTPol timestream processing – spectra</td>
<td>71</td>
</tr>
<tr>
<td>5.4</td>
<td>TDRSS contamination of detector signal</td>
<td>72</td>
</tr>
<tr>
<td>5.5</td>
<td>Bolometer pointing offsets</td>
<td>75</td>
</tr>
<tr>
<td>5.6</td>
<td>Pointing offset drift over time</td>
<td>76</td>
</tr>
<tr>
<td>5.7</td>
<td>Calibrator pulse amplitude fit against bolometer DC level</td>
<td>77</td>
</tr>
<tr>
<td>5.8</td>
<td>Flat fielding coefficients for each detector</td>
<td>78</td>
</tr>
<tr>
<td>5.9</td>
<td>Average beam shapes, from IRAS 08470-4243</td>
<td>80</td>
</tr>
<tr>
<td>5.10</td>
<td>Instrumental polarization in Vela</td>
<td>81</td>
</tr>
<tr>
<td>5.11</td>
<td>Distribution of IP between detectors</td>
<td>83</td>
</tr>
<tr>
<td>6.1</td>
<td>Noise-dominated data</td>
<td>87</td>
</tr>
<tr>
<td>6.2</td>
<td>Histograms of noise model parameters</td>
<td>89</td>
</tr>
<tr>
<td>6.3</td>
<td>Example parametrized PSD estimate</td>
<td>90</td>
</tr>
<tr>
<td>6.4</td>
<td>PSD estimates for each observation of Puppis</td>
<td>91</td>
</tr>
<tr>
<td>6.5</td>
<td>Updated parametrized PSD estimate</td>
<td>92</td>
</tr>
<tr>
<td>6.6</td>
<td>Top correlated noise modes</td>
<td>93</td>
</tr>
<tr>
<td>6.7</td>
<td>PSD estimates as noise modes are removed</td>
<td>94</td>
</tr>
<tr>
<td>6.8</td>
<td>Correlation coefficients for top noise modes</td>
<td>95</td>
</tr>
<tr>
<td>6.9</td>
<td>Simulated input map and TOAST output</td>
<td>97</td>
</tr>
<tr>
<td>6.10</td>
<td>TOAST and naivepol two-dimensional transfer functions</td>
<td>98</td>
</tr>
<tr>
<td>6.11</td>
<td>Comparison between TOAST and naivepol for a point-source map</td>
<td>99</td>
</tr>
<tr>
<td>6.12</td>
<td>BLASTPol and Planck maps of Vela</td>
<td>100</td>
</tr>
<tr>
<td>6.13</td>
<td>SPARO observation regions in Carina</td>
<td>101</td>
</tr>
<tr>
<td>6.14</td>
<td>Carina map comparing SPARO and BLASTPol</td>
<td>102</td>
</tr>
<tr>
<td>6.15</td>
<td>Comparison of SPARO vs. BLASTPol, polarization angle and fraction</td>
<td>103</td>
</tr>
<tr>
<td>6.16</td>
<td>Vela variance map</td>
<td>106</td>
</tr>
<tr>
<td>6.17</td>
<td>Pixel noise distributions for noise-only simulated timestreams</td>
<td>107</td>
</tr>
<tr>
<td>6.18</td>
<td>Pixel noise distribution from array left–right null test</td>
<td>107</td>
</tr>
<tr>
<td>7.1</td>
<td>BLASTPol reference regions compared to Planck</td>
<td>112</td>
</tr>
<tr>
<td>7.2</td>
<td>Preliminary zero-point correction of BLASTPol using Planck</td>
<td>114</td>
</tr>
<tr>
<td>7.3</td>
<td>Polarization pixels rejected by data cuts</td>
<td>118</td>
</tr>
<tr>
<td>7.4</td>
<td>Comparison of I maps in the grid angle H–V null test of Vela C</td>
<td>121</td>
</tr>
<tr>
<td>7.5</td>
<td>Comparison of I maps in the grid angle H–V null test of Puppis</td>
<td>122</td>
</tr>
<tr>
<td>7.6</td>
<td>Comparison of Q maps in the grid angle H–V null test of Vela C</td>
<td>123</td>
</tr>
</tbody>
</table>
Acronyms

ACT The Atacama Cosmology Telescope.
ADC Analog to Digital Converter.
ALMA The Atacama Large Millimeter Array.
BICEP2 Background Imaging of Cosmic Extragalactic Polarization 2.
BICEP3 Background Imaging of Cosmic Extragalactic Polarization 3.
BLAST Balloon-borne Large Aperture Submillimetre Telescope.
BLAST06 BLAST’s 2006 LDB flight.
BLASTPol The Balloon-borne Large Aperture Submillimetre Telescope for Polarimetry.
BLASTPol12 BLASTPol’s 2012 LDB flight.
CG Conjugate Gradient.
CIC Cascaded Integrator Comb.
CMB Cosmic Microwave Background.
CSBF Columbia Scientific Balloon Facility.
DAC Digital to Analog Converter.
DAS Data Acquisition System.
DC Direct Current.
DSP Digital Signal Processor.
EBEX The E and B Experiment.
EIRP Equivalent Isotropically Radiated Power.
FFT Fast Fourier Transform.
FOV Field of View.
FPGA Field-Programmable Gate Array.
FTS Fourier Transform Spectrometer.
FWHM Full Width at Half Maximum.
GLS Generalized Least Squares.
GMC Giant Molecular Cloud.
GPC General Purpose Cluster.
GPS Global Positioning System.
HFI High Frequency Instrument.
HGA High Gain Antenna.
HRO Histogram of Relative Orientations.
HWP Half-Wave Plate.
IAU International Astronomical Union.
IP Instrumental Polarization.
I/O Input/Output.
IR Infrared.
IRAS Infrared Astronomical Satellite.
JTAG Joint Test Action Group.
LED Light Emitting Diode.
MCE Multi-Channel Electronics.
mcp the master control program.
NASA National Aeronautics and Space Administration.
NTD-Ge Neutron Transmutation Doped Germanium.
PCI Peripheral Component Interconnect.
PCA Principal Component Analysis.
PCG Preconditioned Conjugate Gradient.
PSD Power Spectral Density.
RA Right Ascension.
RCW Rodgers, Campbell, Whiteoak (Hα catalogue).
RFI Radio Frequency Interference.
rms Root Mean Square.
SANEPIC Signal and Noise Estimation Procedure Including Correlations.
SED Spectral Energy Distribution.
SPIDER Suborbital Polarimeter for Inflation, Dust, and the Epoch of Reionization.
SPARO Submillimeter Polarimeter for Antarctic Remote Observations.
Herschel SPIRE The Herschel space observatory’s Spectral and Photometric Imaging Receiver.
SuperTIGER Super Trans-Iron Galactic Element Recorder.
SVD Singular Value Decomposition.
TDRSS Tracking and Data Relay Satellite System.
TRIUMF Tri University Meson Facility.
TOAST Time Ordered Astrophysics Scalable Tools.
Chapter 1

Introduction

1.1 Star Formation, Magnetic Fields, and Turbulence

Stars play a fundamental role in astrophysics, fusing elements to provide light, energy, and heavy nuclei. While the star formation rate and initial mass function are well-characterized empirically, the theory behind these observations is poorly constrained and an active area of research [1]. Stars form in molecular clouds, which contain a mixture of hydrogen gas, small molecules, and dust. Dust refers to larger carbon or silicon molecules up to about 1 µm in size, which shield clouds from the galactic radiation field. This prevents the disruption of cool dense clumps that will eventually form stars. These clumps form stars more slowly than gravitational evolution alone would suggest [2]. Two mechanisms have been suggested to explain the delay: magnetic fields, and turbulence.

Where magnetic fields are sufficiently strong, they can provide extra support against gravity [3]. Magnetohydrodynamic evolution allows gas to freely collapse along magnetic field lines, but the field resists orthogonal motion. The magnetic field supports only ions,

---

1 The term “clump” rather than “core” is used as the latter often has the specific interpretation of prestellar core, several of which can form in a clump.
but because these are in thermal equilibrium with the neutral gas, the whole clump is supported. By a process called ambipolar diffusion, the neutral gas can slowly collapse relative to the magnetically supported ions.

In the turbulence-driven model [4], clumps are transient phenomena rather than slowly collapsing objects. Rather than delaying clump collapse, this reduces the efficiency with which clumps form stars. Where magnetic fields are weak enough, they do not play a significant role in the motion of the gas. In this case, the field lines will be pulled around by the gas motion, creating a morphological difference compared to the magnetic-dominated case.

In reality, both turbulence and magnetic fields probably play a significant role in star formation. Measurements indicate that many clouds are roughly magnetically critical [5, 6], meaning gravitational and magnetic energies are roughly in equipartition. To properly address which forces govern star formation, more magnetic field measurements are needed. These should cover a statistically significant number of clouds, on a wide range of scales: from prestellar cores to dense clumps, filaments, and entire clouds.

1.2 Measuring Magnetic Fields

Measuring magnetic fields in molecular clouds is challenging, but several methods have been used with varying levels of success [7].

The only way that magnetic field strength has been directly measured in molecular clouds is via Zeeman splitting of spectral lines [8]. In principle Zeeman splitting can measure all components of the magnetic field. However, kinetic broadening of the spectral lines usually dwarfs the splitting. Just the field component along the line of sight can be measured, with the plane-of-sky signal usually too small to detect. Not all targets can be successfully observed with Zeeman splitting, and there might be biases that affect the ones that can.
Chapter 1. Introduction

Figure 1.1: Cartoons showing how aligned asymmetric dust produces polarization in background starlight (left) and emission (right). (From [9])

An alternate tracer of magnetic fields is the polarization of starlight. This polarization is due to light shining through clouds of aligned asymmetric dust grains, which absorb preferentially along their long axis (fig. 1.1). The typical explanation for the alignment of dust grains and magnetic fields is that radiative torques cause grains to spin, and then spinning charged grains align across magnetic fields [9]. Starlight polarization probes only the orientation of magnetic fields (projected on the celestial sphere), but the coherence of the field direction can be used to roughly infer the strength [10, 11]. Because dust is optically thick to visible light, this method can probe only diffuse regions around clouds and filaments [12], not inside the dense clouds where stars form. This also makes it sensitive to contamination by diffuse foregrounds.

Rather than looking at its effect on starlight, magnetically-aligned dust can be observed directly in the submillimetre, where the $10\,\text{K}$ to $20\,\text{K}$ grains emit thermally with polarization along the grain’s long axis. Molecular clouds are optically thin in the submillimetre, so this technique is less affected by diffuse foregrounds, and can see into dense star forming regions—even to presetellar cores [13]. Seeing completely through the clouds though, requires care to avoid confusion with background sources. Like starlight polarimetry, submillimetre polarimetry is directly sensitive only to the projected direction
of magnetic fields.

In addition to the method of [10], relationships between core and cloud structure can be used to infer magnetic field strength, relative to turbulence or gravity. A subcritical core that collapses under ambipolar diffusion will exhibit an hourglass-shaped magnetic field aligned with the oblate core, as observed by [14]. Similarly, comparing cloud and filament orientations to polarization measurements can inform the magnetic influence on their evolution [15]. Magnetohydrodynamic simulations of molecular clouds have been used to test methods for inferring field strength [16,17]. Both better simulations and a better sample of targets are needed to test theories in this way.

1.3 BLASTPol

While submillimetre wavelengths are a useful tool for studying magnetic fields, they are difficult to observe from ground-based telescopes. There are narrow windows through which it is possible to observe, but the atmosphere remains a bright and variable foreground. Figure 1.2 shows that by balloon altitudes, the atmosphere becomes almost completely transparent. This allows free choice of bands, lower backgrounds, and higher sensitivity. BLASTPol’s wide bands at 250 µm, 350 µm, and 500 µm were chosen to bracket the Spectral Energy Distribution (SED) peak of emission from 10 K to 20 K dust.

BLASTPol is complementary to ground-based telescopes like The Atacama Large Millimeter Array (ALMA) [19] that achieve sub-arcsecond resolution but observe only small targets. At the other extreme, Planck’s High Frequency Instrument (HFI) [20] has mapped the polarization of the whole sky at wavelengths as short as 850 µm (353 GHz) and resolution up to 5’. BLASTPol forms an important bridge between these extremes, with sufficient resolution to see individual gravitationally-bound clumps, and large enough maps to observe entire molecular clouds. This provides a powerful tool for comparing
magnetic fields to cloud structures on a variety of scales.

The BLASTPol bands are also well-suited to study dust alignment physics, via the polarization spectrum \cite{21, 22}.

1.4 My Thesis Work

BLASTPol, the focus of this work, is outlined in chapter \ref{Chapter2} My primary hardware contributions to the experiment are the BLASTbus electronics (chapter \ref{Chapter3}) and computer systems, which are central to the experiment. Additionally, I have contributed software, cable making, debugging, machining, taping, and many other integration and testing tasks required to turn two tons of fancy hardware into a successful semi-autonomous robotic telescope.
I deployed with BLASTPol for two balloon flights, launched in December 2010\(^2\) and December 2012. My focus for the data analysis has been map making, the theory of which is described in chapter 4. The overall analysis procedure is outlined in chapter 5, and chapter 6 covers details of noise and map maker characterization required for believable final maps. Finally, chapter 7 shows the final maps obtained by BLASTPol.

### 1.4.1 Other Experiments

**SPIDER** [23], a balloon-borne polarimeter of the Cosmic Microwave Background (CMB), was developed alongside BLASTPol and uses the same BLASTbus and computer systems. My instrumental contributions to **SPIDER** were similar to BLASTPol, including an expanded design of cryogenic housekeeping electronics (section 3.8). **SPIDER** launched in January 2015. My experience with map making will be directly applicable to analyzing **SPIDER** data.

I have also supported three other experiments that use the BLASTbus electronics: **BICEP2** [24]; the Keck Array [25]; and **BICEP3** [26]. These telescopes, like **SPIDER**, search for the faint B-mode polarization signature of the CMB [27]. **BICEP2** recently published a detection of B-mode signals on degree scales [28], though a subsequent analysis with the Keck Array and Planck reveal that much of the signal can be accounted for by dust [29]. Nevertheless, this is a significant experimental milestone.

\(^2\)Due to a melted filter in the optical path, data from the 2010 flight is of lower quality than 2012 and otherwise not discussed here.
Chapter 2

BLASTPol Overview

2.1 The BLASTPol Instrument

BLASTPol is a 1.8 m balloon-borne telescope with 288 detectors in wavebands at 250 µm, 350 µm, and 500 µm. These bands are sensitive to the peak of thermal emission from 10 K to 20 K interstellar dust, whose polarization traces magnetic fields.

This chapter describes the entire instrument, shown in fig. 2.1. The focus of my work has been computer and electronics systems for data acquisition and automated control. Described in detail in chapter 3, these systems are central to most of BLASTPol’s operations. The non-polarized Balloon-borne Large Aperture Submillimetre Telescope (BLAST) instrument is detailed in [30], and BLASTPol in [31].

2.1.1 Optics

The BLASTPol telescope is a Ritchey-Chrétien reflector. Figure 2.2 shows the complete optical chain of the telescope. The 1.8 m primary (M1) and 40 cm secondary mirror (M2) are at ambient temperature, while the remaining optics are cooled to about 1.3 K to reduce optical load. The flat mirror M4, located at an image of the primary, is a Lyot stop defining the illumination of the primary. In the mask around the secondary, it also
Figure 2.1: BLASTPol during characterization before its 2012 flight. The telescope is visible because the sun shields are not yet fully covered. The starboard side, bottom and rear will be covered, and a large baffle will be installed around the telescope. Because the sun will always be to starboard, the port side sun shields are not covered.
contains a calibration source, which is used to monitor detector gain (section 5.6). An active focus system moves and tilts the secondary mirror, primarily to compensate for diurnal temperature variations in the aluminum primary and secondary. The primary mirror varies from about \(-20\,^\circ C\) to \(-10\,^\circ C\), and the secondary from about \(-30\,^\circ C\) to \(-20\,^\circ C\).

### 2.1.2 Detectors

The BLAST detectors are of the same design as those used by The Herschel space observatory’s Spectral and Photometric Imaging Receiver (Herschel SPIRE) [32, 33]. Silicon nitride micromesh absorbers capture incoming light, then Neutron Transmutation Doped Germanium (NTD-Ge) bolometers measure the optical power [34, 35]. Light is coupled to the absorber by a smooth-walled conical feed, and a waveguide filter. In addition to the feed and waveguide, the band-edges for each detector are primarily determined by metal-mesh low pass edge filters [36]. The average bandpasses are shown in fig. 2.3. Figure 2.4 shows images of the full array and detectors.

### 2.1.3 Polarization

Two components were added to BLAST to convert it from a total-flux photometer to a polarimeter: polarizing grids (analyzers) and a Half-Wave Plate (HWP) (fig. 2.5). The polarizing grids are photolithographically patterned with alternating orthogonal angles, and are placed in front of each feed horn array. Typically, polarimeters have a pair of orthogonal detectors within each feed, to directly measure Stokes parameters (eq. (4.8)). The alternating pattern allows use of neighbouring feeds, along the scan direction, to measure Stokes parameters after a short delay. The H–V null test (section 7.2.1) shows that, without this modulation, much more polarization leakage would be present.

The HWP is a five-layer sapphire achromatic design [37] with meta-material anti-reflection coatings on each side [38]. To reduce emission from the sapphire, the HWP is
Figure 2.2: *Top:* Full-scale optical arrangement, featuring the primary (M1) and secondary (M2) mirrors. *Bottom:* zoomed-in view of the cold optics. The 250 µm and 350 µm arrays are located vertically out of the figure, split by dichroic filters between M5 and the focal plane.
Figure 2.3: Bandpass response of the BLASTPol wavebands. The high noise level and some in-band lines are due to atmosphere. The out of band pickup is an artifact. These results are consistent with BLAST [30], though the older results are cleaner due to the spectrometer being operated in vacuum.

Figure 2.4: Left: Photograph of 500 µm detector array, with feed horns. Right: Micrograph of the detector wafer, showing spiderweb absorber pattern.
Figure 2.5: BLASTPol polarization components. Top: Photograph of photolithographed 350 µm analyzer, inset with a micrograph showing the alternating grid orientations. Bottom: The HWP and gear-driven rotation mechanism.
cooled to 4 K. It is located as far from the telescope focus as was practical, so that asymmetries are illuminated evenly by all detectors. To modulate polarization (section 4.2.2), the HWP is rotated. The drive uses a gear system driven by a shaft that extends outside the cryostat. Potentiometer windings wrapped around the rotor allow a resistance measurement to determine its position. The HWP modulation efficiency is shown in fig. 2.6.

2.1.4 Cryogenics

To cool the detectors and optics, they are housed in a liquid helium and liquid nitrogen cryostat\[40\ \[41\]. Successively colder shells are isolated from each other by vacuum and multi-layer insulation. The outermost shell is cooled to 77 K by a 55 L liquid nitrogen tank, and the innermost shell is cooled to 4.2 K by a 42 L liquid helium tank. In between is a vapour cooled shield, which is cooled to about 35 K by exchanging heat with the cold helium gas that boils out of the helium tank. To reach 1.5 K, a small capillary-fed helium

\[^1\]made by Precision Cryogenics [http://www.precisioncryo.com/](http://www.precisioncryo.com/)
tank is opened to the near-vacuum of the balloon’s float altitude. Finally, a closed-cycle $^3$He adsorption refrigerator \cite{12} cools the detectors to 300 mK.

### 2.2 Gondola

BLASTPol’s balloon gondola has three primary components: an outer frame, inner frame, and sun shield structure. The outer frame is the primary structure of the gondola, supporting both the inner frame and sun shields, and holding most of the pointing, power, and telemetry systems. The inner frame holds the telescope, cryostat, and star cameras. The sun shields, covered in aluminized Mylar, baffle the telescope from the earth and sun, while providing a cool stable thermal environment for the payload systems. To point as close as 45° from the sun, the sun shields are asymmetric, including a 4 m long carbon-fiber baffle directly surrounding the telescope. The gondola and its primary structures are illustrated in fig. \[2.7\]
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Rate (Hz)</th>
<th>Accuracy (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>Sun sensor</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Elevation Encoder</td>
<td>100</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Star Cameras</td>
<td>0.5</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Gyroscopes</td>
<td>1000</td>
<td>0.0667/√h</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of pointing sensor readout rates and accuracy. Inclinometers do not provide azimuth, and are insensitive to pendulations. In addition to the random walk of 4′′/√s, the integrated gyroscopes have a slowly-varying offset of about 20″/s, which must be corrected.

### 2.2.1 Pointing

The BLASTPol telescope pointing systems were based on those of BLAST [30], which in turn were based on experience from BOOMERANG [43]. Pointing involves two related problems: measuring and controlling the gondola attitude.

The primary pointing sensors are the star cameras [44], which provides a very precise absolute attitude measurement. To fill the gaps between star camera exposures, fiber optic gyroscopes provide angular speed measurements. For post-flight analysis (section 5.3), only the star cameras and gyroscopes are needed. During the flight, other coarse sensors are used to help orient the star cameras, as well as to fill in periods when there are not enough visible stars for real-time identification. The sensors are summarized in table 2.1 adapted from [45] (which also provides more details).

Three motors are used to control the telescope’s pointing (details in [47]). A reaction wheel on the outer frame provides fine azimuth control, and is the primary driver of BLASTPol’s scans. To prevent reaction wheel saturation, a motorized pivot dumps excess torque to the balloon through the flight train, which acts like a weak spring. The pivot can also provide torque to increase the turn-around acceleration. Finally, an on-axis elevation motor drives the inner frame relative to the outer frame. The inner frame must be carefully balanced for the elevation drive’s torque to be sufficient. A pumped-fluid
system maintains balance through the flight as cryogens boil off.

2.2.2 Power System

BLASTPol consumes an rms power of 450 W, with instantaneous variations of up to 200 W while scanning. Early in the flight, another 170 W is used for high-bandwidth line-of-sight transmitters.

Flying from Antarctica during the Austral summer, BLASTPol has constant access to solar power. Panels of silicon solar cells are arranged into six parallel units of three panels in series, with an open-circuit voltage of 34.56 V and a maximum power production of 1400 W. A switching charge controller efficiently charges a pair of sealed lead-acid batteries, with a combined 24 V nominal voltage and 40 A h capacity. To reduce noise pickup for BLASTPol12, a separate charge controller and battery system was added for the detector readout electronics.

2.2.3 Computers and Electronics

The control and data acquisition for BLASTPol is carried out by a pair of redundant flight computers. A watchdog circuit (see [48] for details) designates one of the computers as “in charge”, allowing it to transmit on the BLASTbus and serial ports. The watchdog also reboots the computers when they fail to continually toggle parallel port outputs. When a computer is rebooted, the other is designated as in charge. The computers run the master control program \texttt{mcp} on a Linux operating system (stripped down Ubuntu 10.04). Figure 2.8 shows the computer box and its components. Solid state hard drives are used because they can operate in near vacuum. However, note that some models of solid state drives have experienced serious problems during the flight (section 2.4).

The BLASTbus is the primary interface between the computers and the rest of

\footnote{Arcom/Eurotech Apollo, with a 1.6 GHz Pentium M processor and 500 MB of memory}

\footnote{Actually shows SPIDER’s flight computer, with the same components as BLASTPol, but a more open layout}
BLASTPol’s systems. As my primary contribution to the telescope, it is detailed separately in chapter 3. The star cameras have their own computers, commanded over ethernet, and some other digital subsystems are controlled over RS-232 instead of (or in addition to) the BLASTbus.

2.2.4 Commanding and Telemetry

Various radio links to the telescope are provided by NASA and Columbia Scientific Balloon Facility (CSBF). During the first day of the flight, line-of-sight radio provides 1 Mbit s\(^{-1}\) telemetry and very low-latency commanding.

Afterwards, satellite communication systems must be used. The Tracking and Data Relay Satellite System (TDRSS) network provides an omnidirectional antenna and a pointed high-gain antenna, with about 10 kbit s\(^{-1}\) and 100 kbit s\(^{-1}\) of bandwidth respec-
tively. Commands are usually sent as short messages over the Iridium satellite phone network. The Iridium connection also allows short packets to be sent from the payload every 15 min, and to use a modem for a 2 kbit s\(^{-1}\) data link.

Both TDRSS antennas were found to contaminate BLASTPol’s data, and were disabled for most of the flight (section 5.4.3).

2.3 Scan Strategy

BLASTPol observes a target by scanning back and forth in azimuth while slowly slewing in elevation. The azimuth scans are at a constant speed of 0.1° s\(^{-1}\), which modulates 30″ beam-scale structures at 12 Hz, well above the 1/\(f\) knee frequency of the detector noise. Entire scans across BLASTPol’s degree-sized targets can be completed at above the typical knee frequencies of 70 mHz (section 6.2). The scan region is usually specified as a quadrilateral in celestial coordinates, though some smaller targets use fixed-width or circular scan regions.

The elevation slew speed is set so that elevation has increased by a fixed increment at each azimuth turnaround. The size of the elevation increment is chosen so that a full scan up and down a target takes about 15 min. In the data analysis terminology, a full scan up and down is called a chunk. Chunks are usually scheduled as hour-long chunk-sets that observe the target at all four HWP positions. Pointing data for a full chunk-set is shown in fig. 2.9.

The 15 min chunk duration forces some large targets to have a large elevation increment. To prevent gaps in coverage, chunk-sets are dithered with respect to each other and have slightly different elevations at turnaround. Further, to increase angle coverage, care is taken to schedule chunk-sets for each target when it is rising and when it is setting. This good cross-linking is essential for making good maps (chapter 6).

Because cross-linking due to sky rotation is limited in Antarctica to about 30°, an
Figure 2.9: Scan strategy illustrated for a Vela chunk-set. Top: scans in right ascension and declination, showing the quadrilateral box for the target. Bottom: scans in azimuth and elevation as the source moves across the sky. Different colours show chunks at different HWP positions.
attempt was made to scan targets in elevation while slewing in azimuth. This would have improved cross-linking, but the data is not currently used. Rapid movements in elevation cause thermal changes in the cryostat, and the detectors have very large common mode noise. Moreover, the elevation-correlated column density of residual atmosphere strongly contaminates these scans.

Another strategy to improve cross-linking was observing large reference regions. These regions include all of the primary target, and extend outwards along the possible scan directions. This way, there are pairs of crossing scans that reference each point in the target to each other point. Because these scans take a lot of time, they were planned only for the primary science targets, Vela C and Lupus I. The Lupus I reference scan was never completed due to star camera failure.

2.4 2012 Flight

BLASTPol launched on 25 December, 2012 at 18:57 UTC. After its circumnavigation of Antarctica (fig. 2.10), it landed on 10 January 2013 at 22:14 UTC. Its liquid cryogens ran out after 12.5 d, and so the system was shut down for the last few days of the flight, until it reached the termination location. The mean float altitude was 38.5 km, with about 2 km diurnal variation.

Star Camera Failure

During ascent, one of the two bore-sight star cameras rebooted and failed to start again. The same thing happened to the other camera about six days after launch. In both cases, the solid state disks had failed. This is suspected to be due to a firmware flaw in the Intel 320 series drives, likely exacerbated by the increased cosmic ray flux in the Antarctic stratosphere. Four of the same series of hard drive failed on the SuperTIGER experiment[49], which also launched in December 2012.
After the second star camera’s failure, precise targeting of the telescope was no longer possible. The schedule for the rest of the flight was replaced by a pair of very large scans of the Vela and Puppis regions. For these large scans, the scan rate is doubled to $0.2\degree\,s^{-1}$. With small-scale structure lost to poorer pointing, this attempts to better preserve large-scale features.

After the flight, several models of hard drive were subjected to flight-like particle flux using a beam line at the TRIUMF facility[^4]. No permanent failures were observed, including for Intel 320 drives—possibly because only updated models were available after the

[^4]: [http://www.triumf.ca/research-program/research-facilities/main-cyclotron-beam-lines](http://www.triumf.ca/research-program/research-facilities/main-cyclotron-beam-lines)
flight. Nevertheless, future flights plan to use a heterogeneous mixture of drives, including both solid state and spinning-platter hard drives. (To operate in the stratosphere, spinning drives must be in pressure vessels.)

2.4.1 Observation Targets

BLASTPol’s observation targets fall roughly into three classes:

- **Nearby molecular clouds.** These are BLASTPol’s primary targets, for which spatial resolution is high. Vela C is very bright, and Lupus I is very close. Puppis is somewhat more distant and fainter, but visible at times when the other targets are not.

- **Distant molecular clouds.** The Carina Nebula and G331.5–0.1 are very bright massive clouds that are known to be polarized. They have been observed by previous submillimetre polarimeters [50], so provide a useful check.

- **Calibrators.** The compact HII region IRAS 08470-4243 is observed as a pointing calibrator (section 5.5), but with a power-law envelope is not quite a point source. For beam measurements, the hypergiant star VY CMa and planet Saturn are observed.

Targets are listed in table 2.2. More details of each are presented along with the maps in section 7.3.
<table>
<thead>
<tr>
<th>Target</th>
<th>Distance (pc)</th>
<th>Map Area (°²)</th>
<th>Obs. Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela C</td>
<td>700</td>
<td>3.9 / 14.0</td>
<td>43.9 / 10.8</td>
</tr>
<tr>
<td>Lupus I</td>
<td>155</td>
<td>1.7</td>
<td>15.4</td>
</tr>
<tr>
<td>Puppis</td>
<td>1000</td>
<td>1.4</td>
<td>13.2</td>
</tr>
<tr>
<td>Carina Nebula</td>
<td>3000</td>
<td>2.7</td>
<td>4.4</td>
</tr>
<tr>
<td>G331.5–0.1</td>
<td>7000</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td>IRAS 08470-4243</td>
<td>700</td>
<td>1.0</td>
<td>4.9</td>
</tr>
<tr>
<td>VY CMa</td>
<td>1200</td>
<td>0.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Vela Wide</td>
<td>700</td>
<td>23.1</td>
<td>89.5</td>
</tr>
<tr>
<td>Puppis Wide</td>
<td>1000</td>
<td>≈113</td>
<td>38.6</td>
</tr>
</tbody>
</table>

Table 2.2: Targets Observed by BLASTPol. Map area includes all good pixels in the maps, and observation time counts all chunks used for map making. The pairs of numbers for Vela C are its primary and reference scans. The Vela Wide and Puppis Wide targets were observed after the star cameras had failed.
Chapter 3

The BLASTbus Electronics

Balloon-borne telescopes like BLASTPol and SPIDER have many different sensors to read and subsystems to control. The BLASTbus system was developed to accomplish both detector readout and telescope pointing for the BLAST experiment \[30\]. The system also found a niche in cryogenic control and housekeeping. For the BLASTPol \[51\] and SPIDER \[23\] experiments, a second-generation system was designed to lower power consumption while increasing modularity and usability. The second-generation system is described in detail here.

In addition to BLAST, BLASTPol, and SPIDER, the BLASTbus electronics have been used by several other experiments. The first-generation system flew on the EBEX \[52\] telescope for attitude control. For cryogenic housekeeping in ground-based telescopes, the first-generation system has been deployed by ACT \[53\] and BICEP2 \[24\]. The second-generation has been deployed by the Keck Array \[25\] and BICEP3 \[26\].

3.1 The BLASTbus

The BLASTbus is a half-duplex RS-485\[1\] serial bus. The master node of the bus is a PCI board (section 3.2) controlled by a computer, and the slave nodes are BLASTbus

---

\[1\]TIA/EIA-485-A
Chapter 3. The BLASTbus Electronics

Figure 3.1: Oscilloscope traces of BLASTbus serial waveforms. The clock (*magenta*, *middle*) continually switches at 4 MHz. Data (*cyan*, *bottom*) changes on falling edges of the clock, so that its value is stable when sampled on the rising edges. A strobe line (*yellow*, *top*) is asserted low for 32 clock rising edges, to indicate which data values make up a BLASTbus word.

motherboards (section 3.4). An always-driven clock at up to 5 MHz is used for serial communications and to synchronize the motherboards. Nominally, a 4 MHz clock is used, but for Multi-Channel Electronics (MCE) synchronization (section 3.2.1) the MCE’s 5 MHz clock can be used instead. The bus is optoisolated at both the PCI controller and the motherboard nodes.

The serial protocol uses three signal lines: clock, data, and strobe (fig. 3.1). Bus signals are interpreted using a shift register: on each rising edge of the clock, the data bit is shifted into a BLASTbus word. Because clock is always driven, the strobe acts as a shift-enable to indicate when data should be sampled. A command-response architecture is used for the bus, in which the PCI controller transmits to a motherboard node, and then receives a response if necessary. After each PCI controller transmit, it leaves data and strobe undriven for one word length, allowing a motherboard to drive the bus for its response.
Chapter 3. The BLASTbus Electronics

Where:

\[ \begin{align*}
    d & = \text{data} & \text{(16 bits starting at bit 0)} \\
    c & = \text{channel (0-63)} & \text{(6 bits starting at bit 16)} \\
    r & = \text{read flag} & \text{(1 bit at bit 22)} \\
    n & = \text{node (0-63)} & \text{(6 bits starting at bit 23)} \\
    s & = \text{ADC sync bit} & \text{(1 bit at bit 29)} \\
    w & = \text{write sync bit} & \text{(1 bit at bit 30)} \\
    f & = \text{frame sync} & \text{(1 bit at bit 31)}
\end{align*} \]

Table 3.1: A breakdown of the 32 bits in a BLASTbus word.

Each 32-bit word contains 16 bits of data and 16 bits for addressing and synchronization, outlined in table 3.1. The 6-bit node number addresses one of up to 16 motherboards, each of which is assigned four consecutive nodes. All motherboards parse every BLASTbus word, but they ignore those addressed to other nodes. With the 6-bit channel number, up to 64 read channels and 64 write channels can be accessed on each node. The PCI controller indicates reads and writes by setting those respective bits. Read responses from motherboards always set both the read and write bits. All words with the write bit set—writes and read responses, but not read requests—are stored to the data frame. The frame sync bit is set on one special word at the beginning of each frame, and the ADC sync bit is set once during startup, to synchronize all the ADC readouts on each motherboard.

For a 4 MHz main clock, after dropping addressing and command-response cycles, the data bandwidth is 1 Mbit s\(^{-1}\). This was chosen to match the line-of-sight radio transmitter used by balloon payloads. Accounting for gaps between bus words, the true data bandwidth is about 850 kbit s\(^{-1}\). Writes and read requests are organized into a frame, which the PCI controller cycles through periodically—typically at around 100 Hz, at an integer divisor of the data sample rate.
3.2 PCI Controller

The PCI controller board has a mainboard half for the logic and a daughterboard for the electrical interface (fig. 3.2). The mainboard contains an Altera Cyclone Field-Programmable Gate Array (FPGA), which implements the PCI layer, BLASTbus communications, and a Nios II soft core for processing. The daughterboard contains optoisolators and transceivers for two independent buses.

The PCI board controls the bus by looping through the “superframe”. This is a block of memory containing every BLASTbus word to send, in sequence. The PCI board reads each word from memory, transmits it, waits to allow a response, and moves on to the next word. When it encounters a word with the frame sync bit set (table 3.1), the controller waits to transmit until the frame timer indicates the start of a new frame (typically at $\approx 100$ Hz). When the controller encounters a special end word, it returns to the start of
Table 3.2: An example BLASTbus superframe with three-fold multiplexing.

<table>
<thead>
<tr>
<th>00: Frame sync #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>01: Fast channel #1</td>
</tr>
<tr>
<td>02: Slow channel #1</td>
</tr>
<tr>
<td>03: Slow channel #2</td>
</tr>
<tr>
<td>04: Frame sync #2</td>
</tr>
<tr>
<td>05: Fast channel #1</td>
</tr>
<tr>
<td>06: Slow channel #3</td>
</tr>
<tr>
<td>07: Slow channel #4</td>
</tr>
<tr>
<td>08: Frame sync #3</td>
</tr>
<tr>
<td>09: Fast channel #1</td>
</tr>
<tr>
<td>10: Slow channel #5</td>
</tr>
<tr>
<td>11: Slow channel #6</td>
</tr>
<tr>
<td>12: End word</td>
</tr>
</tbody>
</table>

The superframe can contain several subframes, delineated by frame sync words, to allow multiplexing. Fast channels (reads or writes) have a word in every subframe, while slow channels are present in only one. Therefore, slow channels are only encountered at the frame rate divided by the number of subframes. Table 3.2 shows an example superframe with three-fold multiplexing. The superframe is managed by the master control program (mcp) via the bbcpci driver, a Linux kernel module. Read channels typically remain fixed, while the data portion of write channels will be updated as required.

In addition to the BLASTbus, the PCI board generates a biphase encoded signal for the line-of-sight radio transmitter. An identical mainboard with slightly different firmware is used to receive the biphase signal on the ground.

### 3.2.1 External synchronization

The BLASTbus electronics are often used alongside the MCE for readout of Transition Edge Sensor (TES) bolometers. To synchronize the MCE and BLASTbus data, the PCI controller board has been adapted to interface to the MCE sync box in lieu of a second BLASTbus.
This can operate in an asynchronous mode or a synchronized mode. In the asynchronous mode, the BLASTbus operates as it would without the MCEs—with a 4 MHz clock and frame start times based on an internal counter. The most recent MCE frame number is injected as a word in the BLASTbus frame, which allows synchronization to within one frame period (about 10 ms). In the synchronized mode, the BLASTbus clock is replaced by the 5 MHz clock from the sync box, and BLASTbus frames start exactly when an MCE frame starts. In synchronized mode, the BLASTbus frame rate must be an integer divisor of the MCE frame rate.

### 3.3 Design of Second Generation System

Development of the second generation BLASTbus system was primarily motivated by lowering power consumption, increasing flexibility, and improving the user experience. Power was primarily cut by switching to a more efficient Analog to Digital Converter (ADC) chip (section 3.5.1) and by leveraging faster processors to increase the number of channels per motherboard (section 3.4). Flexibility is increased by moving external interface electronics to daughterboards (section 3.5). This both allows finer selection of the distribution of channels (eg. analog versus digital) and simplifies the job of adding new functionality. The most significant user experience improvements are providing a JTAG interface for on-line debugging and allowing the boards to be reprogrammed in place.

The BLASTbus and PCI board (sections 3.1 and 3.2) were not changed from the first generation system. Other communication protocols such as Ethernet were considered, but the existing BLASTbus infrastructure proved sufficiently capable and minimized development work. By upgrading the bus transceivers to match the motherboards, clock speeds of up to 25 Mbit s$^{-1}$ could be supported. While PCI slots are becoming rarer on desktop computer motherboards, a simple passive adaptor allows the current PCI
controller board to be used with the PC/104+ or PCI/104 form factors. These form factors are common in embedded computers, and a simple board rearrangement would allow the BLASTbus controller to fit in their typical stack architecture.

### 3.4 Motherboards and Crates

The motherboards are the central hub of each BLASTbus slave node. In addition to the bus transceivers, they contain an Altera Cyclone II FPGA and an Analog Devices ADSP21369 Digital Signal Processor (DSP). The DSP does the filtering and processing, while the FPGA presents a memory-mapped interface to the BLASTbus and the daughterboards. Each motherboard holds up to three daughterboards, as pictured in fig. 3.3.

The BLASTbus is distributed to up to seven motherboards through the backplane of a 6U Eurocard crate. The backplane RS-485 transmission lines have a characteristic impedance of 120 Ω. When care is taken to terminate the bus with 120 Ω resistors, and use cables with the same characteristic impedance, the bus has been daisy-chained through
two such crates. With just a single crate on the bus, careful termination is not necessary.

The crate also contains various power supplies for the motherboards. 1.2 V and 3.3 V are provided for digital logic. A combination of passive LC filtering and active voltage regulation convert raw 6 V and ±12 V supplies to cleaned 5 V and ±10 V for use on analog daughterboards. BLASTPol’s Data Acquisition System (DAS) crate (pictured in fig. 3.4) consumed 36 W at 24 V DC for six motherboards reading out 375 analog channels.

Each motherboard also contains a watchdog circuit that cycles all of the power supplies if the DSP fails to continuously toggle a reset line. Thick copper layers on the top and bottom conduct heat to the edges of the board. Due to a lack of convective cooling in the balloon environment, the heat conducting layers can have heat straps attached. However, radiation and air conduction alone are sufficient. With the crate walls radiating to the sky, the boards stayed around 0 °C.
Chapter 3. The BLASTbus Electronics

3.4.1 Software and Firmware

The BLASTbus system includes processing at three different levels: the control computer, the DSPs, and the FPGAs. The control computer is the most powerful and simple to program, but has access to data at only the $\approx 100$ Hz frame rate.

The bulk of the low-level data processing happens in the DSP. This operates in a real-time loop at the full $\approx 10$ kHz data sample rate. Processing includes anti-aliasing filters and lock-in amplification (section 3.6), and also application-specific fast control loops (eg. section 3.7 and section 3.8).

The FPGA allows fast (80 MHz) and extremely parallel processing of its signals. This is used for bit-level control of the ADCs, DACs, BLASTbus transceivers, and assorted digital sensors. Further processing could also take place in the FPGA, but in practice the DSP is simpler and adequate.

3.5 Daughterboards

The BLASTbus system’s input and output capabilities are determined by its daughterboards. In practice, only two types of daughterboard have been needed: analog input and digital input/output. Analog outputs are generated by an auxiliary system connected to the digital daughterboard. Where appropriate, specialized daughterboards could be created that offer fully integrated solutions for a variety of applications.

3.5.1 Analog Input (ADC) Daughterboard

Each analog board contains 25 low-power sigma-delta ADCs with 24-bit resolution\(^2\). These use the BLASTbus clock so that readout is fully synchronized (every 384 clock cycles, or 10.4 kHz for a 4 MHz clock). Typically, each ADC channel is paired with a preamp that has 50 k$\Omega$ input impedance and accepts $\pm 10$ V. Alternatively, channels can

\(^2\)Texas Instruments ADS1251
be configured with no preamps, or with the capability to connect directly to thermistors or thermocouples (AD590). Each channel also has a low-pass RC filter at $\approx 60\,\text{kHz}$ to prevent aliasing of high frequency noise. All three varieties are pictured in fig. 3.5 and fig. 3.6 shows simplified schematics.

### 3.5.2 Digital I/O Daughterboard

The digital I/O daughterboard contains six 8-bit optoisolated groups selectable as input or output. Input signals can be as fast as 15 MHz, and a variety of firmware modules allow decoding of signals, such as digital gyroscopes or quadrature encoders. The isolated outputs can drive up to 50 mA for switching relays, but are limited to speeds of about
Figure 3.6: Schematic diagrams for the ADC inputs, in each configuration. From top to bottom: thermistor/AD590, typical preamp configuration, no preamps. Each version contains the ADC chip and passive differential low-pass filter. One of the filter capacitors in the thermometer circuit is replaced with a $2.2\,\text{k}\Omega$ current sense resistor. The preamp circuit uses a pair of op amps with gain set by a differential resistor bridge. The 4.096 V reference is supplied by a single ADR444BRZ, which is current amplified by an OPA2335. Power lines are omitted for clarity.
30 kHz. The digital daughterboard also contains an extra 8-bit group for commanding a DAC output system. Figure 3.7 shows a digital daughterboard, and a simplified schematic is presented in fig. 3.8.

3.5.3 Analog Output (DAC) Auxiliary Boards

Analog outputs are not produced directly on any daughterboard, but on separate DAC boards. Signals for the DACs are distributed digitally as RS-485 to reduce pickup and allow the analog signal to be generated in a cleaner RFI environment.

The 8-bit DAC bus has clock, data, and strobe bits like the BLASTbus (section 3.1), and five bits used for addressing. The system used by BLASTPol (pictured in fig. 3.9) uses the five bits to address five single-DAC boards. An alternate system uses a different transmitter and extra decoder board to address up to 32 DACs, arranged four per board. Figure 3.10 shows a simplified schematic.

DAC outputs are ±5 V differential with 16-bit resolution. They can update as fast as the ADC sample rate, and are also synchronized to the BLASTbus clock.

The analog outputs and inputs have very low noise levels. When a DAC bias signal is fed directly into an ADC channel (like section 3.6, but with no bolometers or extra amplifiers), the digital lock-in achieves about 20 bits of dynamic range.
Figure 3.8: Schematic of a single bit of digital I/O. Each 8-bit group has 8 instances of this, except only a single Direction select line, and two pairs of Input/Output Common lines, which are shared in 4-bit subgroups. On the FPGA side, the direction bit activates one of the input or output buffers. The I/O pins form complete circuits with one of the Input/Output Common lines, and the other should remain disconnected.

Figure 3.9: The DAC boards for analog output. This shows the single-DAC board on top and the five-output transmitter below. An alternate system exists to control 32 DACs.
Figure 3.10: Simplified schematic for the DAC outputs. Digital signals are supplied by an RS-485 receiver, and a pair of op amps produce a differential output.

### 3.6 NTD-Ge Bolometer Readout

NTD-Ge devices are sensitive low-temperature thermistors that are useful in millimetre and submillimetre bolometers\[34\]. Readout of BLASTPol’s NTD-Ge bolometers was the primary performance driver for the BLASTbus system’s analog readout.

BLASTPol’s bolometer readout system is sketched in fig. 3.11. Starting in the BLASTbus DAS, a digital reference sinusoid is generated. This has a $\approx 200\,$Hz frequency, which is exactly twice the frame rate, and faster than the bolometer time constant, but is still slow enough to be well-sampled by the $\approx 10\,$kHz DAC update rate.

The bias generator is a simple DAC, which produces a differential sine wave. A passive voltage divider is then used so that a low-amplitude bias signal can be generated with higher amplitude and lower round-off error at the DAC. The voltage divider has low resistance to minimize Johnson noise, and a small current amplifier is required for the DAC to drive it. The bias signal is shared by all bolometers in each of BLASTPol’s three detector arrays, but the bias amplitude is tuned differently between arrays. A fourth bias signal is used for the cryogenic thermistors (see section 3.8).

The voltage bias produced by the DAC is converted to a nearly constant current bias by load resistors ($\approx 8\,$MΩ), which are larger than the bolometers’ nominal resistance ($\approx 1.5\,$MΩ), and much larger than changes in bolometer resistance during operation. The final cryogenic element is a pair of U401 JFET followers to lower the output impedance and reduce microphonics due to the capacitance of vibrating cables. These
Figure 3.11: Schematic view of the BLASTPol NTD-Ge bolometer readout. The BLASTbus data acquisition system generates a 200 Hz sine-wave bias and digitally lock-in amplifies the signal from its ADCs. The cryogenic electronics include load resistors to quasi-current-bias the bolometer, and JFETs to reduce line impedance and microphonics. A preamplifier filters and conditions the signal for readout.

are placed as close to the bolometers as possible, with the cables in between tightly constrained. The thermally isolated JFET enclosure is self-heated to 140 K, which locally minimizes noise and exceeds their freeze-out temperature of \( \approx 100 \) K.

The JFETs’ signals then pass through the ambient temperature preamplifier, which is connected to the cryostat by a shielded cable bundle. The preamplifier filters the data using a biquad band-pass with 85 Hz bandwidth around the 200 Hz bias frequency. To save power, the preamplifier conditions the signal for direct acquisition by the BLASTbus ADCs, without an extra amplifier on the daughterboard.

Finally, the digital signal is mixed with the reference wave and anti-alias filtered for acquisition. The digital filter, shown in fig. 3.12, leaves just the DC mixer output, which is reported over the BLASTbus and stored to disk. Because the bias is synced to the frame rate, the filter has a null at the bias frequency and the 2f mixer output is strongly
Figure 3.12: Frequency response of the BLASTbus digital anti-aliasing filter. For comparison, a 4-stage CIC filter is shown, with more passband droop and increased sidelobes. The cumulative response at intermediate filter stages is also shown in light grey.

The digital filter is a 4-stage boxcar filter with first-nulls spaced logarithmically between the Nyquist frequency and sample rate. This results in a flatter passband and lower sidelobes than a 4-stage Cascaded Integrator Comb (CIC) filter\cite{56}.

Like a CIC filter, this filter uses just addition and subtraction at each stage, though it requires more memory as data cannot be stored at the decimated rate. For modest decimation of 104 samples, this is not a problem. For the BLASTPol DAS, with 375 channels, there is not enough bandwidth to acquire both the sine and cosine components of the signal. Instead, just the cosine component is acquired and a phase is set to maximize its amplitude, and minimize the sine component.

Performance

Figure 3.13 shows full-system noise spectra from the 2012 flight of BLASTPol. Reading a fixed cryogenic resistor, Johnson noise is the largest contributor, with the remainder due to the JFETs and warm amplifier. Most importantly, the bolometer noise is dominated...
Figure 3.13: Example bolometer noise spectrum from the BLASTPol12 flight. Also shown is the spectrum of a 4 MΩ fixed resistor, used to measure electronic noise. The resistor’s white noise level is close to its Johnson noise, with smaller contributions from the JFETs and warm amplifier. The higher noise of the bolometer is mostly due to photon shot noise. These spectra were taken while the telescope was not scanning, so contain little signal. The bolometer data have been despiked and have had the anti-aliasing filter deconvolved (section 5.4).

by photon shot noise, which exceeds all sources of electrical and readout noise.

That the bolometer has more significant $\frac{1}{f}$ noise than the resistor indicates that its primary contribution is also optical or thermal. As shown in section 6.2.4, most of the bolometer $\frac{1}{f}$ is correlated across the array. Plain resistors and amplifiers also exhibit $\frac{1}{f}$ noise, which is ubiquitous in nature, if not always well understood [57].

### 3.7 Attitude Control

Attitude control involves reading a variety of sensors, commanding motors, and then tying both tasks together into a control loop. With its flexible inputs, programmability, and real-time processing, the BLASTbus system is well suited to these tasks. Attitude control is a major application of the BLASTbus electronics. Because the topic is covered
by two other papers [45, 58], only a summary is presented here.

Many types of sensor are used to measure attitude, both during the flight and in post-flight processing. Most have their signals acquired directly by the BLASTbus, via analog or digital daughterboards. For the star trackers, the BLASTbus is used only to synchronize camera exposures with other data. The primary sensor for control purposes is a set of fiber-optic gyroscopes, measuring rotation rate around three axes. The other sensors serve to provide absolute position information with varying accuracies, sample rates, and reliabilities. More details can be found in Ref. [45].

BLASTPol and Spider use three motors to control attitude: an elevation drive, a reaction wheel for fine azimuth, and an actuated pivot connecting to the balloon for coarse azimuth. The BLASTbus attitude control system commands the motor controllers via its DAC outputs. High-level logic runs on the master control computer, sending set-points and data to the BLASTbus board at the 100 Hz frame rate. In between these updates, the DSP servos the motors using its faster data—mainly the gyroscopes. Details of the scan strategy and the control loops are in Ref. [58].

Polarimeters like Spider and BLASTPol feature another attitude-like quantity: the orientation of half-wave plates, which modulate the input polarization signal. BLASTPol’s half-wave plate [39] is surrounded by a rotating potentiometer, which is DC biased and read out as a simple analog signal. Spider’s half-wave plates use contact-free optical encoders [59]. The Light Emitting Diodes (LEDs) in this system are square-wave biased at 1 kHz using BLASTbus digital outputs, and the reflected photodiode signals are digitally demodulated much like in the NTD-Ge bolometer readout (section 3.6).

## 3.8 Cryogenic Housekeeping

BLASTPol used an ad hoc system of cryogenic housekeeping circuits, which was simplified and generalized for Spider. The simplified system is described here.
While Spider does not use NTD-Ge bolometers, it does have cryogenic thermistors—including NTD-Ge devices at sub-Kelvin temperatures. To read these, wide dynamic range is important, as the resistance can vary by several orders of magnitude over the operating temperature range. At higher temperatures, simpler diode thermometers can be used. To manipulate the cryogenic environment, it is also necessary to control a variety of heaters.

With six independent cryogenic telescopes, Spider needed a simple and effective means to perform these tasks. A unified board was made to handle the needs of each individual telescope. This uses the same form factor, crate, and power cleaning as the BLASTbus motherboards, and provides cryogenic housekeeping with a minimum of extra capabilities on top of what the BLASTbus system supplies already. Each board has circuits for 8 thermistors, 18 diode thermometers, 8 digital heaters, and 2 analog heaters.

The thermistor readout is similar to the NTD-Ge bolometer readout scheme, though somewhat simplified as it does not need to aggressively lower noise. The main simplification is to not include cold JFETs and their isolated cavity. Instead, warm JFETs are used, integrated into the input of the amplifier\(^3\). The bias frequency is made commandable to help find a clean frequency that doesn’t contaminate other systems. Typically, the bias frequency is in the range of 10 Hz to 100 Hz. To accommodate changing frequencies, the bandpass filter used in bolometer readout is replaced by a 5 Hz highpass filter and 500 Hz lowpass filter. With only 50 thermistor channels, full quadrature lock-in is possible, eliminating the need to tune the phase. Noise spectra, calibrated into temperature units, are shown in fig. 3.14.

Diode thermometers are used where the higher precision of thermistors is not necessary, and at temperatures above about 1 K. They are biased by a temperature-corrected 10 \(\mu\)A DC current source\(^4\) and their temperature-dependent voltage is amplified slightly before acquisition by the BLASTbus system. The diode circuit uses a non-differential

---

\(^3\) Analog Devices AD8221  
\(^4\) Texas Instruments LM234
2-wire bias/readout scheme. An example of the diode noise level is also shown in fig. 3.14.

In most cryogenic heater applications, like cycling the helium-3 adsorption fridge, coarse on/off control is desired. These are provided using a solid-state relay\(^5\) driven by a BLASTbus digital output. The relay output voltage and heater resistance can be chosen to set the power level. To coarsely adjust the power, these can also be driven by a pulse width modulated signal. For finely adjustable heating, filtered pass-throughs are available to drive heaters directly with a DAC. BICEP2 and the Keck Array use both types of heaters, passive thermal filters, and feedback from NTD-Ge thermistors to stabilize their focal plane temperatures\[^60\]. BICEP2 achieves a stability of 0.4 nK at \(\ell\) of 100. (This is a measure of data contamination due to uncorrected temperature fluctuations, averaged over detectors and time. The fluctuations are smaller than the NTD-Ge noise and difficult to measure directly.)

---

\(^5\)Omron G3VM-62J1
3.9 Status and Future of the BLASTbus

The BLASTbus was a very natural fit for BLASTPol since the system was required for detector readout and provided all the capabilities necessary for other telescope subsystems. Newer experiments like SPIDER use different specialized detector readout electronics. In the case of SPIDER, the large technology and experience overlap with BLASTPol meant the BLASTbus remained a natural choice. And SPIDER’s attitude control and cryogenic housekeeping requirements still leverage the speed, precision, and scalability of the BLASTbus.

The primary downside of the BLASTbus is that very limited resources are available for continued development and support. The system is deemed feature complete and no significant upgrades are planned. Small fixes and firmware tailoring will continue for SPIDER, the Keck Array, BICEP3, and possibly for similar future experiments. Some of these support issues can be avoided by using commercial alternatives. For example, the next generation BLAST experiment [61] is switching to a new system. Simpler alternatives can also save time, power, or money when the full capabilities of the BLASTbus aren’t required.

In new experiments, the BLASTbus remains a compelling option for acquiring large numbers of very low noise analog signals. Once chosen, its flexibility has proven valuable in adapting to new applications. The BLASTbus has operated stably for years in harsh environments. If full support isn’t possible, the designs, documentation, and code are all open.

---

\[\footnote{[6] From \url{http://www.ueidaq.com/}}\]

\[\footnote{[7] Please feel free to contact me!}\]
Chapter 4

Map Making Theory

Bolometers, like those used by BLASTPol, do not directly image the sky. Instead, timestreams must be analyzed in combination to make a best guess at the underlying celestial signal. This process is called map making and its theory is discussed here.

4.1 Polarization Overview

4.1.1 Stokes Parameters

Following Jackson [62], a general plane wave propagating in the direction \( \mathbf{k} \) with frequency \( \omega \) is:

\[
E(x, t) = (\epsilon_1 A_1 + \epsilon_2 A_2)e^{i\mathbf{k} \cdot x - i\omega t}
\] (4.1)

for basis vectors \( \epsilon_1, \epsilon_2 \) and complex amplitudes \( A_1 = E_1 e^{i\delta_1}, A_2 = E_2 e^{i\delta_2} \).

The Stokes parameters encode the amplitude and phase information in four quantities that are quadratic in the field strength. This means that they can be determined by
intensity measurements.

\[ I = |\epsilon_1 \cdot E| + |\epsilon_2 \cdot E| = E_1^2 + E_2^2 \]
\[ Q = |\epsilon_1 \cdot E| - |\epsilon_2 \cdot E| = E_1^2 - E_2^2 \]
\[ U = 2\Re[(\epsilon_1 \cdot E)^*(\epsilon_2 \cdot E)] = 2E_1E_2 \cos(\delta_2 - \delta_1) \]
\[ V = 2\Im[(\epsilon_1 \cdot E)^*(\epsilon_2 \cdot E)] = 2E_1E_2 \sin(\delta_2 - \delta_1) \]

Because only the difference of phases matters, the parameters are related:

\[ I^2 = Q^2 + U^2 + V^2 \quad (4.3) \]

For quasi-monochromatic light, it is assumed that the complex amplitudes vary slowly compared to the frequency, and then the expressions in (4.2) are replaced by time-averages over many periods. In the general case, eq. (4.3) becomes an inequality, with equality only for fully polarized light. The exact equality, as in eq. (4.3), now defines the polarized intensity \( I_p \):

\[ I^2 \geq Q^2 + U^2 + V^2 \equiv I_p^2 \quad (4.4) \]

To understand the Stokes parameters better, it is instructive to examine three different decompositions of the wave amplitude. First, choose a coordinate system with \( x \) and \( y \) axes that align with \( \epsilon_1 \) and \( \epsilon_2 \). Then, consider two alternate coordinate systems, one with \( a \) and \( b \) axes rotated \( 45^\circ \) from \( x \) and \( y \), and another which includes a \( \pm 90^\circ \) complex phase shift to encode positive or negative helicity. In particular:

\[ \epsilon_x = \epsilon_1 \]
\[ \epsilon_a = \frac{1}{\sqrt{2}}(\epsilon_1 + \epsilon_2) \]
\[ \epsilon_+ = \frac{1}{\sqrt{2}}(\epsilon_1 + i\epsilon_2) \]
\[ \epsilon_y = \epsilon_2 \]
\[ \epsilon_b = \frac{1}{\sqrt{2}}(\epsilon_1 - \epsilon_2) \]
\[ \epsilon_- = \frac{1}{\sqrt{2}}(\epsilon_1 - i\epsilon_2) \]
Then, it is easy to show that (denoting the quasi-monochromatic time-averaging as $\langle \rangle$):

\[I = \langle E_x^2 \rangle + \langle E_y^2 \rangle = \langle E_a^2 \rangle + \langle E_b^2 \rangle = \langle E_+^2 \rangle + \langle E_-^2 \rangle\]

\[Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle\]

\[U = \langle E_a^2 \rangle - \langle E_b^2 \rangle\]

\[V = \langle E_+^2 \rangle - \langle E_-^2 \rangle\]

(4.8)

Therefore, the $I$ parameter is the total intensity between any of the orthogonal “directions”. $Q$, $U$, and $V$ are the differences, respectively, between horizontal and vertical, between the two diagonal directions, and between left and right circularly polarized.

**4.1.2 Mueller Matrices**

Combining Stokes parameters, the complete state of incoherent light can be represented as a vector:

\[s = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}\]

(4.9)

Then, a generic optical element can be represented as a matrix, $M$, which transforms that vector:

\[s' = Ms\]

(4.10)

A special case of interest is rotating the frame of reference. While the total intensity and circular polarization are independent of the coordinate system, the linear polarization components will be mixed into each other. For a rotation by angle $\theta$, $Q$ and $U$ will rotate
into each other at $2\theta$, because polarization is spin-2:

$$
R(\theta) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(2\theta) & -\sin(2\theta) & 0 \\
0 & \sin(2\theta) & \cos(2\theta) & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

(4.11)

This transforms Stokes vectors and Mueller matrices according to:

$$
s' = R(\theta)s
$$

(4.12)

$$
M' = R(\theta)MR(-\theta)
$$

(4.13)

### 4.2 Polarimeter Data Model

#### 4.2.1 Simple Polarimeter

The most basic bolometric polarimeter can be modelled as having a polarizing grid modify an input Stokes vector, and then a total power detector captures the intensity of the remaining signal. If the grid is oriented at an angle $\psi$ relative to the input:

$$
d = \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix} R(\psi) M_{\text{grid,ideal}} R(-\psi) s_{\text{input}}
$$

(4.14)

$$
= I + \cos(2\psi)Q + \sin(2\psi)U
$$

See eq. (4.16) for details on the Mueller matrix of a polarizing grid. Note that different coordinate system conventions exist, which disagree on the sign of $U$ \cite{63, 64}.

Unsurprisingly, this polarimeter using a linear grid is insensitive to circular polarization. If a measurement of $V$ were desired, the system would need a quarter-wave plate.

---

1 $+Q$ always aligns with the $+x$ axis, $-Q$ with the $+y$ axis, and $+U$ with the diagonal in between $+x$ and $+y$. The difference is in the choice of axis directions. The $x$, $y$, and $z$ axes point north, east, and inwards in the International Astronomical Union (IAU) convention, while cosmological literature often has the axes point south, east, and outwards.
Because only linear polarization is of interest to BLASTPol, $V$ is ignored.

### 4.2.2 Polarization Efficiency and Half-Wave Plates

All of the optical elements considered here are special cases of a diattenuating retarder (see [65, Chapter 15]). This is an asymmetric element with transmittances to $E_x$ and $E_y$ of $a$ and $b$ respectively, and a delay between the axes producing a phase shift $\delta$.

$$
M = \frac{1}{2} \begin{pmatrix}
(a^2 + b^2) & (a^2 - b^2) & 0 & 0 \\
(a^2 - b^2) & (a^2 + b^2) & 0 & 0 \\
0 & 0 & 2ab \cos(\delta) & 2ab \sin(\delta) \\
0 & 0 & -2ab \sin(\delta) & 2ab \cos(\delta)
\end{pmatrix}
$$

(4.15)

An ideal polarizing grid has $a = 1$, $b = 0$, and $\delta = 0$. The Mueller matrix for a grid oriented at an angle $\chi$ is:

$$
M_{\text{grid, ideal}}(\chi) = R(\chi) \frac{1}{2} \begin{pmatrix}
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix} R(-\chi)
$$

(4.16)

$$
= \frac{1}{2} \begin{pmatrix}
1 & \cos(2\chi) & \sin(2\chi) & 0 \\
\cos(2\chi) & \cos^2(2\chi) & \sin(2\chi) \cos(2\chi) & 0 \\
\sin(2\chi) & \sin(2\chi) \cos(2\chi) & \sin^2(2\chi) & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
$$

(4.17)

An imperfect polarization efficiency means the grid does not fully reject the orthogonal
polarization component. Typically, this is parametrized by $\epsilon = \frac{\nu^2}{a^2}$, where $\epsilon \ll 1$.[66]

$$M_{\text{grid}}(\chi) = R(\chi) \frac{a^2}{2} \begin{pmatrix} (1 + \epsilon) & (1 - \epsilon) & 0 & 0 \\ (1 - \epsilon) & (1 + \epsilon) & 0 & 0 \\ 0 & 0 & 2\sqrt{\epsilon} & 0 \\ 0 & 0 & 0 & 2\sqrt{\epsilon} \end{pmatrix} R(-\chi) \quad (4.18)$$

An ideal half-wave plate ($a = 1$, $b = 1$, and $\delta = 180^\circ$) can be used to modulate linear polarization. If oriented at an angle $\theta$:

$$M_{\text{HWP}}(\theta) = R(\theta) \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} R(-\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(4\theta) & \sin(4\theta) & 0 \\ 0 & \sin(4\theta) & -\cos(4\theta) & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (4.19)$$

Now eq. (4.14) can be expanded with a non-ideal grid and with a half-wave plate:

$$d = \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix} M_{\text{grid}}(\chi) M_{\text{HWP}}(\theta) R(\alpha) s_{\text{input}} \quad (4.20)$$

Also included here is a rotation of the input Stokes vector by and angle $\alpha$. This angle includes parallactic angle and telescope roll relative to zenith, referencing $Q$ and $U$ to a celestial reference frame. Using eq. (4.18) and eq. (4.19), and neglecting an overall gain factor (since the gain of the readout must already be calibrated, see section 5.6), this simplifies to:

$$d = I + \frac{1 - \epsilon}{1 + \epsilon} \cos(2\chi - 4\theta + 2\alpha)Q + \frac{1 - \epsilon}{1 + \epsilon} \sin(2\chi - 4\theta + 2\alpha)U \quad (4.21)$$

This differs from the simple polarimeter of eq. (4.14) in two ways:
1. The amplitudes of $Q$ and $U$ are modified by the “polarization efficiency”:

\[
\text{polarization efficiency} \equiv \frac{1 - \epsilon}{1 + \epsilon} \quad (4.22)
\]

If not accounted for in map-making, the final $Q$ and $U$ maps must be scaled by this factor. The parameter $\epsilon$ can be measured with the polarimeter itself: it is the ratio of minimum to maximum power response to a fully polarized input source. Using eq. (4.21), with $I = Q, U = 0$:

\[
\frac{d_{\text{min}}}{d_{\text{max}}} = \frac{(1 + \epsilon)I + (1 - \epsilon)(-1)Q}{(1 + \epsilon)I + (1 - \epsilon)(+1)Q} = \epsilon \quad (4.23)
\]

2. The total polarization angle $\psi$ has been broken down into:

\[
\psi = \chi - 2\theta + \alpha \quad (4.24)
\]

This includes the angle $\chi$ of the grid inside the telescope, the angle $\alpha$ of the telescope relative to the sky, and the angle $\theta$ of the HWP. The HWP rotates the polarization by twice its angle, and can be modulated so that each detector independently measures all of the Stokes parameters.

### 4.2.3 Instrumental Polarization

For BLASTPol, an extra imperfect element is added skyward of the half-wave plate, to model the effect of “instrumental polarization” (IP). IP is modelled as a partial polarizer with, in eq. (4.15), $a = 1, b = 1 - e$ (where $e \ll 1$) and $\delta = 0$. During the 2010 flight, there was very significant IP due to a melted filter in the window of the cryostat. If
oriented at an angle $\phi$ and expanded to first-order in $e$:

$$
M_{IP} = R(\phi) \begin{pmatrix}
(1 - e) & e & 0 & 0 \\
(e & (1 - e) & 0 & 0 \\
0 & 0 & (1 - e) & 0 \\
0 & 0 & 0 & (1 - e)
\end{pmatrix} R(-\phi) \quad (4.25)
$$

Or, expanding the rotation and switching to a Cartesian representation

$q_{ip} = e \cos(2\phi)$ and $u_{ip} = e \sin(2\phi)$ (with $e = \sqrt{q_{ip}^2 + u_{ip}^2}$ kept for brevity):

$$
M_{IP} = \begin{pmatrix}
(1 - e) & q_{ip} & u_{ip} & 0 \\
q_{ip} & (1 - e) & 0 & 0 \\
u_{ip} & 0 & (1 - e) & 0 \\
0 & 0 & 0 & (1 - e)
\end{pmatrix} \quad (4.26)
$$

Now the BLASTPol data model is fully specified. Expanding to first-order in $\epsilon$, $q_{ip}$, $u_{ip}$, and $e$:

$$
d = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} M_{grid}(\chi) M_{HWP}(\theta) M_{IP} R(\alpha) s_{input}
$$

$$
= \left[ 1 + \epsilon - e + q_{ip} \cos(2\chi - 4\theta) + u_{ip} \sin(2\chi - 4\theta) \right] I
+ \left[ (1 - \epsilon - e) \cos(2\chi - 4\theta + 2\alpha) + q_{ip} \cos(2\alpha) + u_{ip} \sin(2\alpha) \right] Q
+ \left[ (1 - \epsilon - e) \sin(2\chi - 4\theta + 2\alpha) + q_{ip} \sin(2\alpha) - u_{ip} \cos(2\alpha) \right] U
$$

### 4.2.4 Non-ideal Half-Wave Plates

Continuing with the model of a diattenuating retarder eq. (4.15), two types of HWP non-idealities can be considered: error in phase lag, or slight diattenuation. If the phase lag $\delta$ differs slightly from $180^\circ$, some circularly polarized ($V$) signal will be produced. Because the rest of the detector system is insensitive to $V$, this can be ignored. If the
HWP diattenuates slightly \((a = 1, b = 1 - \sigma)\), it produces terms similar to Instrumental Polarization (IP). These terms vary as \(2\theta\) rather than the usual HWP modulation at \(4\theta\), so can be characterized by observing at angles separated by \(90^\circ\).

The BLASTPol HWP has undergone detailed spectral characterization \([39]\), and is very close to ideal. The primary non-ideality is a frequency-dependent offset in the effective angle of its axes. By including this offset in making maps, the HWP can otherwise be considered ideal.

## 4.3 Map Maker Formalism

### 4.3.1 Linear Model

Section 4.2 defines what a single noiseless detector sees when observing a fixed location on the sky. This needs to be expanded to include all detectors (index \(i\) up to \(N_{\text{det}}\)), all time samples (index \(t\) up to \(N_{\text{samp}}\)), and all locations on a pixelized sky (index \(p\) up to \(N_{\text{pix}}\)). For notational simplicity, eq. (4.14) will be considered, though it is straightforward to generalize to eq. (4.21) or eq. (4.27). Then:

\[
d_{it} = I_p + Q_p \cos(2\psi_{it}) + U_p \sin(2\psi_{it}) + n_{it} \tag{4.28}
\]

Where a noise term \(n_{it}\) has been added. Implicitly, the pixel index \(p\) is related to the detector \(i\) and time sample \(t\) by the detector’s pointing \(x_{it}\), which can be compared to the coordinates of the pixel \(x_p\). More explicitly:

\[
d_{it} = \sum_p \delta(x_p - x_{it}) \left[ I_p + Q_p \cos(2\psi_{it}) + U_p \sin(2\psi_{it}) \right] + n_{it} \tag{4.29}
\]

This can be reinterpreted as a simple linear equation. Concatenate the timestreams from all the detectors into a data vector \(\mathbf{d}\) with length \(N_{\text{det}}N_{\text{samp}}\). Similarly, construct a noise vector \(\mathbf{n}\) by concatenating the \(n_{it}\) values. And create a signal vector \(\mathbf{s}\) with length
3N_{pix} using the I_p, Q_p, and U_p values in each pixel.

\[
\begin{pmatrix}
  d_{00} \\
  \vdots \\
  d_{0N_{samp}} \\
  d_{10} \\
  \vdots \\
  d_{N_{det}N_{samp}}
\end{pmatrix}
\]

\[
\begin{pmatrix}
  n_{00} \\
  \vdots \\
  n_{0N_{samp}} \\
  n_{10} \\
  \vdots \\
  n_{N_{det}N_{samp}}
\end{pmatrix}
\]

\[
\begin{pmatrix}
  I_0 \\
  Q_0 \\
  U_0 \\
  \vdots \\
  I_{N_{pix}} \\
  Q_{N_{pix}} \\
  U_{N_{pix}}
\end{pmatrix}
\]

\[d = \begin{pmatrix}
  d_{00} \\
  \vdots \\
  d_{0N_{samp}} \\
  d_{10} \\
  \vdots \\
  d_{N_{det}N_{samp}}
\end{pmatrix}, \quad
n = \begin{pmatrix}
  n_{00} \\
  \vdots \\
  n_{0N_{samp}} \\
  n_{10} \\
  \vdots \\
  n_{N_{det}N_{samp}}
\end{pmatrix}, \quad
s = \begin{pmatrix}
  I_0 \\
  Q_0 \\
  U_0 \\
  \vdots \\
  I_{N_{pix}} \\
  Q_{N_{pix}} \\
  U_{N_{pix}}
\end{pmatrix}
\]

The mapping between the signal and data is the pointing matrix \(A\), which is huge \((N_{det}N_{samp} \times 3N_{pix})\) but very sparse. In each row \((it)\) it has just three non-zero values, located in the columns corresponding to \(I_p, Q_p,\) and \(U_p\) for the observed pixel \(p\). For row \((it):\)

\[
A_{(it)} = \begin{pmatrix} 0 & \ldots & 0 & 1 & \cos(2\psi_{it}) & \sin(2\psi_{it}) & 0 & \ldots & 0 \end{pmatrix}
\]

(4.31)

In general, the non-zero values will be the coefficients of the \(I, Q,\) and \(U\) terms in the expression for \(d_{it}\).

Now eq. (4.28) can be expressed as a simple linear equation:

\[
d = As + n
\]

(4.32)

### 4.3.2 Solving for the Map

Several methods have been devised to solve for a signal estimate \(\hat{s}\) given the linear model of eq. (4.32) (see[67] for several examples). For computational simplicity, linear solutions are considered: \(\hat{s} = \mathbf{W}d\). Specifically, the Generalized Least Squares (GLS) solution is:

\[
\hat{s} = (A^T \mathbf{N}^{-1} A)^{-1} A^T \mathbf{N}^{-1} d
\]

(4.33)
where $\mathbf{N} = \langle \mathbf{n}\mathbf{n}^T \rangle$ is the covariance of the noise.

This choice is made for several reasons:

1. The generalized $\chi^2$ (the squared Mahalanobis distance[68]) is minimized. Where:

\[
\chi^2 = (\mathbf{d} - \mathbf{A}\hat{s})^T \mathbf{N}^{-1} (\mathbf{d} - \mathbf{A}\hat{s})
\]  

(One can derive eq. (4.33) by setting $\frac{\partial \chi^2}{\partial \hat{s}} = 0$.)

2. Similarly, if the noise is Gaussian, then the likelihood $\mathcal{L}(\mathbf{d}|\mathbf{s})$ is maximized. For this reason, eq. (4.33) is often referred to as the maximum likelihood map.

\[
\mathcal{L}(\mathbf{d}|\mathbf{s}) = e^{-\frac{1}{2}(\mathbf{d} - \mathbf{A}s)^T \mathbf{N}^{-1}(\mathbf{d} - \mathbf{A}s)}
\]  

3. The error $\mathbf{e} = \hat{s} - \mathbf{s}$ is independent of $\mathbf{s}$, so the estimate is unbiased. This is true for any solution with $\mathbf{WA} = \mathbf{I}$ (where $\mathbf{I}$ is the identity matrix), as:

\[
\mathbf{e} = \hat{s} - \mathbf{s} = (\mathbf{WA} - \mathbf{I}) \mathbf{s} + \mathbf{Wn} = \mathbf{Wn}
\]  

4. Amongst all unbiased estimates, it minimizes $\langle ||\mathbf{e}||^2 \rangle$

A quirk of eq. (4.33) is that the covariance $\langle \mathbf{e}\mathbf{e}^T \rangle$ appears in the equation itself.

\[
\langle \mathbf{e}\mathbf{e}^T \rangle = (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A})^{-1}
\]  

This is referred to as the pixel-pixel noise covariance (as opposed to $\mathbf{N}$, which is the sample-sample or time-time covariance).

**Linear Model Extensions**

None of the discussion in section 4.3.2 depends on the particular choice of linear model in section 4.3.1. For any choice of $\mathbf{A}$ and $\mathbf{s}$, coupling some signal linearly into the data,
an estimate $\hat{s}$ can in principle be found. One example is to replace pixels on the sky with Fourier modes or eigenmodes [69]. A common choice, destriping [70, 71, 72], includes baseline offsets to model slowly drifting noise. Other contaminants, such as azimuth-fixed ground pickup or general timestream templates, can also be fit and removed by including them in the linear model [73].

4.3.3 Naive Map Making

If the noise is uniform and white, then $N = I$ and eq. (4.33) reduces\(^2\) to:

$$\hat{s} = (A^T A)^{-1} A^T d$$

(4.38)

In practice, bolometers do not produce white noise, but have a $1/f$ spectrum (section 6.2.2). This means that the data is drifting slowly, which results in stripes in the naive map. The simplest solution is to high-pass filter the data, with a filter $F$:

$$\hat{s} = (A^T A)^{-1} A^T F d$$

(4.39)

Of course, by removing slowly-varying data, both noise and signal are discarded. Also, eq. (4.39) is no longer unbiased. Equation (4.39) is still useful though, because the sparseness of $A$ allows it to be greatly simplified.

According to eq. (4.31), non-zero entries in each row of $A$ occur in a set of three, and only in a location corresponding to a single pixel. Therefore, $A^T A$ will be block-diagonal,

\(^2\) If the noise is white but non-uniform, then $N$ will still be diagonal, and the sums in eq. (4.40) and eq. (4.41) can be replaced with sums weighted by the variance of each sample.
with a $3 \times 3$ block for each pixel of the map:

$$
(A^T A)_p = \begin{pmatrix}
\sum_{it \in p} 1 & \sum_{it \in p} \cos(2\psi_{it}) & \sum_{it \in p} \sin(2\psi_{it}) \\
\sum_{it \in p} \cos(2\psi_{it}) & \sum_{it \in p} \cos^2(2\psi_{it}) & \sum_{it \in p} \cos(2\psi_{it}) \sin(2\psi_{it}) \\
\sum_{it \in p} \sin(2\psi_{it}) & \sum_{it \in p} \cos(2\psi_{it}) \sin(2\psi_{it}) & \sum_{it \in p} \sin^2(2\psi_{it})
\end{pmatrix}
$$

(4.40)

where $\sum_{it \in p} \equiv \sum_{it} \delta(x_{it} - x_p)$ denotes summing over samples with pointing in pixel $p$. This matrix is singular for a fixed polarization angle $\psi_{it}$, because a single angle does not provide enough information to reconstruct the Stokes parameters. Sky rotation, half-wave plate rotation, or differently-aligned bolometers are required so that the sums include a variety of angles.

To solve eq. (4.38) block-by-block now just requires an expression for $A^T d$ in each pixel:

$$
(A^T d)_p = \begin{pmatrix}
\sum_{it \in p} d_{it} \\
\sum_{it \in p} \cos(2\gamma_{it}) d_{it} \\
\sum_{it \in p} \sin(2\gamma_{it}) d_{it}
\end{pmatrix}
$$

(4.41)

With sufficient memory to accumulate 8 sums per map pixel, eqs. (4.40) and (4.41) can be evaluated for all pixels with one pass through the data. Afterwards, the Stokes parameters in each pixel can be found by solving a $3 \times 3$ equation:

$$
\hat{s}_p = \begin{pmatrix}
\hat{I}_p \\
\hat{Q}_p \\
\hat{U}_p
\end{pmatrix} = (A^T A)_p^{-1}(A^T d)_p
$$

(4.42)

Solving eqs. (4.40) to (4.42) is substantially faster and simpler than attempting to solve eq. (4.33). This is useful for calibrations and generating quick-look maps. BLAST-Pol implements this in a program, naivepol, which uses a high-pass filter to whiten its data. naivepol generates its pointing matrix according to eq. (4.27) so that it can
correct for instrumental polarization.

4.3.4 Generalized Least Squares (GLS) Noise Model

For real bolometer data sets, noise is highly correlated. The $\frac{1}{f}$ spectrum correlates samples over time within a single detector, and as shown in section 6.2.4 is also highly correlated between detectors. The primary challenge of solving eq. (4.33) for the GLS map is finding and evaluating the time domain noise weights $N^{-1}$.

For a 5h observation using a single BLASTPol detector sampled at 100 Hz, the noise vector is $n = 1.8 \times 10^6$ samples long. The full $N$ matrix requires storage of $n^2 = 3.24 \times 10^{12}$ elements, and inversion has asymptotic computational complexity of $O(n^3)$. Direct inversion is intractable, so several approximations are made to simplify the problem.

1. The noise is stationary, so that the noise covariance between samples at times $t_1$ and $t_2$ depends only on their separation $C(t_1, t_2) = C(|t_1 - t_2|)$. Then $N$ is a symmetric Toeplitz matrix. Only one row of $n$ elements need to be stored, and $O(n^2)$ algorithms exist to invert it.

2. The noise is stationary and periodic, which makes $N$ a circulant matrix. Then it can be diagonalized by the unitary discrete Fourier transform operator $F$ [74]:

$$N = F^\dagger PF$$

(4.43)

Where the diagonal matrix $P$ has elements $P_{\omega \omega} = P(\omega)$, the Power Spectral Density (PSD) of the noise. Then, the inverse will act on a vector $v$ as:

$$N^{-1}v = F^\dagger (P^{-1}F(v))$$

(4.44)

First $v$ is Fourier transformed, then multiplied by the inverse power spectrum, and
then the inverse Fourier transform yields the result. Using Fast Fourier Transform (FFT) methods, this can be evaluated with $O(n \log(n))$ complexity, and requires storing the $n$ elements of the power spectrum $P(\omega)$.

3. The correlations have limited extent. Often, this is used to assume that separate observation periods are uncorrelated, making $\mathbf{N}$ block-diagonal, with one block per period. This is good approximation when observations are separated in time, and poorer for consecutive observations. For long observations, further limits on correlations are sometimes assumed within an observation block. This makes each diagonal block of $\mathbf{N}$ band-diagonal. In the MADCap approximation \[75\] \[76\], blocks of $\mathbf{N}^{-1}$ are also assumed to be band-diagonal.

4. That different detectors are uncorrelated. While handling full detector correlations in each observation period is sometimes doable \[77\], it is not always practical. The number of correlations scales with number of detectors as $N_{\text{det}}^2$, which is prohibitive for experiments with many detectors. For BLASTPol, section \[6.3.4\] shows that neglecting correlations between detectors is okay. For ground-based instruments, where the atmosphere is a significant correlated foreground, template removal can be used instead of a fully-correlated noise model \[78\]. More optimally, the power from correlated mode templates can be down-weighted by the noise model \[73\].

4.3.5 Iterative Map Making

Except with low resolution or small maps, eq. \[4.33\] cannot be solved directly. The matrix inversion requires $O(N_{\text{pix}}^2)$ memory and $O(N_{\text{pix}}^3)$ time, which rapidly becomes intractable. Instead, the problem is recast as:

$$ (\mathbf{A}^T \mathbf{N}^{-1} \mathbf{A}) \hat{\mathbf{s}} = \mathbf{A}^T \mathbf{N}^{-1} \mathbf{d} $$ (4.45)
This is a simple linear equation \( Mx = b \), where:

\[
M = (A^T N^{-1} A) \quad x = \hat{s} \quad b = A^T N^{-1} d \tag{4.46}
\]

Iterative methods are especially useful in solving this system, because \( M \) never needs to be explicitly constructed. Instead, only its action on a vector is required:

\[
Mv = A^T N^{-1} Av \tag{4.47}
\]

Exploiting the sparseness of \( A \), this is straightforward to evaluate from right to left: project the map-like vector \( v \) into a data vector, apply the noise weighting as per section 4.3.4 and then re-bin into a map.

For the map-making problem, \( M \) is a symmetric positive-definite matrix, for which the Preconditioned Conjugate Gradient (PCG) method provides a very efficient solution. This choice is common amongst CMB map makers [76, 73]. Other methods like Jacobi iteration [66] or complementary filtering [48] have also been used.

### 4.3.6 Preconditioned Conjugate Gradient Method

The PCG algorithm (described very well in [79]), starts with a quadratic form:

\[
f(x) = \frac{1}{2} x^T M x - b^T x + c \tag{4.48}
\]

If \( M \) is symmetric, then the gradient of \( f \) is:

\[
f'(x) = Mx - b \tag{4.49}
\]

Therefore, \( f \) has a critical point at the solution to \( Mx = b \). If \( M \) is positive definite, then the critical point is a minimum and the linear system can be solved by minimizing
The minimization proceeds iteratively through a set of solutions \( \mathbf{x}(i) \). At each solution, the error is \( \mathbf{e}(i) = \mathbf{x}(i) - \mathbf{x} \). The error can’t be calculated without knowing \( \mathbf{x} \), so the residual is used:

\[
\mathbf{r}(i) = \mathbf{b} - \mathbf{M}\mathbf{x}(i) = -f'(\mathbf{x}(i)) = -\mathbf{M}\mathbf{e}(i) \tag{4.50}
\]

From the current solution \( \mathbf{x}(i) \), a direction \( \mathbf{d}(i) \) is searched, so the next solution lies along the line:

\[
\mathbf{x}(i+1) = \mathbf{x}(i) + \alpha(i)\mathbf{d}(i) \tag{4.51}
\]

The parameter \( \alpha(i) \) is chosen to minimize \( f \) at \( \mathbf{x}(i+1) \).

\[
\frac{d}{d\alpha(i)} f(\mathbf{x}(i+1)) = f'(\mathbf{x}(i+1))^T\frac{d}{d\alpha(i)} \mathbf{x}(i+1) = -\mathbf{r}^T(i+1)\mathbf{d}(i) \tag{4.52}
\]

The minimum occurs where the new residual is orthogonal to the search direction. Or, where:

\[
\alpha(i) = \frac{\mathbf{r}^T(i)\mathbf{d}(i)}{\mathbf{d}^T(i)\mathbf{M}\mathbf{d}(i)} \tag{4.53}
\]

A natural choice for the search directions is along the residual (opposite the gradient), in the direction descending most rapidly towards the minimum. However, this choice (the "steepest-descent" method) will search along the same direction multiple times. A more efficient solution would search each direction only once. For a basis of orthogonal search directions, this cannot be done without already knowing \( \mathbf{x} \). Instead, the search directions are taken to be conjugate (with respect to \( \mathbf{M} \)), so that \( \mathbf{d}(i)\mathbf{M}\mathbf{d}(j) = 0 \) for \( i \neq j \).

The wonderful property of this Conjugate Gradient (CG) method is that \( \mathbf{r}(i+1) \) is conjugate to all previous directions except \( \mathbf{d}(i) \). Ensuring conjugacy of the next direction requires projecting out just the previous direction:

\[
\mathbf{d}(i+1) = \mathbf{r}(i+1) + \beta(i+1)\mathbf{d}(i) \tag{4.54}
\]
If $\beta_{(i+1)}$ is chosen so that $d_{(i+1)}^T M d_{(i)} = 0$ then:

$$\beta_{(i+1)} = \frac{-r_{(i+1)}^T M d_{(i)}}{d_{(i)}^T M d_{(i)}} \quad (4.55)$$

Equations (4.51) and (4.53) to (4.55) form the basis of the CG method, though the final expressions are further simplified to reduce computational complexity. For an $n \times n$ matrix $M$, the method will converge in $n$ iterations. In practice, many fewer iterations are required to closely approximate the solution, and the CG method is often used where $n$ is too large for an exact solution.

If $M$ is poorly conditioned, many iterations may still be required. In this case, another symmetric positive definite matrix $P$ is used as a preconditioner. The PCG method results from applying the CG method to a modified linear system that includes the preconditioner (see [79] for details) The PCG algorithm is described in table 4.1.

The preconditioner should be chosen carefully, as a poor choice will make PCG slower than CG alone. $P$ should be easily invertible and approximately equal to $M$ so that $P^{-1}M$ is well-conditioned. This reduces the number of iterations at the expense of one multiplication of a vector by $P^{-1}$ per iteration. Like $M$, $P^{-1}$ can be implicitly defined by this product. For map making, a common choice of preconditioner is the block-diagonal naive pixel-pixel covariance, eq. (4.40).
\[ r = b - Mx_0 \]
\[ d = P^{-1}r \]
\[ \delta_{new} = \delta_0 = r^T d \]

Repeat until \( \delta_{new} < \epsilon^2 \delta_0 \):

\[ q = Md \]
\[ \alpha = \frac{\delta}{d^Tq} \]
\[ x = x + \alpha d \]
\[ r = r - \alpha q \]
\[ s = P^{-1}r \]
\[ \delta_{old} = \delta_{new} \]
\[ \beta = \frac{\delta_{new}}{\delta_{old}} \]
\[ d = s + \beta d \]

Table 4.1: Algorithm for the PCG method (reduces to CG if \( P = I \)). Computation time is dominated by the matrix-vector product \( q = Md \). The end condition is set either by a threshold \( \epsilon \) on improvement of the residual, or by a maximum number of iterations.
Chapter 5

BLASTPol 2012 Data Analysis

The deceiving term *data reduction* is often used to describe this process. Maps of the sky, as an end result of this process, are indeed a significant compression of the experiment’s dataset, but getting there requires *data distillation* and information extraction. Before final maps can be made, significant cleaning and calibration is required for both the detector and pointing data. This work is uncelebrated but critical.

While the broad goals are shared by all bolometric experiments, the specific requirements and methods vary. BLASTPol’s 2012 data reduction pipeline, detailed in the following sections, has the following general steps:

1. Pre-flight calibration
2. Merge and annotate flight computer datasets
3. Solve for telescope pointing
4. Clean detector timestreams
5. Calibrate detector gains
6. Adjust pointing offsets and drifts
7. Characterize telescope non-idealities
8. Make final maps
5.1 Pre-Flight Calibrations

Before flight, the instrument is thoroughly tested and calibrated.

The frequency response (bandpass) of each detector is measured using a Martin-Puplett Fourer Transform Spectrometer (FTS). The BLASTPol FTS attaches to the cryostat input window, and contains optics to fully illuminate all of the detectors. The full end-to-end transmission of the optics (except primary and secondary mirrors) are included in this measurement, including Infrared (IR)-blockers, optical low-pass edge filters, the HWP, beam splitters, polarizing grids, feed horns, and the responsivity of the bolometers. Spectra are shown in fig. 2.3.

Beam maps are made with a chopped 77 K (liquid nitrogen) source mounted on an XY-translation stage. The telescope is fixed, and the XY-stage raster scans the source through the field of view. At 150 m distance, this source is not in the far field, so spacer blocks must be installed to focus the telescope, and the atmosphere is a significant foreground. Given these systematics, the pre-flight beam maps are treated more as a system check than a calibration. Much better results are obtained using observations of a point source in flight (see section 5.7.1).

While mapping beams, an optical reference is placed near the XY-stage, to align the star cameras with the telescope boresight. This measurement is also improved in post-flight analysis (section 5.5), but the pre-flight calibration is needed for accurate in-flight targeting.

5.1.1 Polarization Calibrations

The parameters of the BLASTPol receiver’s data model in eq. (4.27) must be determined: the polarization efficiency; IP; and a reference HWP angle $\theta_0$. These measurements use an unpolarized chopped thermal source described in [81]. Like the FTS, this chopper sits in front of the cryostat window, and is large enough to uniformly illuminate all of the
### Table 5.1: Mean values of polarization calibrations at each waveband.

<table>
<thead>
<tr>
<th>Waveband</th>
<th>IP (%)</th>
<th>Pol. Eff. (%)</th>
<th>( \theta_0 ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 µm</td>
<td>1.5</td>
<td>85.4</td>
<td>15.2</td>
</tr>
<tr>
<td>350 µm</td>
<td>1.1</td>
<td>77.0</td>
<td>10.8</td>
</tr>
<tr>
<td>500 µm</td>
<td>1.0</td>
<td>80.3</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Polarization efficiency is measured using the chopper with a polarizing grid to make the input signal purely polarized. The ratio of minimum to maximum response versus angle gives the polarization efficiency via eqs. (4.22) and (4.23), and the phase of the modulation determines the offset angle \( \theta_0 \). Any offset in the grid angle \( \chi \) is degenerate with \( \theta_0 \), so it is taken to be exactly \( \chi = 0^\circ \) for H bolometers, and \( \chi = 90^\circ \) for V bolometers.

IP is found by using the chopper without a polarizing grid, so that \( Q = U = 0 \). Then, the results are found by comparing signal amplitudes at different HWP angles (\( \theta \)):

\[
q_{ip} = \pm \frac{d(\theta = 0^\circ) - d(\theta = 45^\circ)}{d(\theta = 0^\circ) + d(\theta = 45^\circ)} \quad u_{ip} = \pm \frac{d(\theta = 22.5^\circ) - d(\theta = 67.5^\circ)}{d(\theta = 22.5^\circ) + d(\theta = 67.5^\circ)}
\]

The + sign here corresponds to H bolometers, and − to V, and the parameters \( e \) and \( \epsilon \) vanish to first order.

IP can also be measured using in-flight data, and by leveraging sky rotation can include the effects of optical elements skyward of the HWP (see section 5.7.2). Polarization angle and amplitude can be checked at 500 µm by comparing to previous observations (section 6.3.3). The results are consistent, so the pre-flight calibrations are used.

## 5.2 Merging Datasets and Defining Chunks

Data from both of BLASTPol’s two redundant flight computers must be merged into a unified dataset. After spot-checking that the data agrees between computers, the merge simply selects data from the in-charge computer. The in-charge computer changed once,
about 32 h into the flight, from north to south. During the change, there is a brief period with no data.

Next, the unified dataset is logically divided into chunks. Chunks of data contain a full observation of a target at one HWP position. With BLASTPol’s scan strategy (section 2.3), chunks are typically 15 min in duration and grouped into sets of four, covering each HWP position. Chunks define the noise-stationary block size used for map making (section 4.3.4).

The initial division into chunks is based on notes taken during the flight. This is further refined using flight logs and the data streams. An overview of the observation targets is in table 2.2.

5.3 Pointing Solution

The post-flight pointing solution is based entirely on the fiber-optic gyrosopes and star cameras (details in [45 82]). The star cameras provide a low-rate absolute attitude reference, while the gyroscopes provide high-rate angular velocity data between star camera solutions.

First, the orientation of the gyroscopes relative to the star cameras is fit using data from long slews. The rotation is chosen to minimize error between integrated gyroscopes and star camera solutions at each end of the slew.

In between star camera solutions, the pointing is integrated using a modified Kalman filter [83]. To reduce discontinuities, this is run forwards and backwards in time, and the final solution is the error-weighted average.

Improved pointing from the Kalman filter allows better star identification. Starting with the in-flight solutions, which required at least three stars, this procedure is iterated to find more solutions—including some with just a single star. Figure 5.1 (from [45]) shows Kalman filtering between two star camera solutions. The final residual between
Figure 5.1: Kalman filtered pointing between star camera solutions. The integrated gyroscopes diverge between solutions. Combining forward and backward evolution improves error and limits discontinuities.

Kalman filter and star cameras has an rms of about 3″.

5.4 Detector Cleaning

The map making process assumes, as in eq. (4.32), that the detector timestreams contain only the desired astrophysical signal and Gaussian noise. Unfortunately, the detectors are sensitive to many other things, which must be removed. This includes spikes, radio pickup, thermal changes, and the detector’s transfer function. Figure 5.2 illustrates the effects of the processing stages.

5.4.1 Despiking

The raw detector timestreams are contaminated by many spikes. These features are too large and too brief to be consistent with optical signals from the telescope. Once identified, data around the feature is flagged for removal from further analysis.
Figure 5.2: The effects of BLASTPol’s timestream processing, showing about 1 h of data. 
Top: raw data. Shows level shifts from HWP moves, cosmic ray spikes, and periodic 
calibrator pulses at the end of each chunk. Middle: despiked and deconvolved data. 
Level shifts and long-timescale drifts remain. Elevation-correlated features are visible 
as the cusp in the middle of each chunk. Bottom: fully preprocessed data, containing 
primarily noise and celestial signal. The peaks that remain are scans over the bright 
source RCW 36.
To identify cosmic ray hits, the timestreams are high-pass filtered to remove all signal from the telescope, and the remaining high signal-to-noise features ($> 5\sigma$) are identified as cosmic rays. When a spike is seen by many bolometers in an array, those samples are flagged for the entire array.

The despiking code, adapted from BLAST06, also contains checks for aphysical single-sample data glitches. None were identified for BLASTPol12, possibly because of improvements to the BLASTbus architecture.

Calibration source pulses (section 5.6) and half-wave plate moves also cause short disruptions to the data. Records are kept of when these events occur and they are flagged just like cosmic rays. Half-wave plate moves typically occur in between scans, and can be left out of the data chunks entirely.

### 5.4.2 Deconvolution

As described in section 3.6, the detector data is band-pass filtered in the preamplifier and anti-aliasing filtered in the DAS. The combined transfer function of this filtering is deconvolved to restore high frequency information. To prevent excess high-frequency noise, a new low-pass filter with unity gain up to 30 Hz is applied. Scanning at $0.1^\circ\text{s}^{-1}$, 30 Hz corresponds to a scale of 12 arcsec, smaller than any signal. Figure 5.3 shows how deconvolution affects the spectrum of the detector signals.

The deconvolution uses FFT methods, so the gaps around flagged spikes must be filled with representative data to prevent ringing. These short gaps are filled with white noise plus a line joining the gap endpoints.

### 5.4.3 TDRSS Pickup

Early in the BLASTPol12 flight, the TDRSS High Gain Antenna (HGA) was found to cause significant features in the timestream, as shown in fig. 5.4. This was not detected before flight, as BLASTPol has much higher noise on the ground. The pickup from the
Figure 5.3: Amplitude spectral densities for the timestreams shown in fig. 5.2. **Top:** raw data. Spikes, shifts, and drifts create significant low-frequency power and ringing. The drop at high frequencies is due to the timestream filters. **Middle:** despiked and deconvolved data. High frequency signal is restored by deconvolving the detector transfer function. **Bottom:** fully preprocessed data. Excess low-frequency power has been removed. The low-frequency spikes are at the azimuth scanning frequency and its harmonics.
Figure 5.4: Radio pickup features associated with the TDRSS HGA. The pickup is over twice as large as the signal from the bright source RCW 36 (fig. 5.2). Smaller step-like noise features are also present. The short spike is a cosmic ray hit.

HGA is largest when it is aimed towards the inner frame baffle (section 2.2), suggesting that the coupling is through the telescope. Because the baffle was not covered until the Antarctic deployment, it is unlikely that the configuration maximizing pickup was encountered before launch.

The omnidirectional TDRSS transmitter was also found to cause low-level radio noise. Both transmitters were disabled for the remainder of the flight, except occasionally when high bandwidth downlink was required. The TDRSS transmitters operate at 2287.5 MHz and the omnidirectional antenna has a peak Equivalent Isotropically Radiated Power (EIRP) of 9 dBW. With its narrower directed beam, the HGA is about 20 dB more powerful.

Using a CSBF log of when the transmitters were on, this data is completely flagged as bad. Because TDRSS signal corrupts large amounts of data, simple filling like for spikes is ineffective. Instead, the data chunks are rearranged so that TDRSS signal is not present in any good chunks. The contaminated chunks are discarded completely.
5.4.4 Preprocessing

As a final step before map making, detector timestreams are preprocessed to remove non-Gaussian features and discontinuities. The non-Gaussian features are elevation-correlated cusps, and exponential transients. Assuming that the elevation feature is due to loading from atmospheric column density, a feature proportional to \( \csc(\text{el}) \) is projected out of the timestreams. A two-exponential fit is used to remove transients caused by HWP moves between chunks. The time constants are constrained to be from 10 s to 50 s and 60 s to 600 s. Only the first 30 s of data are fit so that the fast-changing region is matched well.

The residual of these fits is removed by a 5 mHz high-pass filter, below which BLAST-Pol has little useful signal. The filter also removes endpoint discontinuities, which would otherwise disrupt a FFT. The gaps which the deconvolver filled with white noise are now re-filled with a realization of the bolometer noise model (section 6.2). The final result is shown in figs. 5.2 and 5.3.

5.5 Pointing Offsets

The pointing solution (section 5.3) describes where the star camera is pointed during the flight, with a single fixed rotation to roughly align it with the telescope boresight. A simple model is used to relate star camera pointing to the pointing of each detector:

1. Each bolometer has a fixed pointing relative to the telescope boresight. The cryogenically-cooled detector optics box is very rigid and thermally stable. This in turn keeps the relative pointing of each detector very stable.

2. The telescope boresight can drift slowly with respect to the star cameras. This is ascribed to the gondola’s asymmetric and changing thermal environment, which will cause the inner frame to twist.
The bright compact source IRAS 08470-4243 is used to measure pointing offsets. It is observed frequently during the flight, and with sufficient coverage to make complete high-resolution maps for each individual detector. These maps are made in “telescope coordinates”, in which the telescope’s rotation relative to the sky has been removed. The per-detector offsets are measured by fitting a beam model (section 5.7.1) to each detector’s map, and comparing the beam-center positions. The offsets are illustrated in fig. 5.5.

All-detector maps of IRAS 08470-4243 can also be used to track the drift of the telescope boresight pointing. More information is required, though, to fill in the long gaps between these observations. Moreover, for targets at a different azimuth relative to the sun, offsets measured at IRAS 08470-4243 are inaccurate.

To measure the boresight pointing offset for diffuse targets, BLASTPol maps are compared to those from Herschel SPIRE [32]. Using simsky (section 6.1), these maps are reobserved with the BLASTPol scanning strategy and an asymmetric model beam. An offset is calculated that minimizes the residual between the BLASTPol and re-observed Herschel SPIRE maps. This process is repeated for a few iterations until the offset converges. The $350\mu m$ measurement (fig. 5.6) is chosen to represent the boresight pointing. Other wavebands agree within about $10"$.

### 5.6 Detector Gain Adjustment

Due to optical and thermal loading changes over time, the detector responsivity (change in readout voltage per unit of optical power) drifts. To track these changes, a calibrator lamp is pulsed periodically, providing a fixed optical load. Fitting the amplitude of a template pulse gives a measure of responsivity. The calibration source is very similar to the one used by Herschel SPIRE [84] and is designed to be very stable.

To correct responsivity between calibrator pulses, the pulse height is fit against the
Figure 5.5: Bolometer pointing offsets for 250 µm (top), 350 µm (middle), and 500 µm (bottom). The polarizing grid orientations are indicated by the direction of the lines.
Figure 5.6: Drift of boresight pointing relative to star camera, measured at 350 µm. The 'Calibrator' source (IRAS 08470-4243) has its offsets measured by beam fitting, the rest use alignment of diffuse regions compared to Herschel SPIRE. The offsets have a roughly diurnal variation, but also vary from target to target.

detector DC-level. The two are well fit by a line (as shown in fig. 5.7). So for a pulse in optical power $dP = P_0$ there is a voltage pulse $dV$, which varies linearly with the voltage: $dV = V_0(aV + b)$. (Where $a$ and $b$ are the coefficients of the linear fit.) Then, roughly, this can be arranged as a differential equation and integrated to find the input optical power:

$$\frac{dP}{dV} = \frac{P_0}{V_0(aV + b)}$$  \hspace{1cm} (5.2)$$

$$P(V) \propto \log(aV + b)$$  \hspace{1cm} (5.3)$$
Chapter 5. BLASTPol 2012 Data Analysis

Figure 5.7: Calibrator pulse heights versus detector level, used to fit the detector gain model. There is one line of points per bolometer (showing 250 µm). The fits to these lines provide coefficients for the logarithmic gain-correction model eq. (5.2). The slopes differ because the shared bias line does not optimally bias all detectors.

The detectors are insensitive to DC signal, so the integration constant has been discarded. The power delivered to each detector $P_0$ is unknown, so the overall gain must be calibrated separately.

To flat-field the gain between bolometers, individual-bolometer maps are made of the compact source IRAS 08470-4243. Scanned repeatedly as a pointing calibrator (section 5.5), this source is well-sampled by each bolometer. The bolometer gains are adjusted so that they each see the same flux from the source. To ensure that all flux from the asymmetric beam is included (fig. 5.9), the source is integrated within a radius of 150″. A background is subtracted to account for the map offset, integrated over an annulus with radii from 150″ to 180″. Figure 5.8 shows the values of the flat-field gain adjustments across the arrays.

The ultimate tests of the detector gain calibrations in BLASTPol are the map null tests (section 7.2). These exhibit a dipolar leakage pattern more characteristic of beam
Figure 5.8: Flat fielding coefficients for adjusting gain between detectors (relative to central pixel). The $\times$ marks indicate bad detectors, and the $\circ$ marks the first (“A01”) detector in each array.
errors (section 5.7.1) or pointing errors than of gain errors.

5.7 Telescope Non-Idealities

Preliminary maps can be used to characterize the non-idealities of the telescope, for correction in final maps. BLASTPol’s primary non-idealities are an asymmetric beam shape, and slight instrumental polarization (section 4.2.3).

5.7.1 Beam Shape

The beam shape is fit using IRAS 08470-4243, a bright compact source observed to measure pointing offsets (section 5.5). The average shapes at each waveband, shown in fig. 5.9, are obtained by combining all bolometers and all good observations. These are distinctly elongated, with multiple lobes present at 250 µm and 350 µm. The relative amplitudes of the lobes change between detectors, with the upper lobe sometimes brighter. The shape is also observed to vary slightly over time, to a degree that makes detailed modelling difficult but does not significantly degrade the already-contaminated maps. Simulations of the optics including a variety of plausible deformations have not been able to reproduce this structure. These issues are discussed more in [85].

IRAS 08470-4243 is not quite a point source; it is surrounded by diffuse structure and has a power law envelope. However, observations of Saturn confirm all of the beam features. The Saturn data have pointing and coverage problems, so are otherwise not used for analysis.

The fitting procedure is detailed in [85]. At 250 µm and 350 µm beams are fit with three elliptical Gaussians, for the two primary lobes, and a fainter third lobe. At 500 µm, a single elliptical Gaussian is fit. To minimize the effects of sky rotation, beam center is defined as the flux centroid of the all-data maps.

Sky rotation should allow reconstruction of maps with resolution determined by the
Figure 5.9: Average beam shapes from combining all good observations of IRAS 08470-4243. These maps are in “telescope coordinates”, with the rotation of the telescope relative to the sky removed. At 250 µm and 350 µm, the elongated structures are distinctly two-lobed, while at 500 µm only one elongated lobe is present.
Figure 5.10: Polarization in the Stokes $q$-$u$ plane for 250µm detectors observing Vela. Red and green marks indicate polarization measured at high and low parallactic angles. The blue mark indicates the true average polarization of Vela, at the center of rotation.

narrow axis of the beams (section 6.4.1). For early results though, resolution will be downgraded to correspond to the long axis of the beams.

5.7.2 Instrumental Polarization

The IP contributions to the data (eq. (4.27)) respond differently to the sky angle $\alpha$ than the rest of the data. By making separate maps of the source when it is rising and setting, the IP can be measured. BLASTPol’s procedure [81] (based on [86]) plots the polarized flux for each detector in the Stokes $Q$-$U$ plane. At different sky angles $\alpha$, the points will rotate along a circular arc. The center of these circles is the true polarized flux of the source, and the radii are the amplitudes of the IP for each detector. Figure 5.10 shows this rotation for the 250µm detectors.

IP is measured in Vela, the source with by far the most data. Because IP is a property of the optics, it is assumed to be fixed throughout the flight. As a test, the data is divided in half based on observation time, and the IP for the second half of the flight is corrected using data from the first half. The mean residual from this test is close to zero, with deviations below 1%.
Figure 5.11 shows the distribution of $p_{ip} = \sqrt{{q_{ip}}^2 + {u_{ip}}^2}$. 
Figure 5.11: Distribution of IP (%) for all detectors.
Chapter 6

BLASTPol Map Making

6.1 BLASTPol Map Making Software

Several programs are used in the map making process. The most significant are:

- Various preprocessing utilities. Covered in chapter 5.

- `naivemap` and `naivepol` are naive map makers that implement eq. (4.39) for total-intensity and polarized data, respectively. They are fast, and require little data cleaning or characterization before they can produce results.

- `simsky` is the inverse of a map maker. Given telescope pointing data and an input sky map, it evaluates eq. (4.32) to produce detector timestreams. The output can optionally include polarization sensitivity, asymmetric beams, data filtering, instrumental polarization, and noise with various correlations. Except in a few contrived cases, the telescope pointing is chosen to match real in-flight data.

`simsky` can be used to test the map makers with a known input map. It can also reobserve data from other telescopes, typically Herschel SPIRE. More details can be found in [47].
• Time Ordered Astrophysics Scalable Tools (TOAST) [87] is the GLS map maker used to produce final BLASTPol maps. It is a collection of serial and OpenMP/MPI parallel libraries for input and output, map making operations, and on-the-fly simulation. A key design goal, and the reason it was chosen for BLASTPol, is its modularity. This allows it to be easily adapted to different experiments without needing to reimplement much of the complex logic.

TOAST solves for the GLS map (eq. (6.1)) using a highly-parallelized implementation of the PCG algorithm (section 4.3.6). In addition to the GLS map maker, TOAST also includes a destriping map maker based on MADAM [70], and tools for estimating pixel-pixel noise covariance.

6.2 Noise Model

Section 4.3.2 describes how to solve the GLS map, using eq. (4.33) (reproduced here):

$$\hat{s} = (A^T N^{-1} A)^{-1} A^T N^{-1} d$$

The power of this method comes from using the inverse noise covariance $N^{-1}$ to weight modes in the data based on their level of noise contamination. Section 4.3.4 describes how $N^{-1}$ can be approximated as block-diagonal, with blocks corresponding to all data from one detector during one observation interval. The weighting is evaluated in the Fourier domain using the PSD of the noise.

This section describes how the noise PSD model is estimated. Further, the model’s assumptions about stationarity and lack of detector-detector correlations are checked.

---

1 available from: https://github.com/tskisner/TOAST
6.2.1 Initial Estimate

BLASTPol has high signal-to-noise in its timstreams, even for faint targets. Naively estimating the PSD from the timstreams will cause the noise model to include signal modes, down-weighting useful data. Early in the flight, 25 min was spent with the telescope observing a fixed point on the sky, while star cameras were tested. The data from this time are approximately noise-only, with some tiny signal due to the telescope randomly drifting by a few arcminutes.

Using the fully cleaned and calibrated detector data (sections 5.4 and 5.6), PSDs are estimated for each detector during this time. An example is shown in fig. 6.1. Using this measurement for map making requires assuming that the noise is stationary throughout the flight—not just piecewise stationary. Section 6.2.3 shows that this assumption is approximately true.

6.2.2 PSD Parametrization

While the PSD in fig. 6.1 could be used directly by the map maker, it is a noisy estimate and lacks information at low frequencies. Two methods were attempted to resolve this issue: fitting a model; and logarithmic binning plus extrapolation.

The simple model for $\frac{1}{f}$ noise is parametrized by a white noise amplitude $w$, knee frequency $f_{knee}$, and spectral slope $\alpha$ that may differ from unity. The PSD $P(f)$ is given by:

$$P(f) = \frac{w^2 f^{2\alpha} + f_{knee}^{2\alpha}}{f^{2\alpha} + f_{min}^{2\alpha}}$$

(6.2)

A minimum frequency $f_{min}$ is included, below which the spectrum flattens out to a finite value.

The non-linear least-squares fit is performed in a log-log space, due to its wide dynamic range. For most detectors, it works well. The lowest-frequency points are excluded from the fit, since the map maker performs much better without them. This indicates that the
Figure 6.1: Example of noise-dominated data, as used for the initial noise estimate. These data were acquired during a 25 min observation of a fixed point on the sky. Top: Timestream, mostly showing the residual from the preprocessor’s exponential fit (section 5.4.4). Bottom: Amplitude spectral density.
rise seen at the lowest frequencies is an artifact of either this particular dataset, or of the PSD estimation. Histograms of parameter values for all detectors are shown in fig. 6.2.

For a few detectors, slightly elevated noise around 0.1 Hz to 1 Hz results in a bad fit to the model. To improve these cases, a logarithmically-binned spectrum is used instead. For low frequencies, a power law is fit to data below $f_{\text{knee}}$ to extrapolate the $\frac{1}{f}$ noise. This extrapolation is truncated at minimum frequency $f_{\text{min}}$, like the noise fit.

For most detectors, where the model fits well, the log-binned spectrum agrees. For imperfect cases, the log-binned spectrum is more robust and includes features not accounted for by the simple model. Figure 6.3 shows a typical example of both PSD parameterizations. Choice of parametrization does not significantly affect the final maps.

**Noise-weight floor**

BLAST’s *almagest* map maker used a floor of $10^{-5}$ in the relative noise weight at low frequencies. This improved large-scale convergence in maps at the expense of suboptimal noise weighting [48]. A similar effect can be achieved using the $f_{\text{min}}$ parameter of the BLASTPol noise parametrization, by truncating $\frac{1}{f}$ noise in the PSD.

For BLASTPol, the preprocessor explicitly whitens the noise below about 5 mHz, as needed to avoid discontinuities at the endpoints of its short 15 minute chunks (section 5.4.4). For $f_{\text{min}}$ from 1 mHz to 5 mHz, the PSD has power about $10^5$ times above the white noise, resulting in a very similar weight floor to *almagest*.

### 6.2.3 Noise Stationarity, Improved Estimate

Using the initial noise estimate (sections 6.2.1 and 6.2.2) TOAST produces preliminary maps. From these maps, signal timestreams are estimated with *simsky* and then subtracted from the data. With signal subtracted data, improved noise estimates can be made. For CMB experiments like *SPIDER*, refinement of the noise model is much more important, as an accurate pixel-pixel noise covariance is required. For BLASTPol, only
Figure 6.2: Histograms of the noise model parameters (eq. (6.2)) for all detectors. The blue, green, and red outlines indicate detectors at 250\(\mu\)m, 350\(\mu\)m, and 500\(\mu\)m respectively.
Figure 6.3: The noise model (eq. (6.2)) and logarithmic binning applied to the initial PSD estimate. These data are the same as shown in fig. 6.1. Excluding the lowest-frequency points from the noise model improves map maker convergence. Good agreement between the model and binned spectra is typical of most detectors.

improvement to the convergence of maps matters.

This analysis requires a good estimate of the signal, so must exclude map edges where the noise is too high. Good map data is selected by cutting pixels based on the condition number of their IQU covariance matrix (section 6.3.5). Over regions that fail the cut, the resulting noise timestream is interpolated using a line plus a realization of the initial noise estimate.

For bright sources, a significant signal residual remains, easily seen as increased power at the scan frequency. This is due to uncertainty in the asymmetric beam. So, a relatively faint and diffuse source, Puppis, is chosen for the new noise estimates.

Puppis is observed on three consecutive days early in the flight, for about 4.5 h each day. PSD estimates for each observation are shown in fig. 6.4. Compared to the initial estimate, the long observation times provide access to much lower frequencies. This shows the expected $f_{\text{min}} \approx 1 \text{ mHz}$ flattening of the $\frac{1}{f}$ power caused by the preprocessor.

The similarity from day to day is strong, confirming the noise stationarity assumption.
Figure 6.4: PSD estimates for each day Puppis was observed. There is little variation between days.

When broken down to smaller time periods, the $\frac{1}{f}$ noise becomes more varied, but the variations are not obviously related to elevation, HWP angle, parallactic angle, mirror temperatures, or time. The peak at 3.5 mHz is not at any scanning-related frequency, but is close to the frequency of balloon altitude fluctuations.

Figure 6.5 shows the updated noise parameterization, where the effects of $f_{\text{min}}$ are now visible. Compared to the initial estimate, there is also a higher $f_{\text{knee}}$. This indicates that the atmospheric (or thermal) source of $\frac{1}{f}$ variations is modulated slightly faster by scanning.

### 6.2.4 Correlated Noise Between Detectors

To measure the correlation of noise between detectors, a Principal Component Analysis (PCA) is performed on the same non-scanning data used for the initial noise estimate (section 6.2.1). The method used is to decompose a matrix of concatenated data vectors using Singular Value Decomposition (SVD) [88, chapter 2.6]. SVD allows any $m \times n$
matrix $M$ to be decomposed as:

$$M = USV^T \quad (6.3)$$

Where $U$ is an $m \times m$ unitary matrix, $V$ an $n \times n$ unitary matrix, and $S$ is an $m \times n$ matrix with non-zero entries only on the diagonal. (For $m \gg n$ it is advantageous to use an equivalent expansion with $U$ being $m \times n$, and $S$ and $V$ being both $n \times n$.)

For this analysis, $M$ is a matrix in which each column is the data vector from a different detector. Then each column of $U$ is one of the orthonormal modes into which the data can be decomposed, and each column of $V$ indicates the relative contribution of the modes to each detector. The diagonal entries of $S$ are the singular values, which represent the relative contribution of each mode to the entire dataset.

Figure 6.6 shows the shapes of the noise modes at 250\,\mu m, dominated by the slow drift of the zeroth mode. Figures 6.7 and 6.8 show that the zeroth mode is responsible for most of the $1/f$ noise in the detectors, and that it is strongly correlated across the entire array. Similar results are seen at 350\,\mu m and 500\,\mu m. In fact, an analysis including all
Figure 6.6: The top correlated noise modes at 250 µm, scaled by singular value (the first columns of $US$). The zeroth mode is much larger than the others. Modes 1 and 2 contain slight features, but the remaining modes are primarily white noise.

wavebands is still dominated by a single correlated mode. There are slight anticorrelations between the wavebands, captured by modes 1–3 of an all-waveband PCA.

The noise model used by TOAST does not fully account for the common mode noise component. Each detector includes the increased $\frac{1}{7}$ noise amplitude of the common mode, but assumes it is uncorrelated between detectors. Because it is not used for map making, an improved model of correlations is not necessary. This analysis is not repeated for signal-subtracted data taken with the telescope scanning (section 6.2.3). For noise simulations (section 6.3.5), a hybrid model is used: detector correlation coefficients are estimated from this analysis of non-scanning data, while the knee frequencies are taken from the improved model using scanning data. These simulations and a comparison of other map makers (section 6.3.4) demonstrate that for well cross-linked maps it is not a problem for TOAST to neglect correlations between detectors.
Figure 6.7: PSD estimates as the top correlated noise modes are removed from an example 250 µm detector. Removing the zeroth mode removes much of the $\frac{1}{f}$ noise.

6.3 TOAST Characterization

6.3.1 Transfer Function

The most basic test of TOAST is whether it can produce the correct output, given a known input. Two input cases are simulated: a map in which $I$, $Q$, and $U$ contain spatial white noise; and a map containing point sources, some of which are 100% polarized. Both input maps are smoothed with an ideal 40″ FWHM Gaussian beam. The maps use the Vela pointing because it is the largest map and has good cross-linking due to its extended reference region.

Signal-only timestreams are simulated here, as linearity of the map making operation means noise timestreams do not contribute to the transfer function (just the noise model $N$). Section 6.3.5 deals with noise-only maps, and maps made from real data can be considered a sum of signal-only and noise-only maps.

Figure 6.9 shows that the TOAST output looks like the input. The difference between the maps is quantified by the transfer function: the ratio of the Fourier transforms of...
Figure 6.8: Coefficients of the top correlated modes for each detector (the first columns of $V$). Mode 0 is strongly correlated across the array. Mode 1 is anticorrelated with mode 0, dominated by a subset of detectors that have slightly different structure. These detectors are not related in any obvious optical or electrical manner.
the output to input maps. Figure 6.10 compares TOAST’s flat transfer function to naivepol’s, which is not flat. The naive transfer has an x-shaped trough feature from failing to reconstruct structures perpendicular to the scan directions.

Another difference between TOAST and naivepol is visible in the point source simulation, fig. 6.11. In the naive map, shadows are produced around bright sources, along the scan direction. TOAST also produces shadows, though they are shallower due to its weaker filtering and better use of cross-linking. Even for the naive map, shadowing is less severe for Q and U, than for I. The transfer function for the point source simulation looks similar to the spatial noise map.

The point source simulation also shows leakage into polarization around bright unpolarized sources. This is due to BLASTPol’s sampling polarization using H and V bolometers that are pointed differently. When the angle coverage within a pixel is nonuniform, there is leakage proportional to the gradient of signal over that pixel.

### 6.3.2 Comparison to Planck

A great way to check both the map maker and the BLASTPol data is to compare to other datasets. Planck’s HFI [20] has full-sky maps at 545 GHz (550 µm) and 857 GHz (350 µm) [89]. These maps have 5 arcminute resolution, no polarization, and very good control of large-scale structure. Figure 6.12 shows that they agree well where BLASTPol has good cross-linking. Outside this region, large-scale modes become unconstrained, and a faint haze is visible in the BLASTPol map.

A more detailed comparison to Planck can be used to set the zero-level of the BLASTPol maps (section 7.1.2).

### 6.3.3 Polarization Angle Comparison with SPARO

To check polarization, and especially the angle calibration, the Carina Nebula was observed. This Giant Molecular Cloud (GMC) was also observed by Submillimeter Po-
Figure 6.9: Sample of input map compared to TOAST output. Colour scale is arbitrary, and axis scales are in arcminutes.
Figure 6.10: Two-dimensional transfer functions for naivepol and TOAST. naivepol fails to reconstruct structures across the scan directions, resulting in the dark x-shaped feature. Both diverge at beam scales $|k| > 1.5 \text{arcmin}^{-1}$.
Figure 6.11: A comparison between TOAST and naivepol maps for a point-source simulation. Shadowing around point sources is caused by naivepol’s high-pass filter. Because of filtering in the preprocessor, TOAST also shows some shadows. Unpolarized sources leak into polarization, due to pixelization effects. Maps use the same percentile colour scale limits.
Figure 6.12: BLASTPol 350 $\mu$m (top) and Planck 857 GHz (bottom) maps of Vela. The region indicated in the BLASTPol map is where cross-linking is good. Colour scale set to show faint structure.
Figure 6.13: Locations of SPARO measurements (green) and their corresponding reference regions of the three-point chop (red). The circle size shows SPARO’s 4' FWHM beam. The background is BLASTPol’s 500 µm I map.

A SPARO-like view of the sky is made by smoothing the BLASTPol map to SPARO’s 4' FWHM beam size. To replicate the three-point chop, each I, Q, and U measurement have the average value from its two reference regions subtracted. This method compares the SPARO result to the BLASTPol map independently from any offset in the map (see section 7.1.1). The referenced Stokes parameters are converted into polarization pseudo-vectors as per section 7.1. Figure 6.14 shows a map of the polarization pseudo-vectors, similar to fig. 1 from [50].

Figure 6.15 compares the angles and polarization fractions measured by each experiment.

---

2Table 2 from [50] contains a transcription error for the 7 pseudo-vectors in the upper left of fig. 6.14. These results are inferred from fig. 1 from [50], and excluded from comparisons here.
Figure 6.14: Recreation of fig. 1 from [50] comparing the SPARO pseudo-vectors (red) to those inferred from the BLASTPol map (blue). The background is BLASTPol’s 500 μm I map.

The angle agrees very well, with a mean offset of 1°. This validates the pre-flight angle calibration, and no further correction is applied.

BLASTPol sees a systematically higher polarization fraction, with a mean increase of 50%. This discrepancy is not understood. The difference could be physical, due to different observing bands. Or it could be due to systematic errors that were not accounted for—such as SPARO’s pointing. SPARO has only published fractional polarization, so can’t tell whether BLASTPol observes higher polarized flux or lower unpolarized flux. That the SPARO reference regions lie roughly along the BLASTPol scan direction suggests that large-scale offsets in the map would not cause this problem.

If the discrepancy in polarization fraction is not resolved, there is no reason to believe SPARO over BLASTPol. The discrepancy is also largely consistent with a fixed gain mismatch. Such an error would not change the conclusions of any of the science analyses in chapter 8.
Figure 6.15: Comparison of polarization angle (top) and fraction (bottom) between SPARO and BLASTPol. The angles agree, with a mean offset of $1^\circ$. BLASTPol’s polarization fraction is systematically higher.
6.3.4 Effects of Detector Correlated Noise

For total-intensity BLAST data, the Signal and Noise Estimation Procedure Including Correlations (SANEPIC) [77] map maker implemented a noise model including noise correlations between detectors. When the map is scanned along only a single direction, this greatly reduces striping on the scale of the Field of View (FOV). However, when regions of the map are observed at multiple angles, the information from perpendicular scans also removes these stripes. BLASTPol’s observation schedule was chosen such that targets were observed both rising and setting, so that this cross-linked information would always be available.

For polarization data, accounting for detector correlations should be even less significant. Section 6.2.4 shows that the primary correlated mode is a common mode across the array. Therefore, because polarization measurements require differencing detectors, any common mode will already be removed in the process.

Section 6.3.5 demonstrates that noise-only maps remain stripe-free with uncorrelated pixels, even when detector correlations are not accounted for.

6.3.5 Calibrating the Covariance Estimate

In addition to the values $I_p, Q_p, U_p$ for each pixel $p$ in the map, TOAST produces an estimate of the covariance (denoted as $\sigma$) in each map pixel:

$$
\Sigma_p = \begin{pmatrix}
\sigma(I_p, I_p) & \sigma(I_p, Q_p) & \sigma(I_p, U_p) \\
\sigma(I_p, Q_p) & \sigma(Q_p, Q_p) & \sigma(Q_p, U_p) \\
\sigma(I_p, U_p) & \sigma(Q_p, U_p) & \sigma(U_p, U_p)
\end{pmatrix}
$$

These matrices are diagonal blocks from the full pixel-pixel covariance (eq. (4.37)), but evaluated using only the diagonal elements of $N^{-1}$. This approximation allows efficient calculation, like a naive map (eq. (4.40)) except with the sums weighted by the
diagonal elements of $N^{-1}$. In addition to this approximation on $N^{-1}$, approximations on $N$ (section 4.3.4) still apply too.

To test the effect of these assumptions, the covariance estimate is compared to two realizations of a noise-only map. The first is a simulation with noise-only timestreams, using the white noise levels, knee frequencies, and the mean spectral slope from section 6.2.2. Noise correlations between detectors are added with the common-mode correlation amplitudes from section 6.2.4. The second noise-only map is generated with real data from the left–right array-half null test (section 7.2.3). Both cases use the Vela map.

These noise maps should be a realization of the covariance ($\Sigma$). Because the covariance matrix is symmetric and positive definite, it can be Cholesky decomposed as $\Sigma = LL^T$. Then, for a uniform uncorrelated map vector $u$ with $\langle uu^T \rangle = I$, a noise realization will be $n = Lu$. By inverting to $u = L^{-1}n$, testing whether $n$ is a realization of $\Sigma$ is equivalent to testing whether $u$ is uniform and uncorrelated.

An example map of $\sigma^2(I)$ is in fig. 6.16, which shows different variance levels for the Vela map’s deep and reference regions. $\sigma^2(Q)$ and $\sigma^2(U)$ look similar, but with double the variance. The off-diagonal covariance terms have zero-mean, and similar deep/shallow amplitude distributions. The amplitudes of the covariances are much smaller than variances, so $\Sigma$ is treated as diagonal for the rest of this analysis.

In that case, the normalized noise for pixel $p$ and Stokes component $X = I, Q, U$ is:

$$u_{px} = \frac{n_{px}}{\sqrt{\sigma_p^2(X)}} \quad (6.5)$$

The distributions of the normalized noise for the simulated data and the null test map are shown in figs. 6.17 and 6.18. The simulated data is statistically Gaussian and different pixels are uncorrelated. Rather than being 1, the width slightly exceeds $\frac{1}{\sqrt{2}}$, though the factor of 2 is simply due to discrepant definitions of variance between codes. The slight excess in noise is attributed to the detector correlations.
Figure 6.16: Map of the logarithm of the $\sigma^2(I)$ variance for Vela at 350\,$\mu$m. Shows the deep main region and shallower reference region.

The null test map (masked around the source RCW 36 where the test fails), is nearly Gaussian—differing slightly but with high statistical significance. Its width is greater than the simulation, as it includes more uncorrected systematics. The $I$ width is greater the $Q$ or $U$ widths, due to a more significant null test failure in $I$. The null test variance has been corrected by an extra factor of 2 from map differencing.

The conclusion of this analysis is that TOAST’s covariance estimate $\Sigma$ is a good model for the true covariance of the map, to within a constant calibration factor. To account for as many real systematics as possible, this factor is taken to be 0.7348, the mean square of the $Q$ and $U$ widths in the null test.

### 6.3.6 Computational Performance

TOAST is being run on the SciNet General Purpose Cluster (GPC) at the University of Toronto.
Computation time is dominated by the PCG iterations, and within each iteration about 70% of the time is spent applying the noise model $N^{-1}$. Maps typically converge in 50–100 iterations, where the threshold for convergence is $\epsilon = 10^{-6}$ ($\delta_{\text{new}} < 10^{-12}$, see table 4.1). The final map does not change significantly after about $\delta_{\text{new}} < 10^{-6}$.

To fully cache the data and pointing matrix requires 23.8 MB or memory per detector-hour, spread between supercomputer nodes. In addition to the data, preconditioner and covariance information are cached. This is much smaller than the data, but not as easily shared, so the memory usage scales with the number of nodes, typically around 1 GB.
to 3 GB per node. For the Vela 250 µm map, this requires about 166.5 GB for data and 184.3 GB for covariance on 64 nodes (5.5 GB total per node).

The total computation time is around 250 ms shared between nodes, per detector-hour of data, per iteration. This remains true for both large and small maps, with about 50 times different dataset sizes, indicating that the algorithm is parallelized well. When the number of nodes is set based on memory requirements, typical runs take 10 min to 30 min for 50–100 iterations.

### 6.4 Future Work

#### 6.4.1 Asymmetric Beam Correction

The data model of the map maker (section 4.2) does not account for the beam of the experiment. When the beam is symmetric, or when observing without sky rotation (for example, from the South Pole\cite{24, 25, 26, 91}), the result is that the output map is the sky convolved with the beam. With an asymmetric beam and sky rotation, the map will be convolved by an angle-smeared effective beam. In the limit of uniform coverage at all sky angles, the asymmetric beam will be azimuthally averaged into a shape limited by the long dimension of the beam.

However, each scan at a single angle has higher-resolution information across the short axis of the beam. For observations at several sky angles, high resolution information is available along several axes, which can be used to make a higher resolution map.

In the simple case of a beam composed of two identical symmetric lobes with amplitudes $a_1$ and $a_2$, the detector data (eq. (4.28)) becomes:

\[
\begin{align*}
    d_{it} &= a_1[I_{p1} + Q_{p1} \cos(2\psi_{it}) + U_{p1} \sin(2\psi_{it})] \\
          &+ a_2[I_{p2} + Q_{p2} \cos(2\psi_{it}) + U_{p2} \sin(2\psi_{it})] + n_{it} 
\end{align*}
\] (6.6)
where $p_1$ and $p_2$ are the map pixels observed by the two lobes at detector-sample \( it \). Each row of the pointing matrix for this system (eq. (4.31)) will have sets of non-zero elements for each lobe. The output map will be the sky convolved with the shape of a single lobe.

This method can be extended to beam shapes that can be decomposed into several identical symmetric lobes. More generally, the linear data model (eq. (4.32)) can include a beam operator \( B \)

\[
    d = ABs + n
\]

If matrix-vector products by \( B \) and \( B^T \) can be evaluated, then the iterative solutions can include this effect without ever explicitly constructing the matrix. \( B \) should not correspond to convolution by the beam itself, as information is not available at high pixel-scale spatial frequencies. Instead, \( B \) should be a convolution that, when applied to a small symmetric map smoothing kernel, produces the beam shape. Like the discrete lobes case, the output map will then be convolved by this kernel.

6.4.2 SPIDER Map Making

Many of the adaptations required to make TOAST work with BLASTPol data will be directly applicable to SPIDER, after its 2014 flight [23]. With an order of magnitude more detectors, SPIDER will make greater use of TOAST’s parallelization. For detailed Bayesian analysis, it will also make greater use of TOAST’s capabilities for noise estimation and on-the-fly Monte Carlo simulations.
Chapter 7

BLASTPol Maps

7.1 Calculating Polarization Pseudo-Vectors

In submillimetre polarimetry, the Cartesian Stokes parameters for linear polarization, \( Q \) and \( U \), are typically replaced with a polar representation:

\[
P = \sqrt{Q^2 + U^2}
\]

\[
\phi = \frac{1}{2} \arctan \left( \frac{U}{Q} \right)
\]

The \( \arctan \) is evaluated using the \texttt{atan2} function, to identify the correct quadrant, and the factor of \( \frac{1}{2} \) is due to the spin-2 symmetry of polarization pseudo-vectors. Also conventional in submillimetre polarimetry is to use polarization fractions:

\[
q = \frac{Q}{I}, \quad u = \frac{U}{I}, \quad p = \frac{P}{I} = \sqrt{q^2 + u^2}
\]

7.1.1 Reference Regions

Polarization fractions present a problem, however, because BLASTPol’s \( \frac{1}{T} \) noise and filtering make it insensitive to an offset in the map. This means that for each Stokes
parameter, the true values \((I_{\text{true}}, Q_{\text{true}}, U_{\text{true}})\) are related to the measured value by large-scale offsets \((I_{\text{off}}, Q_{\text{off}}, U_{\text{off}})\):

\[
\begin{align*}
q &= \frac{Q_{\text{true}}}{I_{\text{true}}} = \frac{Q - Q_{\text{off}}}{I - I_{\text{off}}} \\
q &= \frac{Q_{\text{true}}}{I_{\text{true}}} = \frac{Q - Q_{\text{off}}}{I - I_{\text{off}}} \\
q &= \frac{U_{\text{true}}}{I_{\text{true}}} = \frac{U - U_{\text{off}}}{I - I_{\text{off}}}
\end{align*}
\]  

(7.4)

To determine the offsets, the map is assumed to have zero true signal over some reference region. For each Stokes parameter, the mean value inside the reference region is subtracted from the whole map. The reference region must be part of the map with good cross-linking and with low signal—at least in \(I\) if polarization measurements are not available. It should also be large enough that noise does not significantly affect the mean signal inside. Because the reference region will never actually contain zero signal (especially in \(I\), see fig. 7.2), the polarization pseudo-vectors must be quoted as relative to the reference region.

Figure 7.1 shows the reference regions chosen for Vela C. The far reference region was chosen as part of the well cross-linked triangle with little signal. Signal estimates are based on Planck HFI \(I\) and on optical extinction measurements. Since the recent release of Planck polarization maps at 353 GHz [92] (850 \(\mu\)m, longer than any BLASTPol band), it has further been confirmed that \(Q\) and \(U\) are low in this region. The reference region has not been further updated, because the total true signal is not of interest in current BLASTPol analysis.

Instead, the reference region is chosen to isolate the Vela C cloud from diffuse galactic foreground and background signal. The near reference region in fig. 7.1 is chosen near to but outside the Vela C cloud. Another approach that has been attempted is to fit a plane across the cloud, rather than a constant value. The plane is constrained along strips north and south of the cloud. The results between the two methods are similar. Data cuts (section 7.1.6) are chosen to reject points that are too small compared to the reference values.
Figure 7.1: BLASTPol near (cyan) and far (green) reference regions compared to Planck 353 GHz $I$ (top) and $P$ (bottom). The region with good cross-linking is indicated in white.
7.1.2 Zero-point Correction with Planck HFI

Preliminary work is underway to calibrate the zero point of the \textit{I} map using Planck HFI data, as done by Herschel SPIRE \cite{93, 94}. For an accurate result, the Planck data must be colour-corrected to match the BLASTPol wavebands. This correction requires knowledge of dust temperature, and possibly gray-body spectral index, throughout the map.

Because Planck HFI’s 857 GHz band is a fairly close match for BLASTPol’s 350 µm band, a non-colour-corrected comparison is possible. The BLASTPol \textit{I} map of Vela C is smoothed to Planck’s 5’ resolution, and then sampled at all Planck data points within the well cross-linked region (fig. 7.1). Figure 7.2 shows the result, which is roughly linear and shows that even the lowest-valued BLASTPol pixels have a flux of about 30 MJy sr$^{-1}$. Some of the non-linearity might be due to convolution artifacts, which Herschel SPIRE corrects by embedding the roughly-corrected map into the Planck map and reconvolving.

Correcting \textit{Q} and \textit{U} is somewhat more challenging as Planck maps at 545 GHz and 857 GHz are unpolarized. The colour correction has to extrapolate much further, from 353 GHz, and the spectral behaviour of polarized dust emission is less well understood. Care will be required to ensure that assumptions about dust model don’t bias the results.

7.1.3 Error Bars

In addition to the maps of Stokes parameters \textit{I}, \textit{Q}, and \textit{U}, TOAST also estimates their variances and covariances. As described in section 6.3.5, the estimated variances are the per-pixel diagonal blocks of the full covariance matrix (eq. (4.37)). Assuming that \textit{I}, \textit{Q}, and \textit{U} are correlated within each pixel, but uncorrelated between pixels, then the
Figure 7.2: Preliminary zero-point fit for BLASTPol (arbitrary units) versus Planck, using Vela C data at 350 µm.

variance for a function \( f(I, Q, U) \) is:

\[
\sigma^2(f) \equiv \sigma(f, f) = \left( \frac{\partial f}{\partial I} \quad \frac{\partial f}{\partial Q} \quad \frac{\partial f}{\partial U} \right) \left( \begin{array}{ccc}
\sigma(I_p, I_p) & \sigma(I_p, Q_p) & \sigma(I_p, U_p) \\
\sigma(I_p, Q_p) & \sigma(Q_p, Q_p) & \sigma(Q_p, U_p) \\
\sigma(I_p, U_p) & \sigma(Q_p, U_p) & \sigma(U_p, U_p)
\end{array} \right) \left( \frac{\partial f}{\partial I} \quad \frac{\partial f}{\partial Q} \quad \frac{\partial f}{\partial U} \right)
\]

(7.5)

Applying eq. (7.5) to eqs. (7.1) to (7.3) yields:

\[
\sigma^2(P) = \frac{1}{P^2} \left( Q^2 \sigma^2(Q) + U^2 \sigma^2(U) + 2QU \sigma(Q, U) \right)
\]

(7.6)

\[
\sigma^2(\phi) = \frac{1}{4P^4} \left( U^2 \sigma^2(U) + Q^2 \sigma^2(Q) - 2QU \sigma(Q, U) \right)
\]

(7.7)
7.1.4 Smoothing Maps and Covariances

The first release of BLASTPol maps will be smoothed to 2′ to reduce the effects of the uncorrected asymmetric beam shape. As described in the appendix of [95], smoothing the map by a kernel $k$ means that the covariance maps must be smoothed by a kernel $k^2$. Further, smoothing polarization maps and covariances must account for the fact that the polarization reference direction on the celestial sphere will vary over a projected map. Due to the relatively small size of the BLASTPol maps, this effect is ignored.

Smoothing the covariances has the secondary effect of reducing the pixel noise levels. Therefore, the polarization detections have high statistical significance.

7.1.5 Noise Bias

The Stokes parameters $Q$ and $U$ can be both positive and negative, with errors based on their (approximately) Gaussian distribution. When combined into the non-negative quantity $P = \sqrt{Q^2 + U^2}$, the uncertainty in $Q$ and $U$ biases the estimate of $P$ high. In the case where $Q$ and $U$ are normally distributed with error $\sigma$ around a true polarization is $P_0 = \sqrt{Q_0^2 + U_0^2}$, $P$ is distributed with a Rice Distribution [96]:

$$f(P|P_0, \sigma) = \frac{P}{\sigma^2} \exp \left( -\frac{(P^2 + P_0^2)}{2\sigma^2} \right) I_0 \left( \frac{PP_0}{\sigma^2} \right)$$

(7.13)
Where $I_0$ is the modified Bessel function of zeroth order. By Taylor expanding the expectation value of eq. (7.13) to leading order in the noise-to-signal ratio ($\sigma/P_0$), one obtains the corrected estimate $\hat{P}$:

$$\hat{P} = P - \frac{\sigma^2}{2P}$$  \hfill (7.14)

This approximation is valid for $P \gtrsim 2\sigma$. Taylor expanding the variance of eq. (7.13) indicates that the error on $\hat{P}$ remains $\sigma$. A better approximation is discussed in [97], for lower signal-to-noise detections or where $Q$ and $U$ have unequal and possibly correlated errors. Equation (7.14) is sufficient for BLASTPol when smoothed to 2′, as the signal-to-noise is high.

### 7.1.6 Data Cuts

Once the data are smoothed (section 7.1.4), referenced (section 7.1.1), and debiased (section 7.1.5), several criteria are used to reject map pixels that are statistically or systematically suspect:

1. **Polarization signal to noise ratio.** Cut pixels where $P < 3\sigma(P)$.
2. **Reference region.** Cut pixels where $I < 3\sigma_{ref}(I)$, where $\sigma_{ref}(I)$ is the standard deviation of $I$ inside the reference region. This rejects pixels that are too close to (or below) the reference value, and prevents diverging polarization fraction at very low $I$.
3. **Instrumental polarization.** Cut pixels where $p < 3p_{ip}^*$, where $p_{ip}^* = 0.001$ is the expected level of uncorrected instrumental polarization in the maps.
4. **Angle uncertainty.** Cut pixels where $\sigma(\phi) > 10^\circ$.
5. **(Optional) Region selection.** Cut pixels outside a region of the map, such as the deep or cross-linked regions of the Vela C map.
6. *(Optional)* Reference region agreement. Cut pixels where $P$ or $\phi$ disagree when computed using two similar reference regions. Typically the comparison is between the near and plane-fit reference regions (section 7.1.1), and the thresholds for disagreement are $3\sigma(P)$ and $10^\circ$.

7. *(Optional)* Null test failure. Cut pixels in regions, such as around RCW 36, where there are very significant failures in the polarization null tests (section 7.2). This is optional because even very significant residuals are smaller than the polarized flux in the same region.

The polarization signal to noise cut and reference region cut identify most of the bad pixels, while the remaining cuts clean up some outliers. Figure 7.3 shows the pixels which are rejected in the Vela C map. Most of the deep region of the scan pass the checks, as do bits of data to the north and west. The latter bits of data are rejected by a region selection cut to either the deep region or to the region of good cross-linking. They are not used for analysis.

### 7.2 Null Tests

To test for systematic problems in the maps, a series of null tests are performed. A null test splits the dataset in half, makes separate maps for each half, and differences the two. Assuming that each half is measuring the same signal, the difference should be entirely noise.

The different tests considered are:

- *Top–bottom* compares detectors in the upper and lower halves of the array
- *Left–right* compares detectors in the left and right halves of the array
- *H–V* compares detectors based on their polarization grid angle
Figure 7.3: Polarization map pixels rejected by data cuts at 250 µm (blue), 350 µm (green), and 500 µm (red). The background is the 250 µm $I$ map.

- **IP** compares detectors with high and low IP

- **Early–late** compares all-detector maps with chunks early or late in the flight

- **Interleaved chunks** compares all-detector maps from an interleaved set of chunks

These tests are performed on the targets with the best data: Vela C and Puppis. Other targets have incomplete, sparse, or bad data that produce noticeable map artifacts and would obviously fail a null test. Because Vela C was the primary target of BLASTPol12, it includes an extended reference region (section 2.3) and the maximum 30° of available cross-linking. Puppis is a lower priority target that was usually observed when Vela C was unobservable. It has a narrow scan and only about 15° of cross-linking. Therefore, structure across its scan direction is poorly constrained.
Notes on null test maps

- All maps and difference maps in this section use the same colour scale, except undifferenced I maps (figs. 7.4 and 7.5), which use a 5× wider scale. The scale is in uncalibrated units, so not otherwise shown.

- Residuals are found not to contain structure on very small scales, so are smoothed with a 1′ Gaussian kernel to increase visibility of large-scale features. This creates ringing features around the map edges.

- Because Q and U null test residuals are similar to each other, only Q is shown.

- For brevity, results are shown at only 250 µm. The results are similar at the other wavebands. At 500 µm, some of the maps do not fully converge, due to problems with the reduced dataset size. This causes some null test failures at 500 µm to look slightly more significant, but in a way that would not impact maps made with all of the data.

7.2.1 Grid Angle H–V

Separating detectors by grid angle means BLASTPol acts as though it had only a single polarizing grid for all detectors. To measure Stokes parameters then requires subtracting measurements made at different HWP positions, which are separated by at least 15 min. Simulations [47] showed that, because this is far below the detector’s 1/7 knee, significant leakage would result. This is why the polarization analyzers were designed with alternating angles (section 2.1.3).

Figures 7.4 and 7.5 show the pairs of I maps produced for Vela C and Puppis, and figs. 7.6 and 7.7 the Q maps, which differ significantly. For better comparison, difference maps are computed, as shown in figs. 7.8 and 7.9.

The prediction of a significant polarization residual is confirmed. In fact, the H–V
null test, unlike the others considered, has larger residuals in $Q$ and $U$ than in $I$, despite the smaller amplitude of the polarization signal.

### 7.2.2 Array Top–Bottom

The array top–bottom null test splits the detectors in half depending whether they are above or below the median pitch pointing offset (fig. 5.5). The difference maps for Vela C and Puppis are shown in figs. 7.10 and 7.11. Because BLASTPol scans are roughly aligned with detector yaw, the top and bottom of the array do not see the same parts of the sky in the same scan. This is a source of scan-parallel streaks in the $I$ residual. For $Q$ and $U$ there is less common-mode drift because H and V bolometers are still implicitly differenced along the scan direction.

### 7.2.3 Array Left–Right

The array top–bottom null test splits the detectors in half depending whether they are left or right of the median yaw pointing offset (fig. 5.5). The difference maps for Vela C and Puppis are shown in figs. 7.12 and 7.13. Because BLASTPol scans are roughly aligned with detector yaw, these two detector subsets will observe the same parts of the sky in the same scan. Some waviness is seen in $I$, but there aren’t streaks like in the top–bottom null test.

This is the cleanest null test map that has been produced, largely consistent with just noise. It was used as a noise realization to calibrate TOAST’s covariance output (section 6.3.5).

### 7.2.4 IP High–Low

Splitting the detectors based on their level of IP (section 4.2.3) is used as a check of the IP correction. Otherwise, with a mixed selection of detectors (see fig. 5.11), it should
Figure 7.4: A comparison of the two $I$ maps produced for the H-V null test of Vela C. By eye, they cannot be distinguished.
Figure 7.5: A comparison of the two $I$ maps produced for the grid angle H–V null test of Puppis. They seem to differ only at the poorly-covered region in the lower left.
Figure 7.6: A comparison of the two $Q$ maps produced for the grid angle H–V null test of Vela C. There are significant differences between the two, including prominent anti-correlations near the map edges.
Figure 7.7: A comparison of the two $Q$ maps produced for the grid angle H–V null test of Puppis. The bands parallel to the scan direction differ.
Figure 7.8: $I$ (top) and $Q$ (bottom) difference maps for the grid angle H–V null test of Vela C. Near the bright parts of the cloud, a dipole-like leakage is present in both $I$ and $Q$, due to pointing or beam errors. In $Q$ there are prominent streaks along the scan direction. Streaks are slightly reduced in the deep region.
Figure 7.9: $I$ (top) and $Q$ (bottom) difference maps for the grid angle H–V null test of Puppis. A faint residual correlated with the $I$ structure can be seen. There are prominent streaks in $Q$ along the scan direction.
Figure 7.10: $I$ (top) and $Q$ (bottom) difference maps for the array top–bottom null test of Vela C. In $I$ there is both leakage of the source and prominent streaking. In $Q$ the map is very consistent with noise, except leakage around RCW 36.
Figure 7.11: $I$ (top) and $Q$ (bottom) difference maps for the array top–bottom null test of Puppis. There are streaks in $I$, but only faint ones in $Q$. 
Figure 7.12: $I$ (top) and $Q$ (bottom) difference maps for the array left–right null test of Vela C. There is some leakage in $I$, mostly around RCW 36, with waviness in the reference scan. In $Q$ the map is very consistent with noise, except leakage around RCW 36. There is a feature in the upper corner of $Q$, outside the cross-linked region.
Figure 7.13: $I$ (top) and $Q$ (bottom) difference maps for the array left-right null test of Puppis. There is a bit of leakage and streaking in $I$, very little in $Q$. 
be somewhere between the top–bottom and left–right null tests in terms of streaking. Figure 7.14 shows the difference maps for Vela C, with somewhat increased leakage around RCW 36, showing the limitations of our IP correction. Puppis is not shown as it is similar to left–right.

7.2.5 Time Early–Late

The early–late null test splits the data by chunk, into those at the beginning or end of the flight. It is sensitive to systematics that vary on long timescales.

However, the dataset for each target can’t simply be divided in the middle, as coverage in both HWP and parallactic angles must be preserved. Therefore, the chunks are first grouped by HWP angle and by high or low parallactic angle, then divided into early–late bins. The Vela C reference scans are also treated separately. Two complete sets of reference scans were conducted, specifically to allow null tests.

Figures 7.15 and 7.16 show the difference maps. There is a significant large-scale residual in $I$, but $Q$ remains quite clean, with just the usual leakage in Vela C around RCW 36, and slight banding in Puppis.

7.2.6 Time Interleaved

Like early–late (section 7.2.5), the time interleaved null test separates the data by chunk. Rather than splitting in the middle, it alternates from chunk to chunk. However, as per early–late, care is taken to divide chunks separately at different HWP and parallactic angles. Figures 7.17 and 7.18 show the difference maps. Because of the shorter separation between chunks in each set, this result is cleaner than the early–late null test—especially in the cross-linked region. Again, $Q$ has slight leakage around RCW 36.
Figure 7.14: $I$ (top) and $Q$ (bottom) difference maps for the IP high–low null test of Vela C. The extra leakage around RCW 36 compared to other null tests indicates a failure to completely correct IP.
Figure 7.15: $I$ (top) and $Q$ (bottom) difference maps for the time early–late null test of Vela C. There is a significant large-scale residual and leakage in $I$, but only a little leakage around RCW 36 in $Q$. 
Figure 7.16: $I$ (top) and $Q$ (bottom) difference maps for the time early–late null test of Puppis. There is striping and leakage in $I$, though only slight streaking in $Q$. 
Figure 7.17: $I$ (top) and $Q$ (bottom) difference maps for the time interleaved null test of Vela C. The $I$ residual is smaller than early–late, and $Q$ remains quite clean.
Figure 7.18: $I$ (top) and $Q$ (bottom) difference maps for the time interleaved null test of Puppis. Both $I$ and $Q$ are cleaner than early–late.
7.2.7 Null Test Conclusions

The null tests presented here have non-zero residual for one of two reasons: large-scale differences from comparing measurements at very different times; or smaller-scale leakage from beam and pointing effects. The amplitude and shape of the residual is understood in the context of each test.

Most importantly, the polarization residuals are very small—except the angle H–V null test which is expected to be bad. In Vela C, there is always some leakage around the bright source RCW 36, but otherwise the difference maps are very clean. Puppis shows some banding, even in polarization. This is due to its poor cross-linking leaving regions across the scan direction unconstrained relative to each other. Nevertheless, with a couple caveats, the BLASTPol polarization maps are quite robust.

More quantitative use of the null tests is difficult. Even in clean parts of the Vela C map there is a small but statistically significant disagreement with pure noise. Data can be cut where there are very significant outliers (section 7.1.6), such as around RCW 36. However, even the greatest outliers remain smaller than the signal in the same region. For maps with significant banding, like Puppis, extra care will need to be taken in their analysis to ensure that conclusions are robust to such errors.
7.3 Maps

BLASTPol observed seven targets in its 2012 flight. False colour maps of Stokes $I$ and $P$ are presented here with blue, green, and red mapped to 250 µm, 350 µm, and 500 µm, respectively. The relative strength of the bands is an indicator of temperature, with cool regions red ($\lesssim 13$ K) and warm regions blue ($\gtrsim 25$ K).

Note: The polarized flux $P$ is always on a colour scale 5% as large as that for total flux $I$. The bright sources Carina and G331.5–0.1 use colour scales 5× larger than the rest. Scales are not shown as the units are uncalibrated. $P$ maps are smoothed to 1' to decrease noise, which produces artifacts around the map edges.

7.3.1 Vela C

The Vela C map is the primary data product of BLASTPol’s 2012 flight. It is the largest map, and the only one with a complete large reference scan.

Vela C is a GMC in the Vela Molecular Ridge undergoing active star formation [98, 99]. The region was included in the galactic field survey of BLAST06, and was found to contain numerous compact sources [2]. Herschel SPIRE has also observed the cloud [100]. Most of the cloud is very red and cold, except a warm HII region around RCW 36.

False colour $I$ and $P$ maps are in fig. 7.19. While $I$ and $P$ look similar, not all of the cloud is strongly polarized. North of RCW 36, there is strongly polarized filament more visible in $P$ than $I$, possibly shaped by the HII region.

Expanded Vela C Polarization Results

Further polarization computations (discussed in section 7.1) are presented for Vela C. Figure 7.20 shows $P$ and $\sigma(P)$ in arbitrary units. These $P$ maps contain essentially the same information as the lower panel of fig. 7.19. The error, $\sigma(P)$, is very uniform and clearly shows the deep and shallow regions of the scan. These results, like all polariza-
Figure 7.19: Vela C false colour map of total flux $I$ (top) and polarized flux $P$ (bottom).
tion computations, are obtained by smoothing the BLASTPol maps to $2'$ and Nyquist sampling the result. At this smoothing scale, signal to noise is very high throughout the deep region.

Figure 7.21 shows $\phi$ and $\sigma(\phi)$. Again, the deep region shows consistently low values for the error, $\sigma(\phi)$. Inside the deep region, $\phi$ is smooth, with a few regions exhibiting fairly sharp changes. The feature around $(l = 265^\circ, b = 1.5^\circ)$ coincides with RCW 36 and may be an artifact. Outside the deep region, $\phi$ is quite noisy.

Figure 7.22 shows $p$ and $\sigma(p)$. These maps show strong effects from having corrected the $I$ offset using a reference region (section 7.1.1). Where $I \lesssim 0$ in the corrected map (around $l$ from $266^\circ$ to $267^\circ$ and $b$ from $2^\circ$ to $3^\circ$), very low values of $p$ result. Surrounding this region, artificially low values of $I$ result in diverging high values of $p$. Where $I$ is large, as in parts of the deep region of the map, $p$ measurements become much more reliable. Also, $p$ is visibly lower where $I$ is large. This is discussed further in section 8.1.

Finally, fig. 7.23 re-expresses the $p$ and $\phi$ information using polarization pseudo-vectors. For the points on and near the cloud, the pseudo-vectors mostly overlap. The length is proportional to $p$, and the angle has been adjusted to represent inferred magnetic field orientation (perpendicular to the polarization). The data cuts from section 7.1.6 are applied, in addition to restricting results to the deep region of the map.

### 7.3.2 Lupus I

The Lupus I cloud is part of a nearby star forming complex [101]. The cloud is currently in the early stages of star formation [102], and unlike Vela C or the Carina Nebula, does not contain any O or B stars. At $\approx 155$ pc [103], Lupus I is the closest star forming region available to BLASTPol, which maximizes spatial resolution. Located well off the galactic plane, Lupus has little confusion from background sources.

Lupus was scheduled for much more observation time, including an extended reference scan like Vela C. This was interrupted by the star camera failure, resulting in a poorer
Figure 7.20: Vela C measurements of $P$ (left) and $\sigma(P)$ (right) in each of the BLAST-Pol wavebands: 250 µm (top, blue), 350 µm (middle, green), and 500 µm (bottom, red). Arbitrary units.
Figure 7.21: Vela C measurements of $\phi$ (left) and $\sigma(\phi)$ (right) in each of the BLASTPol wavebands: 250 $\mu$m (top, blue), 350 $\mu$m (middle, green), and 500 $\mu$m (bottom, red). Units are degrees.
Figure 7.22: Vela C measurements of $p$ (left) and $\sigma(p)$ (right) in each of the BLASTPol wavebands: 250 µm (top, blue), 350 µm (middle, green), and 500 µm (bottom, red). Units are percent.
Figure 7.23: Using polarization pseudovectors to represent $p$ and $\phi$ in Vela C. The length is proportional to $p$, and the angle represents inferred magnetic field orientation. All data that pass the data cuts are present from all wavebands: 250 $\mu$m (blue), 350 $\mu$m (green), and 500 $\mu$m (red).
dataset. The $I$ map in fig. 7.24 has a faint haze towards the south that is likely an artifact. The $P$ map shows a faint but distinct signal. Both $I$ and $P$ are red and cold.

### 7.3.3 Puppis

Puppis is a relatively unstudied cloud, chosen to fit parts of BLASTPol’s schedule that other targets would not. It was selected as a dark cloud in IRAS [104] and with $^{12}\text{CO}$ J1–0 spectral observations from Nanten$^1$ [105].

The Puppis maps shown in fig. 7.25 converge well. $I$ and $P$ are more grey-green than Lupus I or Vela C, indicating warmer dust. Only some parts of the cloud are polarized. A narrow scan and relatively poor cross-linking (only about 15° of a possible 30°) make stripes along the scan direction. These are more visible in the null tests (section 7.2).

### 7.3.4 Carina Nebula

The Carina Nebula (also called the 'Keyhole Nebula' or NGC 3372 [106]) is a well-studied distant bright GMC undergoing high-mass star formation [109]. The bright central region contains two OB star clusters that drive activity in the nebula. One of the clusters contains the hypergiant star $\eta$ Carinae and its associated Homunculus Nebula.

The observation region for the Carina Nebula was chosen to include locations previously observed by SPARO [50]. The scan is wide in RA to also include the reference regions of SPARO’s three-point chop. This allows a direct comparison as in section 6.3.3.

The $I$ and $P$ maps are shown in fig. 7.26. A strong polarized signal traces the structure of the cloud. $I$ is mostly blue and warm, while $P$ is blue to purple in places. The purple colour could indicate a minimum of the polarized spectrum at 350 µm [22]. Carina data was contaminated by TDRSS, resulting in sparser than intended coverage. The map does not converge well and contains a few obvious artifacts.

$^1$not an acronym, Nanten is Japanese for “southern sky”
Figure 7.24: Lupus I false colour map of total flux $I$ (top) and polarized flux $P$ (bottom).
Figure 7.25: Puppis false colour map of total flux $I$ (top) and polarized flux $P$ (bottom).
Figure 7.26: Carina nebula false colour map of total flux $I$ (top) and polarized flux $P$ (bottom). The colour scale is 5x wider than other maps in this chapter.
7.3.5 G331.5–0.1

G331.5–0.1 is an HII region with a small collection of sources clustered nearby on the galactic plane. The sources have different velocity components, and are likely a superposition of two different regions along the line of sight \[110\].

Like the Carina nebula (section 7.3.4), the observation region for G331.5–0.1 was selected with the intention of reproducing SPARO measurements. However, the G331.5–0.1 map has very poor cross-linking (only 8°) and limited coverage, because its observations were interrupted by the star camera failure. Its I map shown in fig. 7.27 contains relatively faint streaks across the scan direction, and the P map is highly contaminated. The poor quality of the map makes comparison to SPARO impossible.

7.3.6 IRAS 08470-4243

The isolated compact HII region IRAS 08470-4243 was observed repeatedly as a pointing calibrator. Most of the scans are very small, focusing on just the source. A few wider scans were conducted, but only at one parallactic angle, resulting in some stripes and shadows in the wider map, seen in fig. 7.28. The polarization around the source might be an artifact, due to the large I gradients.

7.3.7 VY Canis Majoris

The hypergiant star VY Canis Majoris is observed primarily as a calibrator. It is a bright isolated point source that is expected to be unpolarized.

VY CMa has poor cross-linking, and the map is of poor quality. Still, the source is easily identified in the center of fig. 7.29 shaped like BLASTPol’s asymmetric beam. No polarized emission is visible from the star.
Figure 7.27: G331.5–0.1 false colour map of total flux $I$ (top) and polarized flux $P$ (bottom). The colour scale is 5× wider than other maps in this chapter.
Figure 7.28: IRAS 08470-4243 false colour map of total flux $I$ (top) and polarized flux $P$ (bottom).
Figure 7.29: VY CMa false colour map of total flux $I$ (top) and polarized flux $P$ (bottom).
Chapter 8

BLASTPol Science

While maps are an end point to the data reduction, they are the beginning of higher-level analysis and physical interpretation. This chapter presents some of the science that makes use of these maps.

*Note:* results presented here are preliminary and subject to change. Each section references the article in which final results will be published.

8.1 Understanding Polarization as a Tracer

This work is preliminary, and final results will be published in [111].

Submillimetre polarization can be difficult to interpret. It is affected by superposition along the line of sight, averaging within the telescope beam, and by dust grain alignment. BLASTPol can help disentangle these confounding effects.

8.1.1 Temperature and Column Density

Before looking at the polarization, I maps are analyzed to find the temperature \((T)\) and column density \((N)\) of gas in the cloud. This is accomplished with a pixel-by-pixel fit of an SED to the flux observed at 250\(\mu m\), 350\(\mu m\), and 500\(\mu m\). The flux \(F(\nu, N, T)\) is a
black-body intensity $B(\nu, T)$ modified by a power law emissivity $\nu^\beta$ with $\beta \approx 2$ [112]:

$$F(\nu, N, T) \propto N\nu^\beta B(\nu, T)$$ (8.1)

Herschel SPIRE data [100] are used due to their better beam and more advanced zero-point calibration [93]. The results are presented in fig. 8.1. Number density is high in much of the cloud and temperature is low except around the HII regions RCW 36 and RCW 34. Denser regions are colder, with the overall trend shown in fig. 8.2.

8.1.2 Polarization Correlations

In addition to the basic polarization fraction $p$, it is also interesting to consider the dispersion of polarization angles $\Delta \psi$. This measures the average angle difference at a point relative to those on a ring around it (full definition in [95]). For BLASTPol, the scale probed (radius of the ring around each point) is chosen to match the smoothing scale of the polarization maps. Figure 8.3 shows a map of the polarization dispersion.

Figure 8.4 shows the correlations between $p$, $T$, $N$, and $\Delta \psi$. The much observed depolarization of dense regions [113, 114, 95] has been confirmed, with an anti-correlation between $p$ and $N$. The $p$ versus $T$ trend can be fully accounted for by $p$ versus $N$ and $N$ versus $T$. However, neither $p$ nor $N$ are correlated with $T$ near RCW 36, suggesting that the relation of $p$ to $N$ is more fundamental.

There is an anticorrelation between $p$ and $\Delta \psi$, so observed polarization is also reduced by variations in field direction. The variations are averaged either across the telescope beam or along the line of sight. Lack of correlation between $N$ and $\Delta \psi$ shows that this is independent of the depolarization with density. The trends with $N$ and $\Delta \psi$ account for about half of the observed variation in $p$.

While angle averaging is an observational effect, the lower polarization at higher densities lends itself to physical explanations. There could be different populations of
Figure 8.1: Column density (top, in cm$^{-2}$) and temperature (bottom, in K) maps for Vela C using Herschel SPIRE data.
Figure 8.2: Temperature versus column density trend in Vela C. The coloured points are all located around RCW 36 and are separated from the other data.

Figure 8.3: Preliminary map of 500 \( \mu \)m polarization angle dispersion in Vela C. Contours show \( I \). Units are degrees.
Figure 8.4: Preliminary correlations between polarization fraction $p$, temperature $T$, column density $N$, and angle dispersion $\Delta\psi$ in Vela C. Data excludes points around RCW 36.

dust grains in dense and diffuse regions. Assuming the radiative torques theory of grain alignment [9], another explanation is reduced alignment efficiency due to shielding from the interstellar radiation field.

8.2 Orientations of Polarization and Structures

This work is preliminary, and final results will be published in [115].

Because submillimetre polarization traces only the direction of magnetic fields, further analysis is required to deduce field strength. When applied to large-scale galactic fields, the strength is traditionally estimated by assuming a spatially uniform field in which all deviations in direction are due to turbulent mixing [10, 16]. The degree of order in field
directions is then a measure for the relative strength of magnetic fields over turbulence. Inside molecular clouds, where smaller-scale evolution will also influence field direction, the polarization directions can be compared to the orientation of structures in the cloud. Simulations [17] have shown that this method can distinguish different magnetic field strengths, and the method has recently been applied to a selection of targets using Planck data [116].

An analysis of this type has been applied to Vela C 500 μm data. Figure 8.5 shows the Histogram of Relative Orientations (HRO), the angle between each inferred magnetic field orientation and the contours of constant $I$ (500 μm $I$ is a good proxy for column density, see section 8.1.1). The data are subdivided into different density regions, illustrated in fig. 8.6, in which the colours of the contours correspond to the lines in fig. 8.5.

From these histograms, a relative orientation parameter can be calculated, for which $\xi > 0$ means magnetic fields are mostly parallel to density contours and $\xi < 0$ means they are mostly perpendicular. From simulations, the characteristic of regions with strong magnetic fields is going from $\xi > 0$ at low densities to $\xi = 0$ or $\xi < 0$ at high densities. This trend can be very weakly seen in the BLASTPol data, in fig. 8.7. So far, the trend is not significant—just a promising indicator of what a future analysis may show more clearly. Improved correction for the beam shape should help.

8.3 Polarization Spectrum

This work is preliminary, and final results will be published in [117].

While the BLASTPol polarization measurements at each waveband roughly agree, their differences can also be illuminating. An ensemble of previous cloud-averaged polarization measurements [22] indicate that the polarization fraction has a minimum at around 350 μm. Figure 8.8 shows that BLASTPol confirms this result, when averaged over Vela C.
Figure 8.5: Preliminary histogram of relative orientations for Vela C, showing the angle between inferred magnetic field direction and contours of constant density. The different curves show pixels selected at different levels of $I$.

But averaging over the entire cloud discards useful information. Figure 8.9 shows that the ratios of polarization fractions at different wavebands vary over the map. Like $p$ and $\Delta \psi$ (section 8.1), preliminary work is underway to see how these relate to temperature and column density. Similarly, a comparison of sight lines with and without embedded stellar or protostellar sources can test the effects of optical radiation on grain alignment.

### 8.4 Comparison to Near-Infrared Polarization

This work is preliminary, and final results will be published in [118].

The same dust grains that emit submillimetre polarization also absorb and polarize background starlight (section 1.2). Polarization measurements of Vela C have been conducted in I band ($0.79 \mu m$) using the Pico dos Dias Observatory in Brazil (similar to
Figure 8.6: Preliminary map of different density levels selected for HRO analysis. The contour colour correspond to the curves in fig. 8.5.

Figure 8.7: Preliminary relative orientation parameter ($\xi > 0$: mostly parallel, $\xi < 0$: mostly perpendicular) binned by density.
Figure 8.8: Polarization spectra from several measurements of molecular clouds, normalized at 350 \( \mu \text{m} \). Preliminary BLASTPol Vela C results are also shown.

Figure 8.10 shows a comparison between the submillimetre and near-infrared polarization. Near-infrared measurements are not available for dense parts of the cloud, where background starlight is fully extincted, but there remains significant overlap between the datasets. BLASTPol measurements here differ from fig. 7.23 because the near reference region (section 7.1.1) is used here.

The inferred magnetic field angles agree quite well, and fig. 8.11 shows a histogram of the angle differences. Interpretation of optical and near-infrared polarimetry can be challenging as the cloud is only sampled to the depth of the background star. Where stars are in front of or within the cloud, the results will disagree with submillimetre, which always samples the full cloud. An obvious case of this is around RCW 36 (circled region in fig. 8.10) where the near-infrared measurements could not be probing the whole...
Figure 8.9: Preliminary maps of polarization spectrum ratios $p_{500\mu m}/p_{350\mu m}$ (top), $p_{500\mu m}/p_{250\mu m}$ (middle), and $p_{350\mu m}/p_{250\mu m}$ (bottom). Background and contours are 250 $\mu$m $I$. 
Figure 8.10: Preliminary map of submillimetre (BLASTPol 500\,µm, in red) and near-infrared (0.79\,µm, in blue) polarization around Vela C. In both cases, pseudo-vector orientation represents inferred magnetic field orientation. Background and contours are Herschel SPIRE 250\,µm. Cyan box indicates the region in which BLASTPol data are selected.
very dense region. BLASTPol data using the near reference region agrees better than with the far reference, indicating that the near-infrared data mostly sample the Vela C cloud but not galactic backgrounds.

Finally, the degree of polarization can be compared between the submillimetre and near-infrared. This provides a long baseline in wavelength over which to compare against theoretical dust models. Figure 8.12 shows the polarization comparison, along with predictions [121]. The slope is slightly higher than predicted in any of the models, in agreement with a similar analysis over the whole sky [122].

8.5 Conclusion and Future Work

BLASTPol had a successful flight from 25 December 2012 to 10 January 2013 (chapter 2). I primarily contributed the central electronic systems (chapter 3), along with code and

\footnote{Note that, for the second half of the flight, target selection had to be simplified due to star camera failures}
Figure 8.12: Preliminary degree of polarization fit between submillimetre and near-infrared. Coloured lines indicate predictions from dust models.

hardware to integrate these with all of the telescope subsystems.

Since the flight, my focus has been on making the best possible maps from the available data (chapter 4), by adapting the GLS map maker, TOAST. Before maps can be made, much data cleaning and distillation is necessary (chapter 5). GLS map making further requires noise characterization to fully leverage the data, as well as simulations and consistency tests to confirm that it works as intended (chapter 6). Maps have been generated, and null tests confirm that the results are robust (chapter 7). These maps are being used for a variety of higher-level analyses (chapter 8).

Other work is underway to produce even better maps for future analyses. While maps such as Vela C—BLASTPol’s primary target—are already of very high quality, tweaks to the data preprocessing could further improve maps of other targets. Calibrations using Planck $I$, $Q$, and $U$ maps will produce better zero points for the BLASTPol maps than using reference regions (section 7.1.1). Higher resolution can be achieved by measuring
and correcting the asymmetric and variable beam (section 6.4.1). While the second half of the flight lacks bore-sight star cameras, pointing might be reconstructed based on crossing high signal-to-noise sources. For the Vela Wide scan, this would more than triple integration time and double map area around Vela C.

The scientific discussion so far has focused on Vela C, with its large and well-referenced map. But maps of other targets are also of analysis quality, and sample different physical environments. The Carina Nebula (section 7.3.4) has higher temperature, higher density, and more advanced star formation, while the Puppis region (section 7.3.3) is more isolated and less dense.

Follow-up observations like the Herschel SPIRE (section 8.1.1) and near-infrared results above (section 8.4) can also help us learn more about these regions. Molecular line spectra have already been acquired with the Mopra Telescope.\footnote{http://www.narrabri.atnf.csiro.au/mopra/} The velocity and line-width measurements will help disentangle three-dimensional structure of the clouds and measure turbulent energy. Moreover, comparing different molecular tracers with BLASTPol’s polarization results might indicate which parts of cloud best produce polarized emission.

The preliminary results in this chapter are part of an ongoing research program. Efforts will continue to extract more information from BLASTPol’s rich maps of submillimetre polarization.
Bibliography


