Fabrication of GreenPol Telescope and Design of Its Control System

A dissertation submitted in partial satisfaction of the requirements for the degree Bachelor of Science in Physics

by

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This Dissertation of Shulin Li is Approved.

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Abstract

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The cosmic microwave background (CMB) is thought to be leftover radiation from the Big Bang. It is an almost-uniform background of radio waves that fill the universe. Anisotropies observed in the CMB provide information about density fluctuations in the early universe plasma and the polarization of the CMB may hold clues of primordial gravitational waves. However, foreground pollution from synchrotron radiation and dust emission can obscure the genuine effects of cosmological gravitational waves (CGW). So, those noises from polarized sources in our galaxy must be removed first.

The GreenPol Project is committed to map the intensity and linear polarization in B-Mode, a specific form of polarization in CMB and an indication of CGW, with degree angular resolution at several frequencies between 10 and 30 GHz. In specific, our mission is to map galactic emissions and magnetic field and investigate cosmic ray acceleration and propagation.

A fundamental prerequisite of GreenPol experiments is to design and fabricate the ground-based B-mode microwave telescope and relevant equipment (B-machine). In this dissertation, I will introduce the fabrication of B-machine and the design of its control system. As always, we build complicated machine through team work. In chapter 3 and chapter 4, I will concretely present what I contributed and participated.
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Chapter 1

introduction

1.1 Cosmic Microwave Background

Figure 1.1: An image of the cosmic microwave background radiation, taken by the European Space Agency (ESA)’s Planck satellite in 2013, shows the small variations across the sky

The CMB is a relic radiation field that we observe in all directions at a uniform temperature of 3 Kelvin. It is the oldest light we can see—the farthest back both in time and space that we can look. This light last scattered during a hot and dense stage of the early universe.

The epoch at which atoms form, when the universe was at an age of 300,000 years and a temperature of around 3000 K is somewhat referred to as “recombi-
nation”, despite the fact that electrons and nuclei had never before “combined” into atoms. The physics is simple: at a temperature of greater than about 3000 K, the universe consisted of an ionized plasma of mostly protons, electrons, and photons, which a few helium nuclei and a tiny trace of Lithium. The important characteristic of this plasma is that it was opaque, or more precisely the mean free path of a photon was a great deal smaller than the horizon size of the universe. As the universe cooled and expanded, the plasma ”recombined” into neutral atoms, first the helium, then a little later the hydrogen. Once the gas in the universe is in a neutral state, the mean free path for a photon rises to much larger than the Hubble distance. The universe is then full of a background of freely propagating photons with a blackbody distribution of frequencies. At the time of recombination, the background radiation has a temperature of 3000 K, and as the universe expands the photons redshift, so that the temperature of the photons continuously drops up to around 3 K today. We can detect this background of photons and explore the science of universe.

1.2 CMB Polarization

![Figure 1.2: Thomson scattering of radiation with a quadrupole anisotropy generates linear polarization. Blue colors represent hot and red colors cold radiation.](image)

The study of the linearly polarized component is the next stage of CMB investigations. Thomson scattering provides a model of polarizing CMB light. The
intensity of the radiation varies at 90 degrees (a quadrupole pattern) gives a net linear polarization result. Before recombination, Thomson scattering between the photons and electrons was extremely rapid. As scattering randomly changes the direction of the photons, any difference in temperature with direction rapidly goes away. Scattering exponentially reduces the level of anisotropy in the radiation. The observer today then sees the linear polarization vary across his/her sky in a pattern which is literally the projection of the quadrupole anisotropies at recombination.

Any polarization pattern on the sky can be separated into electric (E) and magnetic (B) components. The dominant contribution to CMB polarization anisotropies is from density (or scalar) perturbations in the early universe, but an amazing fact is that these density perturbations only create polarization patterns of a particular type. For a simple geometric explanation of E and B modes, see the diagram below.

![Diagram](image)

Figure 1.3: For both the E mode (left) and B mode (right), the polarization (indicated by the headless lines) varies along the horizontal direction indicated by the wave vector, \( \ell \). For the case of a pure E mode, the polarization is parallel or perpendicular to \( \ell \) (i.e. horizontal or vertical). For a pure B mode, the polarization is rotated by 45 degree with respect to \( \ell \).
These modes are defined by the pattern of the polarization angle field, which is axis symmetric for the E-Mode, while it is rotated by 45° for the B-Mode (see Fig 1.3). The most appealing feature of the CMB polarization is that the scalar perturbations can generates only the E-mode component. Gravitational waves from inflation can source B-mode polarization, so a B-mode search allows us to target the signal of inflation at very high sensitivity without being swamped by the larger E-modes.

1.3 Galactic Foregrounds

![Figure 1.4: RMS anisotropy of CMB compared to Galactic foreground emission (Rayleigh Jeans Temp). Grey is the predicted range for inflation for simple models. The actual signal level is unknown. The red and blue bands show typical high-latitude emission from polarized synchrotron and dust emission within the Galaxy.](image)

For polarization measurements, we focus on two classes of Galactic foreground:

- Synchrotron radiation is emitted by relativistic electrons that travel on spiraling paths in our Galaxy’s magnetic field. The energy spectrum of the electrons leads to a synchrotron spectrum that is brighter at low frequencies and faint at higher frequencies.
• Dust is a general name for microscopic bits of matter in interstellar space. Starlight heats up the dust, causing it to glow in microwaves.

We can see that synchrotron emission dominates the radio sky at frequencies below about 10 GHz, while dust emission dominates at frequencies over 30 GHz. Before looking at CMB fluctuations, contaminations from polarized sources in our galaxy must be removed first.

1.4 Inflation

The inflation model is based on the hypothesis that the universe undergoes a brief period of exponential expansion immediately after the big bang (a super massive singularity). As we know, gravitational waves are wrinkles in spacetime that propagate as waves, produced when large masses interact. So, the rapid expansion creates primordial gravitational waves that imprint a characteristic pattern of information onto the CMB.

If we have small wrinkles or hills and valleys early in the universe, matter will tend to fall into the valleys, eventually producing dense regions that become the sites of galaxies.

![Model of wrinkles in universe](image1.png)  
![Color map of figure (a)](image2.png)

(a) Model of wrinkles in universe.

(b) Color map of figure (a). The color coding refers to the density of matter (dark regions have more matter, light regions less).

**Figure 1.5: Gravitational instability**

As time goes on, matter falls into these wrinkles and starts to build heavier and heavier objects. The crucial period when this process of gravitational attrac-
Figure 1.6: Inflation model. The blue bands are snapshots of the ripples in the density of the universe at various times.[4]

tion and infall can occur is related to an important concept in cosmology called the horizon. Like the horizon on the earth, it is the point beyond which we’re unable to look. Unlike the earth’s horizon, this distance is increasing with time because light from more distant regions has had more time to reach us.

A useful property of the microwave background is that when we look out across widely separated angles, we’re looking at wrinkles on such large scales that this process of infall hasn’t yet begun. We’re looking at the primordial
wrinkles themselves.
Chapter 2

GreenPol Overview

2.1 Motivation

The detection of primordial gravitational waves in the form of large-scale polarization, B-modes in the CMB ranks as one of the most important goals in current cosmology. The millimeter wavelength sky is critical for understanding cosmological foregrounds in order to remove the galactic signature from the cosmological signature. This is especially important in searching for the gravity wave signature from the proposed inflationary era from polarization in the Cosmic Microwave Background (CMB). Our galaxy has two primary and very different emission mechanisms, namely synchrotron emission from high energy Cosmic Rays that dominates below 100 GHz and dust emission from heated interstellar dust grains that dominates above 100 GHz. It is critical that we have a series of very sensitive maps from 10-100 GHz to understand the synchrotron component of our galaxy to combine with the Planck high frequency dust maps from 100-900 GHz. The current WMAP and Planck maps at 23, 30, 40 and 70 GHz are insufficient, especially in polarization which neither satellite was specifically designed to measure and for which there is both insufficient sensitivity and serious systematic concerns. There are two major goals for our longer term effort in Greenland. One is to study the galactic foregrounds by measuring over about 50 % of the sky, doing
for synchrotron what Planck has done for dust, AND to feed these maps and understanding into the deep cosmological maps we will make from Greenland at 10-44 GHz and eventually 100 GHz to search for evidence of gravitational waves from the early universe.

GreenPol will use a microwave telescope designed to measure the polarization of emission from our galaxy at frequencies of 10, 15, 20, 30 44 GHz at Summit Station in Greenland. The purpose of GreenPol is to understand the galactic emission in order to better understand and remove this structure from deep Cosmic Microwave Background (CMB) anisotropy and polarization maps, such as those generated by the Planck mission. By removing the polarized contamination from our galaxy, researchers will be able to generate more sensitive CMB maps, which will help them have a better understanding of the early universe, particularly in the search for primordial gravitational waves, which if found would be strong evidence for the theory of inflation.

2.2 Greenland Site

Increasing scientific activity in Antarctica must face a number of challenges related to the development of the sites available for the future scientific exploitation. The limitation of power supplies and the extreme expense of the logistics for the deployment of new antennas for radio and infrared ground-based experiments in Antarctica as well as its atmospheric opacity make Greenland almost equal to the South Pole site.

Greenland is one of the best observing sites in the world, particularly with respect to precipitable water vapor, and allows coverage of the northern hemisphere, which is less contaminated by the galaxy and is complimentary to southern hemisphere measurements at higher frequencies that study dust contaminated frequencies. A critical factor that is new is that the Planck data has recently shown that the higher frequency (about 100 GHz) polarization measurements
are heavily contaminated by a much more complex dust emission than we had anticipated and at a higher level than anticipated. Since the atmosphere is quite absorptive above 100 GHz and essentially opaque above 300 GHz, with only a few observing frequency windows, in order to fully characterize the dust emission space based systems are needed. On the other hand the lower frequencies below 100 GHz are essentially completely open to observation from the ground. This allows us to make much more detailed measurements of the galactic contamination from ground based measurements. Additionally the advantage of going into space compared to ground is only about a factor of 2 in system noise for the critical bands while at higher frequencies ground observations are much less sensitive than space both due to the increased opacity of the atmosphere and the decreased flux from the CMB at higher frequencies. These two effects give us a strong science case to push to lower frequencies and to use the high altitude site in Greenland (Summit site) as an observing site. Another critical factor
that favors observing at lower frequencies is that the technology we will use to make these measurements uses detectors that are extremely linear compared to the bolometers used at higher frequencies. Thus atmospheric perturbations from water vapor fluctuations and pressure waves will be largely cancelled out to a much higher degree than bolometer based measurements, allowing us to get polarization information on larger angular scales that is critical to understanding inflation.

Figure 2.2: The lines show the sky region covered by a 10 degree (black), 20 degree (blue), 30 degree (white), and 65 degree (gray) opening angle.
2.3 Setup and Instruments

2.3.1 Setup

The experimental setup for each point in the above plot is as follows. Unless stated otherwise, all setups follow the baseline configuration (SN10) of 10-44GHz GreenPol channels + 100-353 GHz Planck channels at a 10 degree opening angle.

- SN10, SN20, SN30, SN65 – opening angle of 10, 20, 30, and 65 degrees. Each frequency channel is weighted by its signal to noise ratio
- Mask04 – Pixels are masked by thresholding the Planck synchrotron polarization, leaving a full sky fraction of 0.73
- Mask05 – Pixels are masked by thresholding the CMB posterior RMS map at 0.4 uK
- U10 – Uniform weighting across frequency channels
- Wide prior – Gaussian priors on the spectral parameters for synchrotron and dust are tripled
- LFI HFI – Planck LFI + HFI channels only
- LFI HFI G10 – Planck LFI + HFI + 10GHz GreenPol channel
- SN10H – 10-44GHz + 90, 143 GHz GreenPol channels
- SN10H P353 – 10-143 GHz GreenPol channels + Planck 353 GHz channel

Combining Planck HFI observations on polarized thermal dust emission with the proposed experiment, our collaborators from the Institute of Theoretical Astrophysics at University of Oslo estimate a limit of $r$ less than 0.02 at 95 percent confidence for the baseline configuration (SN10). This limit is derived from ideal and simplified simulations which account for foregrounds (thermal dust and synchrotron) and white noise, but not instrument systematics. Variations in a number of experimental parameters such as sky coverage, detector weighting, and
foreground priors, have little effect on this limit, making it very robust. GreenPol therefore has the potential to provide the most sensitive low frequency CMB polarization measurements of the northern galactic hemisphere in the foreseeable future.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>44</th>
<th>90</th>
<th>143</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector type</td>
<td>HEMT</td>
<td>HEMT</td>
<td>HEMT</td>
<td>HEMT</td>
<td>Bolo</td>
<td>Bolo</td>
<td>Bolo</td>
</tr>
<tr>
<td>RMS per horn ($\mu K \sqrt{s}$)</td>
<td>316</td>
<td>316</td>
<td>433</td>
<td>361</td>
<td>200</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Horns per telescope</td>
<td>7</td>
<td>13</td>
<td>19</td>
<td>25</td>
<td>40</td>
<td>160</td>
<td>320</td>
</tr>
<tr>
<td>NET per telescope ($\mu K \sqrt{s}$)</td>
<td>120</td>
<td>88</td>
<td>102</td>
<td>72</td>
<td>16</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Mean ($Q,U$) noise per 1° pixel ($\mu K$)</td>
<td>5.1</td>
<td>2.1</td>
<td>2.0</td>
<td>1.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>FWHM beam size (arcmin)</td>
<td>80.0</td>
<td>53.3</td>
<td>40.0</td>
<td>26.7</td>
<td>18.18</td>
<td>8.89</td>
<td>5.59</td>
</tr>
<tr>
<td>Model summary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ($P/\sqrt{2}$) total signal ($\mu K$)</td>
<td>279</td>
<td>90</td>
<td>33</td>
<td>10</td>
<td>3.7</td>
<td>2.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Mean ($P/\sqrt{2}$) Thermal dust ($\mu K$)</td>
<td>0.07</td>
<td>0.12</td>
<td>0.18</td>
<td>0.34</td>
<td>0.63</td>
<td>2.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Mean ($P/\sqrt{2}$) Synchrotron ($\mu K$)</td>
<td>279</td>
<td>90</td>
<td>33</td>
<td>9.4</td>
<td>5.0</td>
<td>0.38</td>
<td>0.12</td>
</tr>
<tr>
<td>RMS (Q) CMB ($\mu K$)</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Thermal dust scaling factor</td>
<td>0.007</td>
<td>0.013</td>
<td>0.020</td>
<td>0.038</td>
<td>0.068</td>
<td>0.22</td>
<td>0.55</td>
</tr>
<tr>
<td>Synchrotron scaling factor</td>
<td>0.133</td>
<td>0.38</td>
<td>1.56</td>
<td>0.45</td>
<td>0.14</td>
<td>0.02</td>
<td>0.006</td>
</tr>
<tr>
<td>Spinning dust scaling factor</td>
<td>0.52</td>
<td>0.44</td>
<td>0.30</td>
<td>0.10</td>
<td>0.020</td>
<td>2e-4</td>
<td>1e-9</td>
</tr>
</tbody>
</table>

Integration time per channel for various experimental setups in telescope-years

| SN10 | S/N weights, 10° radius disk | 0.2 | 0.3 | 1.5 | 6 | 8 | 0 | 0 |
| SN20 | S/N weights, 20° radius disk | 0.2 | 0.3 | 1.5 | 6 | 8 | 0 | 0 |
| SN30 | S/N weights, 30° radius disk | 0.2 | 0.3 | 1.5 | 6 | 8 | 0 | 0 |
| SN45 | S/N weights, 45° radius disk | 0.2 | 0.3 | 1.5 | 6 | 8 | 0 | 0 |
| SN65 | S/N weights, 65° radius disk | 0.2 | 0.3 | 1.5 | 6 | 8 | 0 | 0 |
| U10 | uniform weights, 10° radius disk | 2 | 2 | 2 | 2 | 8 | 0 | 0 |
| SN10H | S/N weights with 90°-143 bolo, 10° radius disk | 0.1 | 0.2 | 0.7 | 3 | 4 | 4.5 | 0.5 |

Evaluated for the baseline scanning strategy with 10° opening angle.

Figure 2.3: Summary of GreenPol instrument properties (top section), model parameters (middle section), and experimental setups (bottom section) for our proposed experiment. Temperatures are given in thermodynamic units.

![Graph showing tensor to scalar ratio r for various experimental set ups at the 95 percent confidence limit. Each point represents the mean of the 95 percent confidence limits evaluated from 20 simulations. The error bar indicates the 68 percent region among the same simulations. The horizontal gray dashed line is the value of the baseline configuration SN10.](image)

Figure 2.4: Tensor to scalar ratio r for various experimental set ups at the 95 percent confidence limit. Each point represents the mean of the 95 percent confidence limits evaluated from 20 simulations. The error bar indicates the 68 percent region among the same simulations. The horizontal gray dashed line is the value of the baseline configuration SN10.
The table above shows the angular resolution, number of feeds, and anticipated sensitivity (based on our laboratory measurements and estimates of the atmosphere) we will have for each of our chosen frequencies. Note that we measure Q and U simultaneously in the polarimeter configuration. Our receivers are very low noise (less than 6K at 10 GHz), thus the CMB is a significant factor in the noise and hence we are not far from being BLIP limited at these low frequencies.

2.3.2 Instruments

Due to the variable weather at Summit, we need a system which is both rapidly deployable and retractable. In order to accomplish this we modified a

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>7</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of feeds/tel (telescopes)</td>
<td>3 (1)</td>
<td>3 (1)</td>
<td>7 (1)</td>
<td>12 (1)</td>
<td>30 (3)</td>
<td>50 (10)</td>
<td>200 (10)</td>
</tr>
<tr>
<td>FHWM, deg</td>
<td>1.7</td>
<td>1.3</td>
<td>0.9</td>
<td>0.65</td>
<td>0.45</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>T sens, $\mu K \sqrt{S}$ 1 horn(array)(total)</td>
<td>520(301)</td>
<td>469(270)</td>
<td>470(178)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q sens, $\mu K \sqrt{S}$ 1 horn(array)(total)</td>
<td>408(235)</td>
<td>368(212)</td>
<td>369(139)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U sens, $\mu K \sqrt{S}$ 1 horn(array)(total)</td>
<td>408(235)</td>
<td>368(212)</td>
<td>369(139)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
standard 20 ft. ISO container with a 40 ft. track system which can slide the telescope into and out of the container when needed. The optical frame rests on a mechanical sub-frame which houses the electronics, azimuth and elevation drive, and track sled. The optics include a primary mirror, grid polarizer, secondary mirror, and detector array. The grid polarizer is a spinning linear polarizing grid that modulates the U and Q polarizations of incoming photons, allowing us to measure them both simultaneously with low loss. This is important since the goal is to measure the microwave polarization. The detector arrays are made up of feed horns that guide the microwaves to antennas, which convert the waves into electrical signals. These signals are passed through low noise amplifiers that must be kept very cold (around 20 Kelvin) to minimize noise. To be able to cool the system the detector arrays are mounted in vacuum tight dewars that are cooled with liquid helium (about 4 Kelvin) supplied by the on board storage dewars. All data, both housekeeping and scientific, will be synchronously acquired by a custom made FPGA system which is under development. After initial capture, the data is passed to a host processor for further analysis and storage.
Figure 2.6: B-machine
Chapter 3

Telescope Components and Manufacture

3.1 Signal Detecting Components

Figure 3.1: Components of signal detecting
The signal detecting part is the most essential and functional portion of the telescope. It consists of a grid polarizer, detector arrays with 10 GHz feed horns, and the optical system (a copper plated primary mirror, a copper plated secondary mirror, and a focal plane that resolves signals). Light comes in from the sky and bounces off the primary mirror to the secondary mirror. Then, the secondary mirror would concentrate the reflected light onto the focal plane of the detector arrays. With beams collected, the antenna horn inside the detector would direct a beam radio waves at a precise frequency of 10 GHz such that the amplifier could pass feasible signals to a central processing unit of FPGA and produce raw data in the storage.

3.1.1 Optical Modeling

An important problem will be accurately modeling our telescope response (radiation) pattern so as to reduce side-lobe contamination and improve systematics. Side-lobes (or back-lobes) are the lobes of the far-field radiation pattern which are outside the main-lobe (where you are pointing) and are caused by diffraction around the optical components of the telescope. This can be a serious issue when your measurements are being dominated by bright sources located away from where you are pointing, leading to high noise sky maps. Fully understanding this response pattern is then essential to knowing what in your measurements is erroneous. The response pattern can also be made less complicated by reducing side-lobe contamination initially with a Baffle, which acts as an extension to the primary mirror. Therefore optimizing this baffle design is an essential component of the GreenPol optics. Signal testing of effects of baffle on the main mirror and resulting signal maps are presented below.

What you are seeing in sub-figure (b) is the convolution between the response pattern map in sub-figure (a), and a 5800 K sun added to the Planck 30 GHz temperature signal extrapolated to 10 GHz, i.e. an estimate of how our telescope would map the sky given these components. Side-lobe pickup of the sun, whose
(a) Telescope response pattern with no baffle or ground/side shielding.

(b) No baffle or ground/side shielding, telescope response to Planck 10 GHz T signal + 5800 K sun on 7/15/2017 at 12 am

(c) Telescope response pattern with baffle and ground, back, and side shielding.

(d) Full shielding + baffle, telescope response to Planck 10 GHz T signal + 5800 K sun on 7/15/2017 at 12 am

(e) Optical Model of GreenPol telescope with addition of Baffle

(f) Full shielding + baffle, main-lobe (3 FWHM from beam center) only response to Planck 10 GHz T signal + 5800 K sun on 7/15/2017 at 12 am

Figure 3.2: Signal testing of effects of baffle on the main mirror and resulting signal maps.
location can be seen in the (side-lobe removed) map of sub-figure (f) to the far right, completely dominates measurements over a large portion of the sky, leaving little room for low noise measurements. With the addition of a baffle and additional shielding, this situation is improved marginally, as can be seen in sub-figures (c) and (d). While a large portion of the sky is still dominated by side-lobe pickup of the sun, there are now more regions of the sky accessible to lower noise measurements. These simulations illustrate the strong need for both an optimized baffle design, which reduces the complexity of our response pattern, and accurate modeling of our response pattern, which is necessary to effectively remove side-lobe contamination in our data and reduce systematics in our final sky maps.

3.1.2 Noise Filtering

Figure 3.3: Microwave testing of bessel-8GHz-filter solution. S21 / S12 represents income channels; S11 / S22 represents outcome channels.

To minimize noise from the inner environment of the detector, we employ
microwave filter chips (made in UCSB clean room) to pick desired frequencies such as 8 GHz, 10 GHz, 15 GHz, etc. From the previous microwave test, you can see that influences of copper shield is negligible since the peak of wave centred pretty well at 8 GHz.

We shield those filter chips with copper substrate and connect them to electronics of the detector below.

![Detector electronics](image)

**Figure 3.4: Detector electronics**

### 3.2 Mechanical Components

The telescope optics focus Cosmic Microwave Background radiation from the sky onto the detectors. In order to point the telescope at any place in the sky, the telescope needs to be able to spin around (this is the azimuth axis) and point from horizon to straight up (this is the elevation axis). Because the telescope is so large and heavy, it needs to be carefully engineered to keep it rigid as it is moved. The most important part is to keep the mirror rigid in exactly the right shape regardless of how the telescope is moved or positioned.
Mechanical components consist of

- Base-frame: including a rail which allows the telescope to slide back and forth (horizontally); a powerful motor which can handle equipment of hundreds of pounds and rotate (azimuth movement) without time delay; a control center that involves and well shields all important electronics such as computer and network.

- Top-frame: including a semicircle roller and gear arrays that allow mirrors and detectors to rotate up and down (elevation movement); strong supporting frames which can rigidly fix mirrors and detectors while rotating; Beam generator and GPS locator which allow real-time tracking of position; temperature sensor for monitoring environment temperature; removable polarizer as needed.

Figure 3.5: Telescope frame overview. The green items are beam generator and receiver for pointing purpose.
When the Galil motor interacts with the detector, there might be noise resulting from either rotation or vibration. In addition, systematic errors like responding delay also contribute to some unexpected ripples in the signal map. So, before we settle other experiments, tests on the level of systematic errors should be done.

From the test results above, we can see there are no obvious spurious signals due to Galil-Detector interactions. The noise is at a level less than 0.0004 volt.
3.3 Processing Procedure

A 500 MHz FPGA board is our centre processing unit. With a GPS connected, we can get real-time information of local time and coordinate, which is very essential in signal detecting because we always need to use time and coordinate information to calibrate the pointing of telescope. USB bridge and general-purpose input/output (GPIO) allow portable storage and make it very convenient to add additional pins as needed. We have 2 ADCs and 15 channels to collect digital signals from FPGA, which makes the data upload speed up a lot. Of course, in order to get fast coordinate (azimuth and elevation) information from detector, we prepare an Azimuth encoder and an elevation encoder.

![Figure 3.8: Key processing units.](image)

The data acquisition is real-time. That means at the moment the detector receive a signal, we will have some numerical records stored in data matrix. So, for
convenience, we let the processor automatically assign file names by GPS time. Majorly, there are two types of data in the storage: pointing data and science data. Pointing data tell where we are pointing for; consequently, it is the calibra-
tion tool for us to modify our information of sky coordinate, sky background, and rotation speed as we take operations on a graphic user interface (GUI) . Science data include the direct information from the detector bridged by the acquisition integrator.

The pointing data passed by the FPGA board will be our level-1 files and store in separate folders by genre. If we want to make a power spectrum or a radiation map, we have to demodulate the science data into T,Q,and U channels first, and then combine them with corresponding level-1 files (pointing data). The goodness of this method is that it speeds up the whole machine because we don’t need to do multi-processing at the same time. Instead, we have pointing information and science information collected separately, also data acquisition and data processing works separately. Moreover, preparing a level-1 folder is helpful to check if there is any data losing (if yes, we can skip those data points) because pointing data and science data are correlated through GPS time and they have to combine before using.
Chapter 4

Control System

4.1 Introduction

The challenge for computer programming of telescope control systems is the automatic control of hardware. Generally, computers are used to control only the dynamic aspects of a telescope such as antenna movement or position tracking. But the task of software as an interface between a human being and the telescope hardware is demanded every day. So, besides handling the automatic aspects of the system, it must configure into a user- friendly environment that all the complexity generated by an array of sophisticated equipment.

In my opinion, the key to achieving software flexibility is to make the system as modular as possible. Rather than thinking of the telescope as a single instrument, the first step is to try and think of it as a laboratory filled with devices or instruments which have to be coordinated to accomplish observations. We want to minimize, at least in software, the need for the various devices to communicate with each other; We want to isolate real-time dependencies within each piece of device software; We want to see if it is possible to coordinate scans via a ”set-up” mechanism common to the software for each device.

The next step toward a modular design is to condense the user requirements
into a minimum number of functions. We determined that there are four basic functions required of a telescope control system: control, monitor, message, and data production. Control predominately requires information owing from the user to the telescope, while the remaining three functions require only that information ow from the telescope to the user. Having a single mechanism to handle all the information within each function greatly reduces the number of interfaces used in the system and hides almost all of the implementation details from the programs.

We build our telescope control system though Python (mostly) and C++. I will show you in details in the following contents.

4.2 Graphical User Interface

4.2.1 GUI Overview

As I introduced before, I characterize the control system into four basic functions required of a telescope control system: control, monitor, message, and data production.

- Control: Movement Modular, including ”direct move”, ”continuous scan”, ”Tracking”, and ”Configuration”, is integrated at the top box of GUI. This is a very fundamental modular for telescope interface. In addition, there are switches for data acquisition (acq-tel), motor motion, configurations, and coordinate transformation (from az/el to ra/dec). Besides, we prepare a stop bottom, which will stop everything, for the sake of emergency.

- Monitor: Feedback block, monitoring parameters such as azimuth, elevation, signal strength, and temperature, is set up to the left bottom of GUI. Moreover, a real-time monitor is placed to the right half of GUI to monitor signal strength and map in real time.

- Message: Users can record instant parameters, plots, and configurations. They can also make comments/labels on those records. For example, a
label: a nutshell of a good day. What makes this function profound is that users can load past records through labels or specific information of time.

- Data production is hidden in the backstage of programs. To start data production, simply switch on "acq-tel".

4.2.2 Move in Real-Time

![Figure 4.1: GUI move function.]

Moving must be the most fundamental demand in user-telescope interface. The most basic operation is to have the telescope moving to any position you want it to be. Usually, we have two coordinate systems for celestial observations: horizontal coordinate system (azimuth, elevation/altitude) and equatorial coordinate system (right ascension, declination). Users can switch between these two coordinate systems by needs. This function allows the user either to manually
move certain degree of coordinate or to move to any desired coordinate. Hence, it is not only good at small angle adjustment but also at position locating.

(a) Horizontal coordinate system.

(b) Equatorial coordinate system.

Figure 4.2: Astronomy coordinate system.

4.2.3 Continuous Azimuth Scan

When we are mapping the sky, especially when we find some signal sources that we are interested in, it’s more convenient to scan over the azimuth as we lock on target sources. Also, due to the mass distribution of our telescope, it’s more steady to rotate horizontally. So, we specifically design a function for continuous azimuth scanning at a fixed elevation. Users can setup a range of scanning (producing a boxing map) and the range of scanning time can be from zero to infinity.

The principal objective is position following, so proportional control is required. But the telescope is always moving, and a proportional system will lag behind unless rate control is also incorporated. Factors such as friction and sticktion and small non-linearities can also disturb the tracking accuracy; these are mopped up by an integrator, so the overall system is described as PID (proportional, integral, derivative) control.
Figure 4.3: GUI azimuth scan function.

```
\[ P \quad K_P e(t) \]

Error \[ I \quad K_I \int_0^t e(\tau) d\tau \]

Process \[ D \quad K_D \frac{de(t)}{dt} \]

Setpoint
```

Figure 4.4: PID feedback loop.
4.2.4 Tracking

Tracking an astronomical body is a very commonly used function in telescope survey. Our database stores coordinates of many well-known celestial objects such as Sun, Moon, Venus, Mars, and Jupiter. If the user cannot find a desired choice in our menu, he/she can also manually input corresponding coordinate information of any astronomical body.

(a) Constant elevation scan. (b) Stepped elevation scan.

Figure 4.5: GUI tracking function.

In this block, we involve a "constant elevation scan" and a "stepped elevation scan". Obviously, stepped El scan is an advanced version of constant El scan; it produces a larger radiation map. However, the advantage of constant El scan is that it focuses on a small range of sky, so it produces more concrete data of a certain spot.

4.2.5 Configuration

In the configuration page, we can setup the observation location, which gives reference to adjust azimuth and elevation counts; we can change velocity and acceleration of telescope moving in (azimuth, elevation).

Notice that we have sections for azimuth offset and elevation offset. It is
possible to have intrinsic problems in telescope pointing. If unexpected bias was detected, we would have to find offsets and adjust the pointing through measurements.

### 4.2.6 Plot Tool

The plot tool is designed to work separately with the main GUI frame to avoid collapse of programs. It visualizes data files in a continuous timeline. Users have freedom to choose either to plot independent figures or overlap them together.

It is very important to monitor the cooler because only low temperature resolve microwave. If the environment is too hot, the hot noise would become significant in our plots. The tool can visualize raw data after demodulation and plot aligned power spectral density, which is very essential in wave analysis. In
addition, mean power spectral density of clear sky is very important in riding out of background noise.

Figure 4.7: Cooler test: temperature drops from room-level to a low value of 120K in 10 minutes.

(a) Raw signal data in all channels for clear sky.

(b) Power spectral density of all channels for clear sky.

Figure 4.8: All channels plot for clear sky.
4.2.7 Data Format

We choose HDF5 as our data file format because it allows us to store different types of data sets in a single file, which boots up the input/output of data flow. HDF5 is a compressed format that not only saves a lot of memory space but also simplifies the programming of I/O.
Chapter 5

Conclusion and Future

I have conducted research in different aspect ranging from manufacturing functional components of telescope to designing the control system and user interface of telescope.

We had deployed our telescope in Greenland near Summit Station in summer 2018. Observing conditions in the microwave at Summit are excellent, and studies of the seeing conditions rank this area among the best in the world. To move further, we still need a long period to carefully calibrate and test our equipment.

The Cosmic Microwave Background is one of the most valuable relics of the Universe. Observation of B-mode polarization can help answer one of the most fundamental questions of modern physics and cosmology — the origin of inflation in the early universe. With more efforts on new generations of telescope, I believe we can see further and clearer and make great breakthrough; just as the Event Horizon Telescope made the first-ever black hole image, I hope we will plot the clearest CMB map ever.
Appendix A

Scan Tests

Figure A.1: T channel scanning result of the moon. The moon looks elliptical because we projected data points on a celestial sphere.
(a) Q channel scanning result of Tau A in (az, el) coordinate.

(b) Q channel scanning result of Tau A in (ra, dec) coordinate.

(c) T channel scanning result of Tau A in (ra, dec) coordinate.

(d) U channel scanning result of Tau A in (ra, dec) coordinate.

Figure A.2: Scan tests of Tau A. Gaps in figures indicate missing data, which can be conquered by longer exposure time.
Appendix B

Clear Sky Data in Greenland Summit

Figure B.1: Output signals of clear sky background.
Figure B.2: Power spectral of clear sky background.
Bibliography


