Integration and Analysis of the Balloon-borne Telescope, SPIDER

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Abstract

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Since the discovery of cosmic microwave background (CMB) in 1965, the cosmological information encoded in it has motivated many ground and space observation programs to attempt to exploit its scientific potential. SPIDER is a balloon-borne telescope designed in particular to map the polarization pattern of the CMB at degree angular scales. SPIDER’s science instruments consist of 6 independent telescopes, operating at 94 and 150 GHz (SPIDER-1), with the second flight augmented by a suite of 285 GHz receivers (SPIDER-2). The cosmological results from SPIDER-1 were published in 2021, including a limit on the cosmological B-mode detection using the XFaster power spectrum estimator as its main pipeline. The second flight of SPIDER is being characterized at Princeton University while waiting for a launch opportunity from Antarctica.

This thesis includes an introduction of CMB polarization, the SPIDER program, and the data analysis and result of SPIDER-1 in Chapter 1. We derive 95% upper limits on the primordial tensor-to-scalar ratio r from Feldman-Cousins and Bayesian constructions, finding $r < 0.11$ and $r < 0.19$ respectively.

Following the results from SPIDER-1, Chapter 2 focuses on the XFaster spectrum estimator that was used as SPIDER’s main analysis pipeline and the SPIDER-1 consistency tests performed using this estimator. SPIDER-1 passes the outlier and distribution null test in two frequencies using 500 end-to-end simulations, with a PTE value of 0.78 and 0.56 respectively for the case of the combined frequencies.

The details of the SPIDER-2 cryogenic system and operation are in Chapter 3, while the 280 GHz telescope integration and characterization are introduced in Chapter 4. New data at 280 GHz from this second flight will complement the first flight, providing archival measurements of the polarized Galactic dust emission.

This document focuses on the personal works that I have done in the SPIDER team, with all other related matters being briefly introduced as supplementary materials for the complete understanding of the thesis. Works, figures and texts that are not directly credited to me will be cited accordingly.
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生幸知以，所行何终
Chapter 1

Introduction

The observation of cosmic microwave background (CMB) radiation started with a serendipitous detection by Penzias and Wilson in Crawford Hill New Jersey in 1964. See Figure 1.1.

![The 15 meter Holmdel horn antenna at Bell Telephone Laboratories in Holmdel, New Jersey. The antenna was 50 feet in length and the entire structure weighed about 18 tons. It was composed of aluminum with a steel base. In 1964, radio astronomers Robert Wilson and Arno Penzias discovered the cosmic microwave background radiation with it, for which they were awarded the 1978 Nobel prize in physics. Source:NASA on The Commons@Flickr](image)

Subsequent to the discovery, a series of observations were conducted to measure and characterize the signatures of the radiation, with increasing sensitivity and control of systematic errors over time.

This chapter introduces the physics behind the CMB, especially the polarization, in section 1.1. Then in section 1.2 I’ll introduce the SPIDER instrument that was designed to detect the $B$-mode polarization signal of CMB, to lead the hardware description detailed in Chapter 3 and 4. The analysis pipeline of SPIDER is introduced in section 1.3 for an understanding of the null test and XFaster work introduced in Chapter 2.
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1.1 The Cosmic Microwave Background

The universe is expanding. As the hot Big Bang cosmological model posits, the cosmic microwave background is a relic radiation from the photon decoupling era when photons cease to interact with the electrons and travel freely through space.

The universe was once in a hot dense state. As it expands, the energy density drops, protons and electrons tend to combine as more stable hydrogen atoms, causing the free electron density to decrease - the recombination phase. In other words, the chemical potential equilibrium in Equation 1.1 goes toward the right side gradually.

\[ p + e^- \leftrightarrow H + \gamma \]  

(1.1)

The probability of a photon interacting with an electron decreases as hydrogen forms, and once the mean free path of photons eventually becomes larger than the Hubble distance, the photons are decoupled from the charged particles and has remained free since then (the last scattering phase). This era is marked at redshift \( z = 1090 \) and temperature 2970 K, when the universe was 370,000 years old.

When we observe the CMB with our microwave antennas, the photons we collect have been travelling straight toward us since the last time they scattered with an electron. Hence through observing and analysing the CMB, many features of the early universe can be unveiled. Modern cosmology research has become a combination of rigid theoretical frameworks and more and more accurate observation to fine select the hypotheses.

1.1.1 The \( \Lambda \)CDM Recipe

Modern cosmology is built under the cosmological principle: The spatial distribution of matter in the universe is homogeneous and isotropic when viewed on a large enough scale. Under this principle and the fact that the universe is expanding, we apply the Friedmann-Robertson-Walker(FRW) metric to Einstein’s field equation (Eq. 1.2, notice that the cosmological constant is included on the right-hand side) to get the first Friedmann equation that gives the expansion rate in terms of the matter and radiation density \( \rho \), the curvature \( k \), and the cosmological constant \( \Lambda \) (Eq. 1.3):

\[ G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}, \]  

(1.2)

\[ H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3c^2} \rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}, \]  

(1.3)

where \( c \) is the speed of light, \( G \) is the gravitational constant, and \( H \) is the time-dependent Hubble parameter\(^1\).

\(^1\)The derivation of the first Friedmann equation can be found in many textbooks and is therefore omitted here.
We then decompose the matter and radiation density $\rho$ into energy densities of different components of the universe based on their own equation of state calculated from Boltzmann equations, in terms of the present-day density parameters for various species $\Omega_x$ (dimensionless, Eq. 1.4) and the critical density $\rho_{\text{crit}}^2$:

$$\Omega_x \equiv \frac{\rho_x(t = t_0)}{\rho_{\text{crit}}} = \frac{8\pi G \rho_x(t = t_0)}{3H_0^2},$$  \hspace{1cm} (1.4)

$$H(a)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2(\Omega_c + \Omega_b)a^{-3} + \Omega_{\text{rad}}a^{-4} + \Omega_Ka^{-2} + \Omega_{\Lambda}a^{-3(1+w)}.$$  \hspace{1cm} (1.5)

In Eq. 1.5 the subscript $x$ is replaced with $b$ for baryons, $c$ for cold dark matter, $\text{rad}$ for radiation (photons and relativistic neutrinos), and $\Lambda$ for dark energy. $w$ is the equation of state parameter of dark energy. The various $\Omega$ parameters add up to 1 by construction, and the simplest implementation of this treatment is called $\Lambda\text{CDM}$ ($\Lambda$ cold dark matter), and it is frequently referred to as the standard model of Big Bang cosmology.

The $\Lambda\text{CDM}$ model uses six independent parameters (baryon and dark matter density $\Omega_b h^2$, $\Omega_c h^2$, age of the universe $t_0$, scalar spectral index $n_s$, curvature fluctuation amplitude $\Delta^2_R$, reionization optical depth $\tau$) and some fixed natural values (such as $w = -1$) to describe the universe. Six is the smallest number of parameters needed to give an acceptable fit to current observations, and some extended models allow the fixed values such as the tensor-to-scalar ratio $r$ to vary, see section 1.1.3.

### 1.1.2 CMB Physics and Observation

The $\Lambda\text{CDM}$ model is not a model that has explicit physical theory for the origin or physical nature of dark matter or dark energy. It is based on various observations and the Occam’s razor principle - when you do not need an extra parameter, don’t add it in. Experiments are designed to either refine the parameters or possibly detect deviations. For example, observations have shown that the radiation density is very small today, and the current universe is dominated by dark energy - by anchoring the values of $\Omega_{\text{rad}}$ and $\Omega_{\Lambda}$.

Among all these observations, the CMB provides strong support for the Hot Big Bang model, and it has a unique position in revealing the mysteries of the universe.

A nearly perfect blackbody

The spectrum of CMB was measured accurately over a wide range of wavelengths by the FIRAS instrument on satellite COBE (1989), and was confirmed to be a nearly perfect blackbody spectrum along with other experiments. See Figure 1.2.

This isotropic microwave signal is consistent with a theory which predicted microwave radiation as a relic of an early state of the universe that was once hot, dense, opaque, and nearly homogeneous. It is then mapped at greater angular resolution by the Wilkinson Microwave Anisotropy Probe (WMAP) (2001), and the Planck satellite (2009) and lots of

\[\text{\textsuperscript{2}}\text{The critical density $\rho_{\text{crit}}$ is the present-day density which gives zero curvature $k$, assuming the cosmological constant $\Lambda$ is zero, regardless of its actual value.}\]
Chapter 1. Introduction

Figure 1.2: Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at 10 cm and longer wavelength. Reference: G.F. Smoot[1]

other experiments. These experiments found that after removing the dipole distortion in CMB temperature map caused by Doppler shift, there are order of $10^{-5}$ fluctuations in the uniform 2.7255 K map. See Figure 1.3.

Temperature fluctuation

There is copious information one can extract from the anisotropy of the CMB. It is widely agreed that the observed structure in the universe originates from primordial fluctuations of matter and energy that grew through gravitational instability. These perturbations evolve within a spacetime geometry that is spatially flat on the largest observed scales.

To better present this information, we consider the density fluctuations $\delta T / T$ at a given point $(\theta, \phi)$ on the sky:

$$\frac{\delta T}{T} (\theta, \phi) \equiv \frac{T(\theta, \phi) - \langle T \rangle}{\langle T \rangle}.$$

(1.6)

This is defined on the celestial sphere, so could be expanded in spherical harmonics:

$$\frac{\delta T}{T} (\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi).$$

(1.7)
1.1. The Cosmic Microwave Background

Many theoretical models make an assumption that the CMB is a Gaussian random field, under which the temperature fluctuation \( \delta T \) is Gaussian distributed, so are the spherical harmonic coefficients \( a_{\ell m} \) in each multipole \( \ell \). The most useful statistics is then the variance of the \( a_{\ell m} \)’s:

\[
C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle. \tag{1.8}
\]

Notice there are \( 2\ell + 1 \) modes in each multipole. The variance \( C_\ell \) is called the CMB angular power spectrum as it characterizes the size of the fluctuations as a function of angular scale \( \ell \). Our universe is then one realization of a given model. See Figure 1.4 for an example.

As shown in the Figure, different multipole ranges of the spectrum reveal different mechanisms of the universe. For example, the larger scales with \( \ell < 100 \) describe the scales that have not yet evolved significantly. Fluctuations at these scales are a result of the combination of gravitational redshift and intrinsic temperature fluctuations, and are usually referred to as the Sachs-Wolfe effect. The smaller scales, between \( 100 < \ell < 1000 \), are gravity-driven acoustic oscillations that happen in photon-baryon fluids.\(^3\)

On the observation’s side, this paradigm has proven to be in remarkable agreement with the majority of all observation tests. The observed CMB fluctuations are Gaussian-distributed. The power spectrum is nearly scale-invariant, and encodes correlations on

\(^3\)For details of this discussion, see [2].
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Figure 1.4: A theoretical CMB temperature anisotropy power spectrum using a standard ΛCDM model from CMBFAST. The tensor contribution is also shown in the dashed line with an arbitrary normalization. Figure taken from [2].

scales larger than the horizon during recombination.

It is customary to plot the function in $\ell(\ell + 1)C_\ell / 2\pi$, which tells us the contribution per logarithmic interval in $\ell$ to the total power of the cosmic microwave background. For example, see Figure 1.5.

So far we have linked observations of the CMB with predictions from theoretical model. Comparisons between the two can be used to fit for the cosmological parameters, or sieve out the models that contradicts observation results.

1.1.3 Primordial Tensor Modes and CMB Polarization

The ΛCDM paradigm doesn’t specifically answer the question of how the universe started or why the current universe has features such as Λ domination. Mechanisms within different contexts have been proposed to answer these questions without being inconsistent with the observations. Among those, the inflation hypothesis comes in to solve these problems by assuming that there was a period of the universe when the expansion was accelerating[3]. The mechanism agrees with the well-studied scalar perturbations, while also predicts a spectrum of tensor perturbations - primordial gravitational waves. These primordial gravitational waves have wavelengths on the Gpc scale

---

4CMBFAST is a code package. See https://lambda.gsfc.nasa.gov/toolbox/tb_cmbfast_ov.cfm.
5There are other popular scenarios that introduce primordial tensor modes, among which the most widely accepted explanation for their origin is in the context of cosmic inflation.
1.1. The Cosmic Microwave Background

**Figure 1.5:** A combined CMB-only TT power spectrum measurement as a function of angular scale up to $\ell = 4000$. The plot shows CMB lensed bandpowers from recent ACTPol, Planck, and SPT measurements marginalized over Galactic and extragalactic foreground emission and Sunyaev-Zel’dovich effects. For comparison, a theoretical curve is shown that was calculated by the LAMBDA group using parameters of the Planck team 2015 best-fit PlanckTT+lowP $\Lambda$CDM model. *Image Credit: NASA / LAMBDA Archive Team.*

and cannot be observed by LIGO-like experiments with current technology, but they induce distortions in the CMB especially on large scales and leave a distinctive fingerprint on the CMB polarization maps - the B-modes.

**Generating polarization**

A concise mathematical proof rigidly shows that the scalar metric perturbations in inflation theory is not introducing $B$-mode in the CMB and only the tensor perturbation does\[4\] [5]. This paragraph briefly introduces the generation of CMB polarization in a series of conceptual discussions.

Two steps are taken to understand this matter.

One, the Compton scattering in the recombination era generates polarization with and only with a non-zero quadrupole pattern in anisotropic radiation. See Figure 1.6. After the linear polarization is introduced, we then adopt the Stokes parameters as a useful tool to describe the polarization generated. See left side of Figure 1.7.

Notice that the local $Q$ and $U$ polarization parameters, while being complete to describe a headless polarization vector field, are not rotational invariant. For example, when you rotate angle $\psi$, they transform as spin-2 fields: $(Q \pm iU)(\hat{n}) \rightarrow e^{\pm 2i\psi}(Q \pm iU)(\hat{n})$. 
Chapter 1. Introduction

**Figure 1.6:** The classical demonstration of how quadrupole anisotropy generates polarization. Two pairs of opposite un-polarized photon scatters with an electron (only one of each pair is shown). Temperature differences in these photons made the photon that scattered off have different intensity at perpendicular directions, hence this photon is polarized. *Figure taken from [6]*

**Figure 1.7:** *Left:* Q and U Stokes parameters to describe components for polarization. It is worth noting that these values, while straightforward to measure, are not coordinate-invariant. Their behavior changes over rotations. Hence it’s important to decompose them into gauge-invariant E and B modes. *Right:* The E and B-modes are curl-free divergence field, and divergence-free curl field respectively, as their electromagnetic analogies. Note that if reflected across a line going through the center the E-patterns are unchanged, while the B-patterns get interchanged as a pseudo-scalar. *Concept drawing from [7].*
The harmonic analysis of \( Q + iU \) therefore requires expansion on the sphere in terms of spin-2 spherical harmonics:

\[
(Q + iU)(\hat{n}) = \sum_{\ell,m} a_{\ell m}^{(\pm 2)} [\pm 2 Y_{\ell m}(\hat{n})].
\] (1.9)

In understanding their statistical behaviors, a useful thing to do is to decompose them into two scalar (spin-0) fields, \( E \) and \( B \), that are divergence and curl fields respectively:

\[
E(\hat{n}) = \sum_{\ell,m} a_{\ell m}^E Y_{\ell m}(\hat{n}),
\]

\[
B(\hat{n}) = \sum_{\ell,m} a_{\ell m}^B Y_{\ell m}(\hat{n}),
\] (1.10)

where \( a_{\ell m}^{E,B} \)s are the linear combinations of spin-2 \( a_{\ell m} \)s:

\[
a_{\ell m}^E \equiv -\frac{1}{2} (a_{\ell m}^{(2)} + a_{\ell m}^{(-2)}),
\]

\[
a_{\ell m}^B \equiv -\frac{1}{2i} (a_{\ell m}^{(2)} - a_{\ell m}^{(-2)}).
\] (1.11)

The polarization signal is small compared to the temperature anisotropy due to the limitation of free electrons at that era. This is confirmed by observed results in which the EE power spectra are smaller than the temperatures by roughly a factor of 1/50.

Two, the scalar component of the spatial tensor perturbations can only generate \( E \)-mode, while \( B \)-mode can only be generated through tensor perturbations. We explain this in symmetry. While a single plane-wave scalar perturbation is directed along one axis, the quadrupole corresponding to this radiation can only form with azimuthal symmetry around this axis. See Figure 1.8. However tensor mode doesn’t need to hold this symmetry.

**Primordial \( B \)-modes and observation**

The discussion above leads to adding a new parameter into the simplest 6-parameter \( \Lambda CDM \) scheme, the tensor-to-scalar ratio \( r \), being defined as the ratio of perturbation amplitudes of tensor and scalar modes \( A_T, A_s \) respectively,

\[
r = \frac{A_T}{A_s}.
\] (1.12)

An non-zero \( r \) measured from observations would provide high constraint on models that involve a primordial tensor perturbation. See Figure 1.9.

After we linked the parameter \( r \) and observational data, constraining theoretical models is made possible by observing polarized CMB fields. A one sentence conclusion is, if we observe a \( B \)-mode in CMB polarization after taking into account of CMB lensing and foreground dust emission, we know that it comes from a tensor perturbation - the primordial gravitational waves, without other fluctuations and contaminations.
Chapter 1. Introduction

Figure 1.8: Polarization pattern generated by a scalar perturbation aligned with the \( x \)-axis. When observed along the \( z \)-axis, the quadrupoles generated can only form an \( E \)-mode polarization with its direction either perpendicular or parallel to the direction of perturbation, shown in the 3rd row. A tensor mode could generate quadrupole pattern that is rotated by 45° around the \( z \)-axis coming out of the page. *Figure taken from [8].*

Figure 1.9: \( B \)-mode CMB polarization anisotropy spectrum generated by tensor modes for two different \( r \) values 0.001 and 0.05. It’s clear that the \( E \)-mode is dominating the polarization spectra with the currently allowed values of \( r \). On small scales, \( B \)-mode polarization is generated by the gravitational lensing effect due to intervening structure acting on the primary \( E \)-mode polarization. The experimental measurements have detected this lensing signal. *Figure taken from [9].*
CMB $B$-modes are then the most sensitive probe of primordial tensor modes and has its unique position in modern cosmology.

1.2 The SPIDER Instrument

I now introduce the SPIDER telescope, a balloon-borne instrument designed to map the polarization of the cosmic microwave background on degree angular scales. It targets the $B$-mode signature of primordial gravitational waves in the CMB described in section 1.1.

Balloon-borne telescopes have their unique positions in CMB observation as background thermal emission and fluctuations are largely reduced in the stratosphere. SPIDER’s first long-duration balloon (LDB) flight in January 2015 deployed a total of 2400 antenna-coupled transition edge sensors at 95 GHz and 150 GHz. The second flight, which was delayed due to global pandemic COVID-19, is planning to have an additional 1536 detectors of 280 GHz together with some of the best performing detectors from the first flight. The 280 GHz telescope/insert will be described in detail in Chapter 4. A brand new cryogenic system was also made for the second flight and the details of the SPIDER-2 cryostat will be described in Chapter 3.

1.2.1 Telescopes, Focal Plane and Detectors

SPIDER was designed to be a modular instrument, where six independently controlled monochromatic refracting telescopes are housed within a single liquid helium cryostat, and supported and pointed by a lightweight carbon fiber gondola. (Figures in Chapter 4.) This design has made inserts reusable for different cryostats and three of the first flight inserts were recycled in the second flight cryostat. The design also cools down the entire insert to 4K up to the objective lens.

Figure 1.10 shows the complete optical path going from sky to the end of the baseplate, which mounts to the bottom of the 4K main tank in the cryostat. Starting from the baffles, photons go through a vacuum window, a stack of filters, polarization modulator (half-wave plates in our case), and two optical lenses to finally reach the detector plane.

Optics

Each receiver is an axisymmetric two-lens cryogenic refractor. The 4K high density polyethylene lenses (objective and eyepiece) are cooled down to 4K, and focus light onto a 300mK focal plane. The blackened cold stop and internal baffles surrounding the optics are cooled to 2K in order to reduce stray photon loading on the detectors. A sapphire half-wave plate (HWP) mounted to a 4K flange skyward of each insert is rotated to a new fixed orientation angle twice daily to provide polarization modulation.

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6 The text in this section follows citation [10] “A Constraint on Primordial $B$-Modes from the First Flight of the SPIDER Balloon-Borne Telescope by SPIDER Collaboration” of which I participated in the writing. Text is modified and extended to include the SPIDER-2 instrument.
Chapter 1. Introduction

Figure 1.10: A complete CAD model of the optical path from SPIDER-1. The 4K+ elements are mounted at the different stages of the cryostat, where the window buckets sit at the top dome of the cryostat, and thermal filters are installed on cryo stages VCS1 and VCS2 (vapor-cooled shields, see Chapter 4). The half-wave plates (HWP) are mounted right before the 4K inserts, which are then inserted into the main tank slots. Figure taken from [11].

Each receiver looks at the sky through a series of reflective metal-mesh and Nylon filters to reduce infrared loading on the cryogenic system and detectors as well as a thin ultra-high molecular weight polyethylene (UHMWPE) vacuum window. Single-layer antireflection teflon coatings that match to each frequency are attached to each side of the HWPs, lenses, vacuum windows and relevant filters.

Focal plane unit

The sensors in SPIDER are Ti and AlMn TES detectors respectively for 95/150 GHz and 280 GHz detectors (SPIDER-2 only).

The focal plane wafer is patterned with an array of polarization sensitive pixels. For the first generation, two interpenetrating arrays of slot antennas were coupled to the detectors[13]. For the 280 GHz, an array of feedhorn antennas was used[14]. A complete measurement of partial linear polarization (I,Q,U) is obtained for each pixel through rotation of the HWP and the sky. A microstrip feed network coherently couples optical power from antennas to the thermally isolated bolometer island. The TESes are read out using a time-division SQUID multiplexing system. Both of these are housed within extensive magnetic shielding.
1.2. The Spider Instrument

Figure 1.11: A 150 GHz focal plane unit of Spider-1. Left: the underside of a fully populated 150 GHz focal plane during assembly, with the $8 \times 8$ grid of pixels visible on each of the four tiles. Middle: A microscope image of a bolometer island and surrounding dipole antenna array. Right: A close-up image of the island, with both TES devices and the meandering gold resistor clearly visible. Figure modified from [12].

1.2.2 the Cryogenic System

In order to run these transition edge sensors on a balloon, a bespoke cryogenic system was designed for each flight to make the flight duration as long as possible. A design of the first-flight cryostat can be found in [15].

The cryostat consists of two liquid helium tanks: a $\sim 1200$L main tank and a $\sim 16$L superfluid tank. The main tank is maintained at 1bar pressure during the flight, providing 4K cooling power from $^4$He to the telescopes and 4K stage of the $^3$He sorption coolers. The boil-off from the main tank flows through heat exchangers on each of two vapor-cooled shields that intercept the radiative and conductive parasitic loads on the cryogenic system and cool the infrared filter stack. The superfluid tank provides cooling power at 1.6K to the 2K stage of $^3$He sorption cryo-fridges and internal 2K optical components.

The superfluid tank fills continuously from the main tank through a capillary system, and is maintained at the ambient pressure of the altitude at float (about 6 mbar). The superfluid system is pumped down on the ground and maintained at low pressure during launch and ascent with a small diaphragm pump on the gondola. The $^3$He sorption cryo-fridge cools down the focal planes to 300mK.

Details, integration and characterization of the second-flight cryostat can be found in Chapter 3.

1.2.3 the Gondola and Integration

The cryostat is supported within a lightweight carbon fiber gondola[16]. A reaction wheel and motorized pivot scan the gondola in azimuth, while a linear drive steps the cryostat in elevation[17]. Absolute referencing of the payload orientation is provided by a suite of three star cameras: one attached to the cryostat and oriented along the boresight axis, the other two mounted to the gondola’s outer frame on a rotating table that allows them to track the sky during azimuthal scans. See Figure 1.12 for a drawing of the gondola system.
Information from the star cameras is combined with that from GPS receivers, sun sensors, encoders, and gyroscopes to enable in-flight pointing and post-flight point reconstruction. Control and monitoring of the pointing and cryogenic systems is performed by a pair of redundant flight computers interfaced with the custom BLASTbus electronics[18].

A sun shield protects the instrument and optics during the 24-hour Antarctic summer daylight. Continuous electric power is provided by a 2 kW solar panel system, while various arrays provide commanding, telemetry, and location information during the flight.

1.3 Data Analysis Methodology and Result

The quality and quantity of CMB data have improved dramatically over the past decades. Anisotropies in the CMB have been measured by dozens of experiments and the size of data collected will keep expanding, providing a deeper understanding of the CMB in different aspects. While different experiments have different focus on questions to answer, they all go through similar steps from raw data to parameter constraints. See Chart 1.13.

The remainder of this section will briefly introduce data analysis that was performed in SPIDER-1 and its result.

The text in this section follows citation [10] "A Constraint on Primordial B-Modes from the First Flight of the SPIDER Balloon-Borne Telescope by SPIDER Collaboration" of which I participated in the writing. Text is modified to suit the purpose of introducing a complete analysis pipeline.
1.3. Data Analysis Methodology and Result

Figure 1.13: A naive overview of how to get from raw data to likelihood and parameter constraints. Each single step of the analysis pipeline is non-trivial. Different estimators implement this differently, while in SPIDER’s case, a large ensemble of simulation maps and a hybrid of Monte Carlo and quadratic estimator, XFaster, were used to produce both bandpower and likelihood estimations.

1.3.1 Analysis Pipeline in SPIDER-1

The effort of converting a large data set of time-ordered data (TOD) to CMB maps and eventually cosmological parameters is nontrivial given the large dataset modern observations usually produce. The first flight of SPIDER retrieved 2.1TB of TOD. These data were carefully analyzed and provided a constraint on the tensor-to-scalar ratio $r$. SPIDER-2 will follow the same analysis steps with pipeline modifications if new systematics needed extra care.

Low level data processing and mapmaking

The abbreviated discussion from raw data to calibrated maps and simulations of the sky will be presented here. Details of these can be found in previous theses: [12], [19] and [20].

"Chunking"

SPIDER’s raw data consist of 2.1TB of time-ordered samples. Samples are grouped into contiguous 10 minute chunks. These evenly partition the periods between HWP angle steps and divide only at turn-arounds of the azimuthal scan. The chunk length is chosen to be insensitive to the changes in telescope elevation or cryogenic temperatures but contain a sufficient number of samples for estimating low-frequency noise.

---

8In the comparison pipeline: Noise Simulation Independent (NSI), the chunking is done differently. See section 1.3.1.
**Timestream cleaning**

The intermittent and quasi-stationary noises are the two broad classes of correlated noise in the SPIDER timestream data in addition to the expected Gaussian uncorrelated noise.

**Intermittent** noise encompasses noise sources that appear to be discretely on or off at any given time. The primary sources of intermittent noise are the telemetry transmitters on board the payload. Other sources include cosmic ray interactions in the detectors and various glitches or step discontinuities due to the multiplexing readout.

**Quasi-stationary** noise consists of non-astrophysical signals that are partially correlated across the field of view and change very little over multiple azimuthal scans. These have a peak-to-peak amplitude typically less than $3 \, mK_{CMB}$, and vary slowly over time. It is believed that the majority of this contamination is sourced by sidelobe pickup primarily from the Earth’s limb. Additionally, RF-coupled interference was observed in some of the detector channels.

These noises are treated in different ways in timestream cleaning. The intermittent noise is mitigated by **flagging** affected detector samples: they are tagged, replaced with constrained noise realizations, and excluded from map-making. For intermittent noise that has step discontinuities, in addition to flagging the discontinuity itself we adjust the data using a linear fit to data before and after the event. Simulations show that it has negligible effect on signal response. Quasi-stationary noise is mitigated by time-domain **filtering** of this flagged data set conducted at full detector sample rate.

**Detector calibration**

In-flight data are used for the absolute calibration to monitor gain fluctuations and to refine pre-launch estimates of beam response and pointing offsets. The absolute calibration is derived by cross-calibrating degree-scale power with *Planck* temperature anisotropy data at 100 and 143GHz. This procedure finds the absolute calibration factor and parameterized beam model that minimizes the difference with the *Planck* temperature spectra at a per-detector level in the range $100 < \ell < 275(375)$ for the 95 (150) GHz frequency band. The absolute calibration is obtained by finding the scalar $c$, that minimizes total deviation:

$$
\sum_{\ell = \ell_1}^{\ell_2} R_{\ell} \equiv \sum_{\ell = \ell_1}^{\ell_2} \left| c \frac{\hat{C}_{TT}^{\ell}}{\hat{C}_{TT,ref}^{\ell}} b_{\ell}^{Planck} b_{\ell}^{SPIDER} - 1 \right|
$$

where $\ell_1 = 100$ and $\ell_2 = 275(375)$ for the 95 (150) GHz frequency band. We use $\hat{C}_{TT}^{\ell,ref}$ to represent a temperature power spectrum calculated using maps obtained from rescanning the *Planck* half-mission reference maps while $\hat{C}_{TT}^{\ell}$ is calculated from single-detector maps cross-correlated with a *Planck* half-mission map. The beam transfer functions, $b_{\ell}^{Planck}$ and $b_{\ell}^{SPIDER}$, quantify the relative sensitivity the *Planck* and SPIDER spatial response as a function of multipole. We use a simple Gaussian beam model to extend this calibration to other angular scalars included in our analysis. Each telescope is fit with
a single common beam model which is then used to determine an independent calibration factor for each individual detector.

**Pointing offset**

Each detector’s pointing relative to the boresight star camera solution is initially characterized by maximizing the cross-correlation between single-detector SPIDER temperature maps and *Planck* maps. To reduce error, a model for each detector tile is fit to the individual detector offsets. These initial pointing offsets are refined using a time-domain “deprojection” technique\[22\]. This method involves fitting for perturbations in leading-order beam systematics - calibration, pointing offset, width and ellipticity - using time-domain templates generated from *Planck* temperature maps and their derivatives.

**Mapmaking**

The processed data are binned into a two-dimensional map of the microwave sky by combining detector signal timestreams with reconstructed pointing and polarization angles. See Chart 1.14.

**FIGURE 1.14:** A demonstration of low level analysis pipeline from Local Sidereal Time (LST) day timestream to map. The detector signals input to the map maker are flagged, cleaned, and filtered before having calibrations applied. The input pointing timestreams are constructed by combining the boresight pointing and HWP angles with per-detector polarization angles and pointing offsets. Maps are made for each receiver and then combined by frequency band.

Maps are made for each receiver and then combined by frequency band. The resulting maps use HEALPix pixelization\(^9\) with $N_{\text{side}} = 512(\sim 6.9'\text{ resolution}).$

SPIDER’s cleaning and filtering process makes noise in the data largely uncorrelated among channels and over time, with an approximately diagonal noise covariance between detector samples. This simplification allows the maps to be constructed with

simple weighted sums in each pixel, which in turn makes it computationally feasible to simulate large ensembles of time-domain simulations that include all relevant aspects of the experiment. The weights are inverse noise variances of the cleaned and filtered data.

**Simulated maps**

Using the same flagging, filtering, beams, pointing, and polarization angles as SPIDER, the simulated data can include signal from an input sky map, random noise generated from a power spectral density, and/or various injected glitches and systematics.

Noise simulations are generated separately for each detector and are derived from the power spectral density of signal subtracted timestreams, averaged over all 10-minute chunks of data. As such the fiducial noise model assumes the detector noise is stationary and uncorrelated over the course of flight.

Signal simulations can be made from Gaussian random realizations using a power spectrum as a source, or from known signals such as Planck. In order to simulate the effects of various instrumental properties and systematics, channel parameter values may be applied differently when simulating timestreams.

The simulations will be talked about in detail in Chapter 2.

**Power spectrum estimation and null tests**

Two parallel power spectrum estimation pipelines have been developed for SPIDER. XFaster, a maximum likelihood estimator; and a simpler Noise Simulation Independent (NSI) pipeline. Each pipeline begins with a set of maps constructed from independent subsets of SPIDER’s data, from which we construct a set of cross-spectra. XFaster uses four data subsets, each combining every fourth 10-minute chunk of data - the same chunks used for low-level processing. The NSI algorithm benefits from having a larger number of cross-spectra - this pipeline works with 14 data subsets composed from interleaved 3-minute chunks.

Each pipeline ultimately produces a spectrum and covariance matrix for $33 \leq \ell \leq 257$, binned into nine “science” bandpowers with an $\ell$ width of 25. One lower ($8 \leq \ell \leq 32$) and two higher bandpowers are also computed for each pipeline in order to accurately account for their leakage into the nine bins used for cosmological analysis. The bin starting at $\ell = 8$ was found to contain residual systematic signals, and the bins above $\ell = 257$ contribute little to the cosmological and foreground constraints; thus, they are excluded from the science bins. Throughout the following, unless explicitly stated otherwise, the lowest or first bin refers to the first science bin, i.e. that starts at $\ell = 33$.

**XFaster**

XFaster iteratively solves for bandpower deviations from a fiducial full-sky signal model using an approximation for the likelihood of cut-sky $a_{\ell m}$ modes. This signal model is constructed using the MASTER formalism [23], in which the mode-mixing from the mask is computed analytically (including an $E$-$B$ mixing component), the beams are pre-computed, and the filter transfer functions are estimated from an ensemble of 1000 $\Lambda$CDM simulations run through the full map-making pipeline.
In addition to the signal power, XFaster also estimates the instrumental noise from the auto- and cross-spectra of the input maps. An ensemble of 1000 time-domain noise simulations is input to the pipeline to provide a fiducial noise model. The noise model is itself iteratively recalibrated by including deviations from the fiducial model as parameters in the likelihood maximization alongside the signal bandpowers.

Details of the XFaster algorithm and the (null) power spectrum estimation pipeline will be talked about in detail in Chapter 2.

**NSI** the Noise Simulation Independent (NSI) pipeline uses the cross-spectra of 14 temporally independent maps at each observing frequency, generated from interleaved 3-minute data chunks. All possible cross-spectra are constructed from the map ensemble, providing 91 at each single frequency (95×95 GHz or 150×150 GHz) and 196 with one map at each frequency (95×150 GHz), for a combined total of 378 cross-spectra. The bandpowers are estimated from the noise-weighted mean of all cross-spectra. The associated statistical uncertainties are estimated from the distributions of these cross-spectra by computing the standard error on the mean with jackknife resampling.

The NSI pipeline uses a two-dimensional “transfer matrix” to correct the power spectra for mode mixing and power attenuation from filtering. This approach considers the leakage from a given multipole bin to all others, both within the same spectrum and between spectral types \((TT, EE, BB)\). The transfer matrix is constructed from a simulation ensemble in which each simulated map has a source spectrum with only one non-zero multipole bin, which is set to the value of the appropriate fiducial ΛCDM spectrum. When the maps are processed with the NSI pipeline, the ratio of the output and input spectra encodes the leakage from that bin to all others. Further discussion of this method and its impact on the recovered spectra is provided in [24].

**Null test** Null tests check for systematic noise residuals in the differences between pairs of maps, constructed from various splits of SPIDER’s data by time period or detector set. The pairs of maps are chosen to share a common signal but to have independent noise, and to maximize the residuals from possible systematic effects within the data. If the power spectra of these differences are consistent with statistical noise, then we have evidence that systematic errors probed by the splits do not significantly contaminate the maps. These tests are performed separately for both the NSI and XFaster pipelines. Chapter 2 provides a total description of the null analysis for SPIDER-1.

**Parameter likelihoods**

Two approaches are taken to construct and sample the parameter likelihood for the tensor-to-scalar ratio \(r\). The two approaches differ in the way that parameter covariance is propagated. The XFaster likelihood construction is Gaussian in the \(a_{m}\) coefficients, and the algorithm can naturally be adapted to sample that likelihood as a function of parameters other than bandpowers. It samples a likelihood of the \(a_{m}s\) as a function of the three-dimensional parameter space of \(r\), and \(as\), the foreground template fitting parameters, which then is marginalized into a final posterior on \(r\).
The NSI method and SMICA, an independent foreground cleaning method, proceed instead from the bandpowers computed, assuming Gaussian likelihoods for the CMB bandpowers in order to sample additional parameters. It samples a profile likelihood in $r$, which optimizes over foreground parameter dependence in a separate step. All other $\Lambda$CDM parameters are held fixed. Details of the likelihood sampling can be found in [10].

1.3.2 SPIDER-1’s Results

In SPIDER-1’s analysis, the XFaster pipeline is used as our baseline given its generality and self-consistency. The result from the first flight of SPIDER will be shortly presented here.

Polarization maps

With the analysis described in section 1.3.1, the polarization maps are shown in Figure 1.15.

![Polarization maps](image)

**Figure 1.15:** Q and U polarization maps as observed by SPIDER’s 95 and 150GHz receivers. The maps have been smoothed with a 10’ Gaussian for clarity. The temperature-to-polarization leakage from the map maker is subtracted, although this effect is not visible by eye. The white outline indicates the sky region used to compute power spectra (2,480 square degrees), though the additional point source mask is not shown.
1.3. Data Analysis Methodology and Result

Power spectra

The power spectra are estimated using the XFaster estimator from the polarization maps, with 1000 end-to-end simulations used as Monte-Carlo ensembles. See Figure 1.16.

![Power spectra figure](image)

**Figure 1.16:** Raw power spectra from the XFaster and NSI pipelines. Spectra are computed for each of the two frequency bands individually in the left and middle column, and the combined best estimated spectrum from both frequencies is shown in the right column. The best fit Planck $\Lambda$CDM power spectrum from is shown in grey. Error bars do not include sample variance in order to better compare the instrumental noise estimates between the two power spectrum pipelines.

Model and remove diffuse Galactic emission are essential in recovering polarized CMB signal especially on large scales. We implemented a variety of methods to disentangle the Galactic and cosmological signals in both spectra and map domain. In both analyses, the emission from interstellar dust is assumed to be the only polarized foreground in our
region. A harmonic-space method was used to assess the contribution of the Galactic synchrotron emission to the polarized signal and found it negligible for the cleaning purpose.

The map domain template-subtraction assumes that the spatial morphology of the polarized emission from interstellar dust is frequency independent, such that it can be projected out of a map at a given frequency by fitting a scalar amplitude to a morphological template of the emission.

The spectrum domain, Spectral Matching independent Component Analysis (SMICA) is done to recover the CMB component from our raw spectra. It calculates the cross-spectra that preserve the joint correlation structure between the input maps, and the power is then partitioned among individual components based on their spectral shape. The fitted components uniquely determine the weight assigned to each map and allow recovery of component-separated maps. It then differs from the template-subtraction method in that it assumes little about the spatial morphology, but adopts a rigid model for the spectral energy density of the dust foreground.

Their consistency is assessed as shown in Figure 1.17 where all pipelines remove significant foreground power in the low $\ell$ bins and yield $EE$ spectra in good agreement among them and with the $\Lambda$CDM model. The details of these foreground removing methods and pipeline validation can be found in an upcoming foreground paper from the SPIDER collaboration.

Likelihoods

Here I show a summary of $r$-likelihood values from the XFaster pipeline with nominal upper limits. Similar numbers have been computed for other methods and can be found in [10]. The 95% upper limits on the primordial tensor-to-scalar ratio from Bayesian and Feldman-Cousins constructions find $r<0.19$ and $r<0.11$ respectively. See Figure 1.18 and Figure 1.19.

The XFaster likelihood result gives a $r_{mle} = -0.21$. We find that 6% of simulations with input $r=0$ yield a $r_{mle} < -0.21$ which suggests such a value is not inconsistent with expected noise fluctuations. Subject to the physical constraint that $r \geq 0$, imposing a flat prior on $r$ and truncated for $r < 0$, we obtain a 95% Bayesian upper limit of $r < 0.19$. In the Feldman-Cousins approach([25]) where a classical confidence interval for $r$ is constructed, the observed $r_{mle}$ yields an upper limit of $r < 0.11(95\%CL)$.

1.4 Conclusion

The SPIDER project is designed to detect a unique polarization signal - primordial $B$-mode of the cosmic microwave background, which tests the prediction of primordial gravitational waves under the construction of inflationary cosmological model.

The instrument consists of a 1300 L Helium cryostat that houses the six telescopes, and a gondola system to mechanically support the instrument. SPIDER-1 flew in January 2015 with three 90 GHz and three 150 GHz telescopes and collected 1.2 TB of data. SPIDER-2 which is deploying three 280 GHz telescopes, is under planning.
1.4. Conclusion

To analyze the large volume of SPIDER-1’s data, a detailed analysis pipeline is crafted with multiple independent-yet-consistent methods, of which the main pipeline XFaster gives an upper limit of 0.11 and 0.19 from bayesian and classical interpretations respectively on the tensor-to-scalar ratio $r$.

SPIDER-1’s result had shown that the polarized Galactic dust emission is observed with high signal-to-noise. An improved characterization of the foreground emission is the focus of SPIDER-2’s upcoming flight.

The following chapters will focus on each topic that I contributed to most in the SPIDER project, which includes the null test pipeline and results that validates the data of SPIDER-I, the SPIDER-2 cryostat system and it’s integration, and the SPIDER-2 receiver system and it’s testing.
Figure 1.18: The combined XFaster likelihood for $r$ and $\alpha$, imposing no priors on these parameters. $1\sigma$ constraints for the 353-100GHz template are shown in the panel titles.

Figure 1.19: Feldman-Cousins 95% confidence interval on $r$ as a function of $r_{mle}$, derived from template-subtracted XFaster likelihoods. For each input $r$, 300 XFaster simulations were made to produce a histogram of $r_{mle}$, which we smooth by fitting a Gaussian model in a good fit. At each input $r$, 95% of simulations results lie between the dotted orange lines.
Chapter 2

SPIDER-1 Null Tests

Null tests are useful and standard tools for checking data self-consistency in many fields, including CMB analysis. In this chapter I will introduce the null tests that I did for SPIDER-1 CMB data analysis in detail. \(^1\)

In section 2.1, the XFaster spectrum and likelihood estimator used as one of the two data processing pipelines for SPIDER-1 analysis is introduced. The null test pipeline using XFaster, and the development and discussion of that, will be presented in section 2.2. Following the results, the statistical analysis and further discussion of the null spectra are given in section 2.3.

2.1 The XFaster Power Spectrum and Likelihood Estimator

The quality and quantity of CMB data have improved dramatically over the past decades. Data sets are far too large for brute-force calculations, calling for faster, more complex and modern analysis methods without losing too much information in going from measured time-ordered-data (TOD) to power spectra. The building block of which is the likelihood function.

With the likelihood function we can determine the central value of parameters of a theoretical model, which are best estimated where the likelihood function is at the maximum; along with error bars, determined by the width of the likelihood function around its peak.

This section will introduce the detailed algorithm, assumptions, and implementations behind the XFaster bandpower estimator. A small subsection will also briefly introduce the parameter estimation that XFaster does. While it is not a main ingredient for this chapter, it helps to understand the SPIDER-1 result talked about in chapter 1.

2.1.1 A Pseudo-\(C_\ell\) and Quadratic Estimator

XFaster is a method that tries to blend in the maximum-likelihood approach into a traditional Monte-Carlo estimator. In a traditional formalism, it is common to use a large ensemble of signal and noise simulations to estimate power spectra. These end-to-end

\(^1\)Texts and figures in this chapter are taken or modified from citation [26], “The XFaster Power Spectrum and Likelihood Estimator for the Analysis of Cosmic Microwave Background Maps”, of which I co-authored with Dr. A. Gambrel and Dr. A. Rahlin.
simulations are used in a way where noise bias is subtracted from the cut sky power spectrum, and then divided by a transfer function that is calibrated using the signal ensembles [23]. This method gives an unbiased estimate of the bandpowers as long as the noise and signal simulations are good representatives of the data, and their covariance is determined from the simulations.

However, it is non-trivial to produce accurate simulated map ensembles which an accurate covariance estimation requires. As generating the simulation ensemble is computational expensive, this method can become inefficient for modern data sets.

When blending in a likelihood method, XFaster allows the use of a quadratic estimator to obtain the power spectrum with a simultaneous estimate of a Fisher matrix - a natural error estimation. It also reduces the number of simulations required, and these simulations do not necessarily need to be a fiducial match to the data, as long as the minimum-set required by the noise and filter biases calculation is achieved.

Likelihood

Let’s first consider a full sky maximum likelihood analysis.

It is common to expand the pixel temperature fluctuations $T(\hat{n})$ on the celestial sphere in terms of spherical harmonic functions, $Y_{\ell m}$, as

$$ T(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n}). \quad (2.1) $$

Based on the Gaussian assumption for the CMB likelihood function of the observed data, one can write down the maximum likelihood estimator (MLE) for $N$ pixels measurement:

$$ L(d|\theta) = \frac{1}{(2\pi)^{N/2}|C|^{1/2}} \exp\{-\frac{1}{2}dC^{-1}d^t\} \quad (2.2) $$

where $C$ represents the covariance of the data vector $d$ and $\theta$ is the set of model parameters. The full covariance $C$ can be written as two parts $C(\theta) = S(\theta) + N$: the signal covariance $S(\theta)$, depends on the model parameters $\theta$ and is usually diagonal in the harmonic space for full sky observations; and a noise covariance part $N$ which is not usually diagonal.

Because of Gaussianity, the signal can be further described by an m-averaged power spectrum amplitude $C_\ell$ for each multipole: $C_\ell = \delta_{\ell\ell'} \delta_{mm'} S_{\ell m\ell'm'}$.

It can be shown that$^2$ the maximum likelihood solution for the power spectrum is:

$$ C_\ell = \frac{1}{2} \sum_{\ell'} F^{-1}_{\ell\ell'} \text{Tr} \left[ \left(C^{-1} \frac{\partial S}{\partial C_{\ell'}} C^{-1}\right) \left(C_{\text{obs}} - \langle N \rangle \right) \right] \quad (2.3) $$

$^2$While this is not obvious, the detailed calculation can be found in many books. The basic idea is making a commonly used assumption: $\Delta\Delta \rightarrow \langle \Delta\Delta \rangle = C_{\text{obs}}$ where $\Delta$ represents the observed data.
where $C^{\text{obs}}$ is quadratic in the coefficients of the expansion of the observed map, and the Fisher information matrix $F_{\ell\ell'}$ for the $C_\ell$ parameters is:

$$F_{\ell\ell'} = \frac{1}{2} \text{Tr} \left[ C^{-1} \frac{\partial S}{\partial C_\ell} C^{-1} \frac{\partial S}{\partial C_{\ell'}} \right]$$  \hspace{1cm} (2.4)

With equations 2.3 and 2.4, one could establish an iterative method of solving for the $C_\ell$: Make an initial guess of $C_\ell$, update the Fisher matrix with new covariance matrix, recalculate $C_\ell$ until finding the converging solution.

A quick evaluation of equation 2.3 suggests that, as one iteratively solves $C_\ell$, the result will, ideally, asymptotically get close to where the averaged noise ensemble $\langle N \rangle$ reduces bias of the data covariance $C^{\text{obs}}$, leaving an estimated signal covariance only.

**XFaster**

XFaster([26]) is a maximum likelihood estimator, built as a hybrid of Monte Carlo estimators (such as MASTER[23] and PolSpice[27]) and iterative quadratic estimators (such as [28]).

To circumvent the matrix operation problem for an iterative method on cut-sky observations, XFaster introduces isotropic, diagonal approximations of the Master methods([23]) into the iteration making it possible to handle a cut-sky observation. In this case, the noise becomes a diagonalized Monte Carlo estimated bias and the signal is summed into bands to average down the correlations induced by fractional sky coverage.

It then requires a minimal number of simulations, and does not require them to be precisely representative of the data to estimate accurate covariance matrices for the bandpowers. This formalism works with polarization-sensitive observations and also data sets with identical, partially overlapping, or independent survey regions.

We start demonstrating this method by introducing the cut-sky notation.

**2.1.2 Likelihood Approximation**

When experiments observe only a fraction of the sky, or when a portion of the sky is excluded to avoid foreground biases, an expansion over full-sky spherical harmonic basis functions will no longer yield orthonormal modes. The spherical harmonic coefficients, or pseudo-$\tilde{a}_{\ell m}$s, obtained in this way will be statistically correlated between modes $m$ and $\ell$ in the sense that $\langle \tilde{a}_{\ell m} \tilde{a}^*_{\ell' m'} \rangle \neq \delta_{\ell \ell'} \delta_{mm'}$ where $C_{\ell} \tilde{C}_{\ell}$ is the cut-sky, pseudo angular power spectrum defined as

$$C_{\ell} \tilde{C}_{\ell} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2$$  \hspace{1cm} (2.5)

The tilde ($) indicates that the quantity is computed in the partial sky.
Hivon et al. [23] shows how the geometry of the mask applied to the data can be used to calculate the coupling between $\overline{a}_{\ell m}$ coefficients. In turn, under an assumption of isotropy, this can be used to define a linear relationship between the ensemble average of cut- and full-sky angular power spectra:

$$\langle \mathcal{C}_\ell \rangle = \sum_{\ell'} K_{\ell \ell'} \mathcal{C}_{\ell'}$$

(2.6)

where $\langle a_{\ell m} a_{\ell' m'}^\ast \rangle = \delta_{\ell \ell'} \delta_{mm'} C_\ell$ holds on the full sky and $K_{\ell \ell'}$ is a coupling kernel that can be computed from the sky mask. This expression can be generalized to include polarization [27].

Assuming the full-sky $a_{\ell m}$ coefficients are Gaussian distributed, then the cut-sky $\overline{a}_{\ell m}$s must also be Gaussian since they are related by a linear transformation. We can then rewrite the likelihood (2.2), $L$, as

$$L(\mathbf{d}|\theta) = \frac{1}{\sqrt{2\pi |\mathbf{C}|}} \exp \left( -\frac{1}{2} \mathbf{d}^\dagger \cdot \mathbf{C}^{-1} \cdot \mathbf{d} \right)$$

(2.7)

where $\mathbf{d}$ is a generalized data vector containing the observed $\overline{a}_{\ell m}$, $\theta$ is a vector of model parameters, and the generalized, cut-sky covariance matrix $\mathbf{C}$ is still the sum of the signal and noise components of the model,

$$\mathbf{C}(\theta) = \mathbf{S}(\theta) + \mathbf{N}$$

(2.8)

where $\mathbf{S}$ is the signal, which depends on the model parameters, and $\mathbf{N}$ is the noise. The likelihood for the data given the parameters $\theta$ can be interpreted as the likelihood for the parameters given the data $L(\theta|\mathbf{d})$ assuming uniform Bayesian priors in $\theta$.

In principle, the exact likelihood of equation 2.7 can be used to estimate model parameters by defining the full, non-diagonal $\ell, m$ structure of the covariance $\mathbf{C}$. In practice this is not feasible because of the size of the covariance matrix and the difficulty in defining the full anisotropic structure of the noise term.

XFaster approximates the likelihood in equation 2.7 using two simplifications.

The first is an assumption of isotropy, using equation 2.5 to assign equal variance to $m$ modes for each multipole $\ell$, the same as full sky handling. The second is to construct the model covariance using power averaged over bins in multipoles, or bandpowers.

Averaging the power in this way reduces the effect of correlations between multipoles induced by the partial coverage. XFaster uses bandpower parameters that retain the full $\ell, \ell'$ coupling but approximates the likelihood as diagonal in $\ell$. 


2.1.3 Bandpower and Noise Model

Since in XFaster, the output spectrum is parameterized in bins, we parameterize the signal portion of the model, $S(\theta)$, by introducing the bandpower deviations $q_b^{XY}$, where $b$ is a generalized index indicating the multipole range and $XY$ indicates the 6 cross-spectrum polarization combination, $TT$, $TE$, $EE$, $BB$, $EB$ and $TB$.

We then construct the signal shape operator $\tilde{C}_{b\ell}$ that the $q_b$ factors modify.

### Bandpower deviation and shape operators

The model signal component for the XFaster likelihood covariance $eC_{\ell\ell}'$ can be defined using so-called bandpower shape operators $eC_{b\ell}^{XY}$:

$$eS_{XY}^{ij\ell} = \sum_b q_b^{XY} \tilde{C}_{b\ell}^{XY}$$

(2.9)

Equation 2.9 is valid for $XY \in \{TT, TE, TB, EB\}$. However, the cut-sky mask results in the mixing of $E$- and $B$-modes, which must be accounted for in their spectral models. The remaining spectral components are:

$$\tilde{S}_{XY}^{ij\ell} = \sum_b q_b^{XX} \tilde{C}_{b\ell}^{XX,j} + \sum_b q_b^{YY} \tilde{C}_{b\ell}^{YY,j}$$

(2.10)

where now $XX$ and $YY$ are the combinations $EE$ and $BB$, and the $\tilde{C}_{b\ell}$ terms mix $BB$ power into the $EE$ signal model and vice-versa.

Following the MASTER formalism, the bandpower shape operators are written as:

$$\tilde{C}_{b\ell}^{XY} = \sum_{\ell'} \chi_{b\ell'}^{XY} K_{\ell\ell'}^{XY} F_{\ell'}^{XY} (B_{\ell'}^{XY})^2 \tilde{C}_{\ell'}^{XY}$$

(2.11)

with time-domain filter transfer function $F_{\ell'}^{XY}$, beam window function $B_{\ell'}^{XY}$, mode-coupling kernels $K_{\ell\ell'}^{XY}$, and model spectrum $\tilde{C}_{\ell'}^{XY}$. The model spectrum $\tilde{C}_{\ell}^{XY}(S)$ for the CMB is computed using the CAMB package[29]. The $\chi_b(\ell')$ is a binning function, and one can assume different binning shape within a band.
Equation 2.11 is valid as written for \( XY = TT \), but must be modified to construct the remaining bandpower kernels. The \( EE \) kernel terms are:

\[
\begin{align*}
\tilde{C}_{b\ell}^{EE,ij} &= \sum_{\ell'} \chi_{b\ell'}^{EE} + K_{\ell\ell'}^{ij} F_{\ell'}^{EE,ij} \left( B_{\ell'}^{EE,ij} \right)^2 C_{\ell'}^{EE(S)}, \\
-\tilde{C}_{b\ell}^{EE,ij} &= \sum_{\ell'} \chi_{b\ell'}^{BB} - K_{\ell\ell'}^{ij} F_{\ell'}^{EE,ij} \left( B_{\ell'}^{EE,ij} \right)^2 C_{\ell'}^{EE(S)},
\end{align*}
\] (2.12)

and similarly for \( BB \). \( +K_{\ell\ell'}^{ij} \) are the polarization mode-coupling kernels. In particular, \( -K_{\ell\ell'}^{ij} \) accounts for the \( E - B \) mixing terms. The \( EB \) cross bandpower kernels are:

\[
\tilde{C}_{b\ell}^{EB,ij} = \sum_{\ell'} \chi_{b\ell'}^{EB} \left( +K_{\ell\ell'}^{ij} - K_{\ell\ell'}^{ij} \right) F_{\ell'}^{EB,ij} \left( B_{\ell'}^{EB,ij} \right)^2 C_{\ell'}^{EB(S)}. \] (2.13)

Finally for \( XY \in \{ TE, TB \} \) we have:

\[
\tilde{C}_{b\ell}^{XY,ij} = \sum_{\ell'} \chi_{b\ell'}^{XY} K_{\ell\ell'}^{ij} F_{\ell'}^{XY,ij} \left( B_{\ell'}^{XY,ij} \right)^2 C_{\ell'}^{XY(S)}, \] (2.14)

where the mode-coupling kernel \( K_{\ell\ell'}^{ij} \) describes the coupling between temperature and polarization.

Now the bandpowers are averaged into bands by binning, and the \( \tilde{C}_{b\ell}^{XY} \)s are what we call the band shape operators in XFaster, which is the exact shape that the spectrum would have within a given band after filtering and beam effects, and is determined from simulations of an assumed underlying power spectrum \( C_{\ell}^{XY(S)} \).

**Fitting shape operators to the data** is the essence of the XFaster algorithm, which is parameterized by \( q_b \), the bandpower deviations.

The \( \tilde{C}_{b\ell}^{XY} \)s for \( TT, EE, \) and \( BB \) CMB shape spectra for the SPIDER 150 GHz cross-spectrum are shown in Figure 2.1.

The computation of these components of the bandpower shape operators and their values for SPIDER, are given in the next paragraphs.

**Mode coupling kernels \( K_{\ell\ell'} \)**

On a masked sky, correlations between multiplies induced by the masking can be computed analytically from the mask by using the mode-mode coupling kernel \( K_{\ell\ell'} \). Decomposing the mapped sky into spherical harmonic coefficients gives us:

\[
\hat{a}_{\ell m} = \int d\hat{n} T(\hat{n}) W(\hat{n}) Y_{\ell m}^* \\
= \sum_{\ell' m'} \hat{a}_{\ell' m'} \int d\hat{n} Y_{\ell' m'} W(\hat{n}) Y_{\ell m}^* \\
= \sum_{\ell' m'} \hat{a}_{\ell' m'} K_{\ell m' \ell' m'} [W].
\] (2.15)
2.1. The XFaster Power Spectrum and Likelihood Estimator

Figure 2.1: The CMB bandpower shape operators ($\tilde{C}_\ell$) for $TT$, $EE$, and $BB$ cross-spectra, including SPIDER 150 GHz masking, filtering and beam smoothing. The binning operator $\chi_{bl}$ is piecewise linear with equal-sized bins of width $\Delta \ell = 25$. The colors alternate by bin, with the sum of the contributions from each bin (i.e., the signal model $S_\ell$ with $q_b = 1$) given by the red line. The underlying $BB$ shape spectrum is constant in $\ell(\ell + 1)C_\ell$ to have appreciable input power for determining the filter transfer function. The estimated data spectra have been found to be insensitive to the choice of shape spectra. The mode-coupling matrix terms that mix $E$ and $B$ polarizations ($-\tilde{C}_{bl}$) are also shown (orange); these mixing terms contribute additional power in the tails for each bin, most visible in the $BB$ model. Figure taken from [26].

where the coupling kernel is defined as

$$K_{\ell m' m''} = d\hat{n} Y_{\ell m'} W(\hat{n}) Y_{\ell m''}^*.$$  (2.16)

To compute this, we make the approximation that the mask is azimuthal symmetric, $K_{\ell m' m''} = \delta_{mm'} K_{\ell m m''}$. The kernels for temperature and polarization field are then:
\[ K_{\ell\ell'} = \frac{(2\ell' + 1)}{4\pi} \sum_L (2L + 1) w_L J_0^2, \]

\[ \pm K_{\ell\ell'} = \frac{(2\ell' + 1)}{16\pi} \sum_L (2L + 1) w_L J_2^2 (1 \pm (-1)^{\ell + \ell' + L}), \]

\[ \times K_{\ell\ell'} = \frac{(2\ell' + 1)}{8\pi} \sum_L (2L + 1) w_L J_0 J_2 (1 + (-1)^{\ell + \ell' + L}) \]

(2.17)

where the ± and \( \times \) kernels account for mixing between the different components, and the Wigner 3J symbol \( \mathcal{J}_n \) are introduced:

\[ \mathcal{J}_0 = \begin{pmatrix} \ell & \ell' & L \\ 0 & 0 & 0 \end{pmatrix} \]

\[ \mathcal{J}_2 = \begin{pmatrix} \ell & \ell' & L \\ 2 & -2 & 0 \end{pmatrix} \]

(2.18)

Above, the \( w_\ell \) is the power spectrum of the mask computed from spherical harmonics decomposition:

\[ w_\ell = \frac{1}{2\ell + 1} \sum_m |w_{\ell m}|^2 \]

(2.19)

where \( w_{\ell m} = \int d\hat{n} W(\hat{n}) Y_{\ell m}^* \).

The kernels are computed analytically from the provided mask and the symmetric approximation is worse at lower \( \ell \) where fewer modes are averaged together. This makes sense since a masked sky just physically has less information for larger angular scales. The ± kernels are used to compute \( EE, BB \) and \( EB \) power spectrum terms, with the − term in particular used to account for mixing between \( E \) and \( B \) due to the mask. The \( \times \) kernel is used to compute the \( TE \) and \( TB \) spectra. The kernels for the SPIDER mask are shown in Figure 2.2.

**Input beam window functions**

The beam window functions \( B_\ell \) are an input to the XFaster algorithm. One window function is required per map, and the estimated error on the beam can also be input to the pipeline. The error may be marginalized in computing the cosmological parameter likelihoods to account for these uncertainties.

The beam terms in the bandpower shape operators are constructed as the product of the individual beam windows for each of the two maps indexed by \( i \) and \( j \):

\[ \left( B_{\ell}^{XY,ij} \right)^2 = B_{\ell}^{XY,i} \cdot B_{\ell}^{XY,j} \]

(2.20)
2.1. The XFaster Power Spectrum and Likelihood Estimator

and the beam error terms are included by adding derivatives of the model with respect to each beam window to the signal covariance.

For SPIDER, the beam window functions are computed by cross-correlating SPIDER data maps at 95 GHz and 150 GHz with Planck at 100 GHz and 143 GHz, respectively\(^3\). The beam is modeled as a Gaussian function, with an approximate FWHM of 41 arcmin at 95 GHz and 29 arcmin at 150 GHz. The errors on the average beams are determined from the distribution of estimated detector beams at that frequency. The beam window functions and 1σ statistical errors obtained from distribution of estimated detector beams at that frequency for SPIDER are shown in Figure 2.3.

\(^3\)We use release 3.01 of the Planck HFI maps. Details see Section 1.3.1.
Filter transfer function $F_\ell$

The filter transfer function accounts for the effects of any filtering that was done in the low-level analysis.

In practice, observations of the sky are binned into maps from time-ordered data, which must be filtered to remove systematics like scan-synchronous noise or noisy frequencies. This filtering suppresses signal modes at certain angular scales, and the resulting bias must be computed empirically by comparing an input model spectrum to the spectra of an ensemble of simulations which have been filtered identically to the on-sky data. As in the MASTER formalism, we approximate the filter transfer function $F_\ell$ as a spherically symmetric function of only $\ell$-modes. We also assume that the transfer function is independent of the input signal spectrum used to compute it. We have verified that this is a good assumption for CMB spectra, and in particular that the $BB$ CMB spectra are insensitive to reasonable changes to input spectra.

To find the filter transfer function, one could run the same filtering and mapmaking pipeline on simulated time-stream data that was generated using the pointing solution of the experiment on a map realization of $\Lambda$CDM.

The filter transfer functions $F_\ell$ are computed in the same way as bandpowers (section 2.1.4), but substituting the average of signal-only simulations for the observed data, and setting the $F_\ell$ term in the signal model to 1. The remaining non-unitarity of the $q_\ell$ values is the binned transfer function $F_b$. Transfer functions are computed for $TT$, $EE$, and $BB$ spectra, independently for each map, since the filtering may differ significantly between maps. The $TE$, $EB$, and $TB$ transfer functions are approximated as the geometric mean of their component transfer functions, e.g., $F^{TE}_\ell = \sqrt{F^{TT}_\ell F^{EE}_\ell}$.
2.1. The XFaster Power Spectrum and Likelihood Estimator

When constructing the signal model using the binned transfer function $F_b$, we expand $F_b$ to the full $\ell$ range using a constant value in each bin. The transfer function term for each cross-spectrum in the signal model is then the geometric mean of the transfer functions for each of the two maps indexed by $i$ and $j$:

$$F_{XY,ij}^\ell = \sqrt{F_{XY,i}^\ell \cdot F_{XY,j}^\ell}.$$  \hspace{1cm} (2.21)

The SPIDER $EE$ and $BB$ transfer functions are shown in Figure 2.3.

Residual noise calibration

The XFaster likelihood approximation also enables an estimation of noise calibration parameters. Uncorrelated noise enters the covariance matrix as a diagonal term. To account for inaccuracies in our noise simulations, we fit a scalar parameter $n_b^i$ per bin as a correction to the noise model:

$$\tilde{N}^{XY,ij}_\ell = \delta^{ij} \sum_b \chi_{XY}^\ell \left(1 + n_b^i\right) \langle \tilde{N}_\ell^i \rangle$$  \hspace{1cm} (2.22)

where $\langle \tilde{N}_\ell^i \rangle$ is the mean spectrum of an ensemble of noise simulations. Noise is treated differently from signal, in that we model it directly in the cut-sky power spectrum with no polarization coupling. In principle, noise is coupled across polarizations, but this is difficult to account for analytically in the cut-sky spectra.

Clearly, if the binning structure of the $q_b$s and the $n_b$s are too similar and/or if the template biases $\langle \tilde{N}_\ell^i \rangle$ have a similar $\ell$ dependence to the shape templates $C_{XY}^\ell$, this extension will introduce significant degeneracies in an auto-spectrum analysis. The degeneracies are broken by including multiple cross-spectra, where noise biases do not contribute. This has been found for SPIDER to sufficiently decouple the signal and noise parameters, though increasing the bin width for the $n_b$ parameters in comparison to that for $q_b$ would further address this potential issue. The piecewise linear model for the noise calibration means the $n_b$ “noise residual” parameters can be estimated jointly with the signal $q_b$s and can be marginalized over using the full Fisher matrix, once the estimator has converged to the maximum likelihood solution.

2.1.4 the Bandpower Estimator

Now that we have introduced every term in the shape operators, we can start bringing together the XFaster estimator. The ingredients introduced above are used to construct the signal and noise covariances in equation 2.7 and 2.8. In the XFaster approximation the covariances are block-diagonal by $\ell$. The sub-blocks are built from the cross-spectra of $N$ maps and polarizations with each sub-block as follows:

$$\tilde{C}_\ell^{ij} = \begin{bmatrix} \tilde{C}_\ell^{TT} & \tilde{C}_\ell^{TE} & \tilde{C}_\ell^{TB} \\ - & \tilde{C}_\ell^{EE} & \tilde{C}_\ell^{EB} \\ - & - & \tilde{C}_\ell^{BB} \end{bmatrix}_{ij}$$  \hspace{1cm} (2.23)
where $i$ and $j$ index over the $N$ independent maps.

Formulated in this way, the matrix $\mathbf{\bar{C}}_\ell$ is the covariance of the $\tilde{a}_{\ell m} X_{ij}$s that make up the generalized, observed data vector $\tilde{\mathbf{d}}$ in equation 2.2. The block-diagonal form of the covariance means the data vector can be pre-compressed into spectra:

$$
\mathbf{\bar{C}}_{\ell}^{XY,ij} = \frac{1}{2\ell + 1} \sum_m \tilde{a}_{\ell m}^X X_{ij}^{a_{\ell m}} Y_{ij}^{a_{\ell m}}
$$  \hfill (2.24)

Here and elsewhere, we use the hat symbol ($\hat{}$) to distinguish matrices of data pseudo-spectra from general matrices of pseudo-spectra.

Then the log-likelihood, up to an overall constant, can be written as

$$
L \equiv \ln L = -\frac{1}{2} \sum_{\ell k} (2\ell + 1) g^k_\ell \left[ \mathbf{\bar{C}}^{-1}_\ell \cdot \mathbf{\bar{C}}_\ell + \ln \mathbf{\bar{C}}_\ell \right]_{kk}
$$  \hfill (2.25)

where $k$ indexes over polarization and independent maps in the sub-blocks (see Equation 2 in [30]). The factor $(2\ell + 1)$ appears as a degree of freedom due to the block-diagonal form. The coefficient $g^k_\ell$ accounts for the effective number of modes from each map that contribute to the final trace for each multipole:

### The $g_\ell$ mode counting factor

As masking of the sky throws out modes and reduces the observed bandpower, a weighting factor $g_\ell$ is introduced accounting for the change to the effective degrees of freedom in the likelihood induced by both map weighting and the "missing" contributions to the covariance in the block-diagonal likelihood approximation.

To calculate $g_\ell$, we first estimate an overall $\ell$-independent starting amplitude based on the ratio of mask moments introduced in [23]:

$$
g = f_{\text{sky}} \frac{w_2}{w_4},
$$  \hfill (2.26)

where $w_n$ is the $n^{th}$ moment of mask $W$ with

$$
f_{\text{sky}} w_i = \frac{1}{4\pi} \int d\hat{n} W^i(\hat{n}) = \sum_p W^i_p ,
$$  \hfill (2.27)

where $p$ is the pixel index for the mask $W$ and $f_{\text{sky}}$ is the fraction of the sky covered by the mask. which would reduce matrix traces in equations into sums over $\ell$, $\text{Tr} \rightarrow \sum_\ell (2\ell + 1) g_\ell$.

We have found that the application to SPIDER requires a more accurate counting of modes, likely due to the presence of high signal-to-noise polarization modes at large scales for which the coupling structure is most complicated. In practice, we find a that a second-order correction to the overall amplitude $g$ by a factor of $(1 + 4f_{\text{sky}})$, combined with an empirical Monte Carlo estimate of the $\ell$-dependence, is required for the correct calibration of the Fisher matrix when compared to end-to-end simulations.
2.1. The XFaster Power Spectrum and Likelihood Estimator

Figure 2.4: The $g_\ell$ effective mode-counting factor as estimated for SPIDER’s rectangular mask, \textit{latlon}. The predominant effect is a constant approximate 6% retention of the full sky power after masking (0.058), providing roughly 4300 and 8000 modes for 95 GHz and 150 GHz respectively. An additional $\ell$-dependent reduction results from “missing” contributions to the covariance due to approximations in the construction of the likelihood. This component is empirically calibrated with simulations. Figure taken from [26].

Thus, we also compute an empirical Monte Carlo estimate of the $\ell$-dependence. We do that by estimating the final $g$-correction iteratively by computing bandpowers for 1000 signal-only simulations that have been filtered in the same way as the data, and comparing the scatter of the ensemble of bandpowers to the diagonal of the Fisher matrix (\textit{i.e.}, XFaster’s estimate of the error bar). We use the ratio as an estimate of the $g$-correction, feed it back into the estimate of the ensemble of bandpowers and repeat the process until the correction converges.

Figure 2.4 shows the amplitude of the total $g_\ell$ factor per bin, using both signal simulations and null (noise-dominated) simulations. The latter are discussed in more detail in section 2.2.

Likelihood maximization

Now as we have constructed the final covariance matrix, we can rewrite the maximum likelihood estimator (equation 2.3) and the Fisher matrix (equation 2.4) in the form of cut-sky modification with the trace term reduced by $g_\ell$, and binned parameters $\theta$, which include all $q_b$s and $n_b$s that are allowed to vary freely:
The Fisher matrix is given by

\[ F_{bb'} = \frac{1}{2} \sum_{\ell k} (2\ell + 1) g_k^\ell \left[ \frac{\partial \bar{C}_\ell}{\partial \theta_b} \cdot \bar{C}_\ell^{-1} \cdot \frac{\partial \bar{C}_\ell}{\partial \theta_{b'}} \cdot \bar{C}_\ell^{-1} \right]_{kk}, \]  

(2.28)

where we have used the same notation convention as in Equation 2.25 and the index \( b \) now runs across all parameters in the set of \( q_b \)s and \( n_b \)s.

In practice, starting from an initial guess with \( \theta_b = 1 \), we calculate an updated solution at each iteration using

\[ \theta_b = \frac{1}{2} \sum_{b'\ell k} F_{bb'}^{-1} (2\ell + 1) g_k^\ell \left[ \bar{C}_\ell^{-1} \cdot \frac{\partial \bar{C}_\ell}{\partial \theta_{b'}} \cdot \bar{C}_\ell^{-1} \cdot \left( \bar{C}_\ell - \bar{N}_\ell \right) \right]_{kk}. \]  

(2.29)

It is helpful to notice that with uncorrelated, diagonal noise terms in equation 2.23, when solving for \( q_b \)s, the derivative terms will only have the signal covariance \( \bar{S}_\ell \):

\[
\frac{\partial \bar{S}_\ell}{\partial q_b^{TT}} = \begin{bmatrix} \hat{C}_{TT} & 0 & 0 \\ 0 & \hat{C}_{TE} & 0 \\ 0 & 0 & \hat{C}_{BB} \end{bmatrix}, \quad \frac{\partial \bar{S}_\ell}{\partial q_b^{EE}} = \begin{bmatrix} 0 & \hat{C}_{TE} & 0 \\ 0 & \hat{C}_{TE} & 0 \\ 0 & 0 & \hat{C}_{BB} \end{bmatrix}.
\]

\[
\frac{\partial \bar{S}_\ell}{\partial q_b^{TB}} = \begin{bmatrix} 0 & 0 & \hat{C}_{TB} \\ 0 & \hat{C}_{TB} & 0 \\ \hat{C}_{TB} & 0 & 0 \end{bmatrix}, \quad \frac{\partial \bar{S}_\ell}{\partial q_b^{BB}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \hat{C}_{TE} \\ 0 & \hat{C}_{TE} & 0 \end{bmatrix}.
\]

(2.30)

This is equivalent to a Newton-Raphson minimization method. Iterations can be terminated when a convergence criterion is satisfied. We terminate when the maximum of the absolute fractional change in \( \theta_b \) is below some threshold, typically \( 10^{-3} \).

Note that the mode-counting factor \( g_\ell \) enters into the elements of the Fisher matrix (and therefore, the resulting uncertainties on the parameters), but is effectively divided out in Equation 2.29, so mis-calibration may result in biased uncertainties but not biased parameter estimates.

**Revisit \( F_b \)**

As described in 2.1.3, the transfer function is computed by setting the transfer function term in Equation 2.29 to be 1, and estimate the \( q_b \)s using simulated signal maps. By doing this, the mode coupling Kernels \( K_{\ell \ell'} \), the correlation between the spectra and binning effect are all accounted for. As the binned power spectrum deviations \( q_b \)s are
used, the estimator for the transfer function will be binned as a value per bin, $F_b$, instead of on an $\ell$ basis.

We can write down the exact solution for $F_b$ now:

$$F_b = q_b^{\text{transfer}} = \frac{1}{2} \sum_{b'\ell k} F_b^{-1} (2\ell + 1) g_{b'}^k \left[ S_{\ell}^{-1} \frac{\partial \tilde{S}_{\ell}}{\partial q_{b'}} \cdot \tilde{S}_{\ell}^{-1} \cdot (\tilde{C}_{\ell} - \tilde{N}_{\ell}) \right]_{kk}. \quad (2.32)$$

Since we are using signal only simulated maps as inputs, the $(\tilde{C}_{\ell} - \tilde{N}_{\ell})$ term will be noise free, and is equivalent to the simulated signal-only spectra: $\tilde{S}_{\ell}$.

The recipe

Now as we have everything we need for the estimator, I’m going to summarize the pipeline as following:

1. Generate ensembles of signal-only and noise-only simulations.
2. Use the signal simulations to compute the binned transfer function $F_b$, by iteratively solving for equation 2.32 and equation 2.28.
3. Use the noise simulations to compute the noise bias term, $\langle \tilde{N}_{\ell} \rangle$, following equation 2.22.
4. Iterate equation 2.29 and 2.28 to solve for the maximum likelihood parameters $q_b$ and $n_b$.
5. Evaluate the Fisher matrix (2.28) one final time at the maximum likelihood point. This gives us an estimate of the error (the inverse Fisher matrix) as the Fisher matrix is an estimation of the curvature of the maximum likelihood.

2.1.5 Parameter Likelihood

The definition of an approximation for the data likelihood (Equation 2.25) introduces the possibility of circumventing the power spectrum and associated bandpowers altogether. Since the space of models can be scanned directly as a function of cosmological parameters $a$, we can define a likelihood for $a$, given the data $\tilde{d}$, using the Bayesian chain formalism

$$L(a | \tilde{d}) \sim P(a) L(\tilde{d} | a), \quad (2.33)$$

where $P(a)$ is the prior in the cosmological parameters, such as the tensor-to-scalar ratio, $r$. For details of this implementation, see [26].

2.2 XFaster Null Test Pipeline

A null test, or a "jackknife test" as in the SPIDER-1 result paper([10]), is to take the CMB Time-ordered-Data(TOD) and split it in two halves, either spatially or temporally, then evaluate the "null" of the difference between the two halves, which in a ideal world...
would be perfectly zero with uncorrelated white noise, if given infinite amount of good, fluctuated as perfect Gaussian data samples.

Through the null test evaluation, one can form a good sense of how reliable the experimental data set is, quantify how good the low-level analysis processes are at flagging and filtering out the systematic noise from the instrument, and get a good measure of expected correlating noise between different data splits.

Passing a null test means that low-level residuals do not remain at the level of sensitivity that we care about, such as intermittent pickup from Iridium communication transmitters or scan-synchronous noise in SPIDER-1’s case.

### 2.2.1 Null Test Pipeline

It is important to use a consistent estimation pipeline for each null split and signal spectra. With the XFaster estimator, null spectra can be evaluated using the same method one would use to calculate a signal power spectrum. The majority of the null test analysis follows exactly as the signal analysis. This includes all low-level analysis details: cleaning, filtering, pointing, calibration, etc. See section 1.3.1.

#### Half maps

The simulated half-maps are made in the same pipeline as the full maps. Different splits of half maps are made from different combinations of half detectors. For each half-data map, a simulated observation of a Planck map is also made, the simulations are made using the same detector/time splits as the SPIDER half-data map. We use the Planck maps as estimates of the expected signal since they capture both CMB and foreground power, the latter of which is consistent with being the dominant source of residual power at large scales in our null maps.

We subtract the simulated Planck maps from our half data maps. The subtracted data maps made from each of the two splits are differenced, and then spectra and covariances are estimated from the difference maps in the XFaster power estimator pipeline that is described in section 2.1, with details determined in section 2.2.3.

In XFaster null tests where each of the tests used 500 simulated maps in particular, the simulated half maps with same sim-index label for different null tests are generated using the same random seeds, which means that the half maps that share the same seed are simulations of a same random sky.

This is particularly important for null correlation tests; see section 2.3.2 for details.

#### Null spectrum estimation

In a null analysis, the filter transfer function can only be estimated from ensembles where the signal is not negligible. It is therefore computed using the ensemble average of the two simulated signal-only half maps. The theoretical model spectrum for null tests is flat, and once the spectrum has converged, the final Fisher matrix for a null spectrum is calculated without the sample variance component. This is done by setting the final signal $q_b$ parameters to a very small value thus nulling out the signal covariance.
The noise component term for null tests (appearing both in the covariance and data debias terms in Equation 2.29) includes both signal and noise residuals, along with their correlations, as these terms all contribute to the expected variance and biases in the data spectra. Unlike for the total signal spectra, these terms are included for off-diagonal elements (cross-spectra of different half-maps) of the covariance as well; This is because all auto and cross-spectra must account for expected residual signal and noise due to different filtering between the half maps.

As an alternative to debiasing the data for the expected signal and noise residuals in spectrum-space, the pipeline also has the option to subtract residuals with known morphologies in map-space. When such maps are used, the covariance matrix noise term does not include signal contributions, since there is no sample variance in the debias term. For example, to estimate signal residuals for the SPIDER null tests, we use Planck frequency maps processed and differences in the same way as the data null maps, instead of using CMB signal simulations. The frequency mismatch between the SPIDER and Planck bands could be accounted for, but was found to affect results negligibly.

We find that this map-space subtraction properly accounts for foreground residuals due to slight differences in the time-domain filtering between the two halves, which dominate our null signal residuals at large scales for some data splits. This method also allows us to accurately model the morphology of the residuals, and eliminates the need to account for sample variance from the subtraction in the covariance matrix. The Planck-subtraction method has been tested with half-missions and half-rings, with negligible differences between the two. This confirms that the residuals subtracted in this manner are dominated by signal rather than by noise in the Planck data.

The mode-counting factor $g_\ell$ is expected to be different for nulls in comparison to total signal spectra due to the different relative contribution of sample variance to the error (Figure 2.4). Sample variance only affects the null test bandpower errors through its contribution to the uncertainty of the expected signal residual that debiases the data spectrum. The mode counting factor cannot be empirically calibrated for null tests using signal-only simulations, because the remaining signal after debiasing with the expected signal spectrum for a signal-only simulation is nearly zero, which makes the covariance matrix singular and thus non-invertible. Instead we add noise to the simulations, and calibrate $g_\ell$ iteratively in the same fashion as for total signal spectra.

We have found that the resulting $g_\ell$ is somewhat sensitive to the noise level used in its calibration. Thus, we use the noise residual terms $n_i^b$ (Equation 2.22) calculated for the data to rescale the $a_{\ell m}$ coefficients of the simulated noise maps as $\sqrt{1+n_i^b} a_{\ell m}$. This modification affects both the $S \times N$ and $N \times N$ terms of the covariance matrices.

### 2.2.2 Selection of Data Splits

The suite of null splits is listed below. There are 10 different null tests we did for SPIDER-1. The first 5 are based on channel location within the focal plane; see Figure 2.5. Two additional spatial detector splits are based on pointing relative to payload azimuth (dependent on the orientation of each receiver about its boresight axis, see Figure 2.6), and frequency response, as shown in Figure 2.7.
In order to be informative, we specifically chose the data splits that would probe our sensitivity to known or potential issues in our data.

- **Inner/Outer Focal Plane Rows**, split by physical row on the focal plane. We have observed reactional wheel synchronous noise that is more prevalent in the inner focal plane rows, so this split would probe that potential systematic.

- **Inner/Outer Focal Plane Radius**, split by distance of the detector from the center of the focal plane. This probes beam shape, which becomes increasingly elliptical toward the focal plane edges.

- **Diagonal Tiles of a Focal Plane**, split focal planes into sets of two tiles diagonally across from each other. Since each tile is fabricated independently, this would test for detector tile non-uniformity in fabrication.

- **Checkerboard**, split the detectors in a checkerboard pattern. This test probes our noise model, since we do not expect systematics to vary on this basis.

- **Alternating Mux Column**, split every other readout column. This probes differences in the SQUID readout among columns.

- **Port/Starboard Detectors**, split by detector pointing azimuth. This would be sensitive to sidelobe pickup of the Galaxy or the Sun, which are on opposite sides of the azimuthal scan.
2.2. XFaster Null Test Pipeline

![Figure 2.6: An example showing X1 (150 GHz) detector splits based on pointing relative to payload azimuth of detectors. White channels are turned off, open or bad TES during the flight. Figure made by Dr. Anne Gambrel.](image)

- **High/Low Band Center**, split all detectors within a frequency by their measured band center. This probes detector sensitivity to frequency differences.

  The final 3 splits are by time throughout the mission.

- **Left/Right Scan**, split azimuthal scans into left-going and right-going directions. This probes time constant effects.

- **Alternating Days**, split into every other day. This probes half-wave plate systematics, since full polarization angle coverage for a given detector requires four independent HWP angles, which corresponds to two days of observing time.

- **Early/Late Flight**, split each of the two scan strategies into early and late halves. This probes longer trends, such as effects from cryogen loss.

### 2.2.3 Null Test Development

In the **SPIDER result paper** [10], the final statistics of null tests were estimated from the finalized null spectra that are deemed to be good evaluations of our scientific data. For every null test, there are many parameters and conditions one could set, and each of these options would make a difference in the final result. In this section I will present a detailed description of the development for the null tests and conclude with the final choices we made for the tests.
Chapter 2. SPIDER-1 Null Tests

Figure 2.7: An example showing X1 (150 GHz) detector splits based on the band center result from FTS measurements. White channels are turned off, open or bad TES during the flight. Figure made by Dr. Anne Gambrel.

Figure 2.8: A simple chart of local-sidereal-time (LST) day splits description.

During the several years of null test pipeline development, one of the largest issues that we encounter in the early stage was convergence issue, which is a high-level analysis issue that could be caused by various reasons. It happens at the iteration stage of XFaster where bandpowers fail to converge to a stable point within the fractional change threshold for the final $q_b$ factor iteration. While one could set this condition to different marginal small values in XFaster, it turns out that the exact numerical value of the criterion was trivial as long as it’s small. However, tweaking other null test settings helped with this problem, because as one could imagine, more prior knowledge of how the likelihood function looks (for example, a better guess of what noise our data contains), would be helpful in solving both the convergence and getting good estimation of the data.

Another large improvement we made was to try to compare our XFaster pipeline null
tests result with null tests from a completely different power spectrum estimator NSI, to see if our null tests are sensitive to estimator choice. Since these two pipelines are very different, in the later development, we made various changes to make the options effectively equivalent for both pipelines so we can have a justified comparison between the two, while of course without manipulating the results themselves.

### Masks and apodization

The first thing that we need for null tests is the mask. While one could definitely construct a good mask through the raw data itself, on the matter of null tests there were two masks under consideration: the "latlon" mask, a relatively larger sky-coverage (4.7%) mask made from a conservative yet arbitrary estimate of the sky coverage in latitude and longitude cut; and the "vpol" mask, that was created by Johanna Nagy in her circular polarization analysis paper[31], and has a smaller sky-coverage compare to the latlon mask. See Figure 2.9.

![Figure 2.9: Two binary masks under consideration. Data within the brown masked area is included in the analysis and the beige area is excluded.](image)

In our sky region, we also cross check our map with Planck point source mask that was published[^4], and then subtract all point-sources out from our sky with a standard radius of 0.5°.

The apodization level of a point source removed mask could help with convergence issue and doesn’t affect the actual null bandpower results too much. This is due to a couple of reasons, mostly because that non-apodized sharp edges would cause ringing in spherical harmonics domain that might cover up the underlying interesting small features, also a smoother likelihood function is easier to converge when it’s less likely to be trapped in local minima as iteration progresses. However, too much apodization might introduce fake features in the spectra.

Thus it is necessary to tweak the apodization level of the point source removed latlon/vpol mask. After applying the point-source mask to the regional masks, masks with the different level of apodization are made by convolving a smoothing beam that’s at targeting resolution. The point source mask comes with a standard 0.5° radius for

[^4]: from the Planck Point Sources Catalogue for the HFI
every point source. Any apodization that was done is outside that radius: we smooth out the edge of the point source outwards with additional range beyond the 0.5° radius.

In our test we tried a couple of different apodization ranges: no apodization, 0.5°, 1°, and 2° for both latlon and vpol masks. The results showed that 2° apodized latlon masks had convergence issues with some of the nulls, while vpol masks tend to behave well for all apodization levels. In order to have sky coverage as large as possible, we decided to choose the non-apodized point source removed latlon mask as our nominal masks for XFaster null tests. This mask covers 1964 square degrees with uniform weighting, consisting of the 1992 square degree rectangle. The point source mask excludes 1° diameter circular regions around objects from the Planck compact object catalog, plus a 2° region around the bright radio galaxy NGC 1316.

This mask was established prior to the calculation of the signal power spectra in order to avoid potential bias.

![Point Source removed latlon mask with no apodization. The largest is cut with 2°, the bright radio galaxy NGC 1316. This is the final mask we used in our null hence signal analysis. Among a handful of simple mask options, this mask was the largest subset of the data that was well-conditioned and passed null tests.](image)

**FIGURE 2.10:** Point Source removed latlon mask with no apodization. The largest is cut with 2°, the bright radio galaxy NGC 1316. This is the final mask we used in our null hence signal analysis. Among a handful of simple mask options, this mask was the largest subset of the data that was well-conditioned and passed null tests.

**Number of signal and noise simulations and ensemble average subtraction**

In XFaster one could set different numbers of signal/noise sims, as they are treated independently and have different uses in calculations. Signal simulations were used to compute the transfer function $F_\ell$, while as noise simulations were used to compute the $N_\ell$ term for the covariance matrix as well as shapes for the residual terms for the auto spectra. Since they are treated separately, we tested different numbers of noise and signal sims for the null spectra, and found that in cases where more than 100 simulations are used, the resulting bandpowers weren’t affected by the number of simulations at the level that we care about. See Figure 2.11.

Ideally, XFaster pipeline should work fine enough for a couple of sims as referencing point. However while resolving convergence issue, we found that adding number of simulations helps bandpowers to converge while they did not change the bandpowers.
2.2. XFaster Null Test Pipeline

The signal and noise simulations were also used to compute an ensemble average, as an expected residual that comes from our pipeline. In that case, we were subtracting $C^S_\ell + C^N_\ell$ terms from the computed null spectra at the end of calculation. Since all the terms that used signal or noise simulations are separable, one could have different numbers of signal and noise simulations.

Later in development, we found out that while computing the ensemble average, the signal cross noise terms were not accounted for and were not insignificant for null tests. So ensemble average was updated later using $C^{S+N}_\ell$ instead of $C^S_\ell + C^N_\ell$ to handle cross terms properly. This required signal and noise to have the same number of simulations, and were set to 500 each for the null tests.

However, the agreement between numbers of signal and noise simulations is not required any more after we changed to Planck map subtraction for accounting expected residuals. See 2.2.3. Although we still followed the convention of 500 simulations for both signal and noise.

Bin sizes and bin ranges

The binning size for the spectra were determined under two considerations: a large bin size would not be informative enough for data presentation especially at the multiple range of interest, since the interesting features might be covered up when the bin is too wide, while as a too small bin size would inflate the error bars beyond informative level because of sample variance, as well as introduce correlations due to partial sky.
coverage. In partial sky analysis we always want to find the smallest yet uncorrelated bin size.

A bin size of $\Delta \ell = 25$ was arbitrarily determined at the beginning of SPIDER-1 analysis and was tested for kernels of pseudo-$C_\ell$s method in order to have as independent bins as possible. It has been shown that it worked quite well with null tests compared to other binsizes such as 20 or 30.

During development, starting points for the multiples of $\ell_{\text{min}} = 2$ and $\ell_{\text{min}} = 8$ were used back and forth. A $\ell_{\text{min}} = 8$ starting point was chosen to be the minimal $\ell_{\text{min}}$ that wouldn’t cause XFaster calculation errors, and in null test evaluations the first bin ($\ell = 8 \sim 33$) was always neglected. $\ell_{\text{min}} = 2$ was used a while until the final range was set to $\ell_{\text{min}} = 8, \ell_{\text{max}} = 407$ in order to get a better agreement with the NSI pipeline.

**Refitting noise model**

The refitting of the noise model was originally introduced to help with noise marginalization for 90 GHz $\times$ 150 GHz only spectra to make XFaster nulls have a better comparison with the NSI pipeline. This method is tested on simulations and is deemed to work, and significantly helped with the noise fitting as we know our original noise model wasn’t ideal.

The refitting is done by using the residual fit in a original null test run to modify the $a_{\ell m}$s of the noise simulated maps, and a second null test run in which we recompute everything from the map level with the $a_{\ell m}$s modified noise maps (section 2.2.1). Although the noise marginalization did not work in the end, the refitting of the noise model made noise fittings better. Moreover, the mode-counting factor $g_\ell$ is found to be not totally independent of the noise shape amplitude through testing. So in the final null test pipeline, noise model refitting was used for all the simulated runs where the residue fit of the bandpowers from the data null test is used as the modification to the noise maps of simulation runs.
The correction factor

The correction factors were a critical high level fix that we introduced in XFaster null pipeline to account for mode counting and biased bandpowers estimation. In the early stage of null tests, we found out that instead of being flat, our PTE distributions were skewed towards unity for data, while as when testing on simulations the distribution is also skewed (See 2.3.1 for detailed description of PTE distribution).

The simulation test shows that the XFaster pipeline is in some way systematically over-estimating the error bars that caused a biased $\chi^2$ distribution that’s independent of our data. To fix this, we implemented a fix that corrects the error bars to make simulations have uniform PTE distributions.

The step-by-step method of computing a corrector factor is described here:

1. Run XFaster null tests on a large ensemble ($N$ number) of simulations. From which $N$ bandpowers and error bars are computed.

2. Calculate the correction factor $C_{corr}$ as the ratio of the standard deviation of the $N$ bandpowers, which is the expected standard error of the bandpower from simulations, to the median of the $N$ error bars XFaster calculates for those simulations, which is a good representative of XFaster calculated errors (diagonals of the computed covariance matrix).

$$C_{corr} = \frac{\text{Standard Deviation of N bandpowers}}{\text{Median of N errors}}$$ (2.34)

3. Multiply the data run XFaster error by the correction factor, $C_{corr}$.

However, although the correction factor works well in terms of fixing the $\chi^2$ distribution, when compared to the null test results from NSI pipeline, we observed that after the correction factor had been applied, XFaster typically had larger error bars than NSI in the null tests but not in the non-null spectrum. Before the correction factor was implemented, XFaster had a good agreement with NSI in terms of error bars.

To solve this discrepancy, the correction factor was then applied to the bandpowers instead of error bars as a divisor term instead of multiplication. The two pipelines agree better with each other after this fix. This shows that XFaster was underestimating the bandpowers by a factor of $C_{corr}$ instead of overestimating the errors.

It is necessary to point out that whether applying the correction factor to bandpowers or to error bars does not affect the estimation of the $\chi^2$ distribution, as it was essentially applied in the same place for a $\chi^2$ number calculation. Understanding the nature of this bias is independent from one’s evaluation on passing a null test or not as long as it’s applied. Later in the XFaster code package development, the one-time correction factor was no longer needed as we implemented the iterative method of $g_l$ factor into the null tests to make the pipeline closer to the signal estimation. See next section.
The $g_\ell$ factor for null tests

Through both nulls and non-null pipeline testing we originally found that the covariances don’t a priori match the simulated distribution of bandpowers. That was because we hadn’t accounted for mode loss due to the masking and filtering. A $g_\ell$ factor was introduced to solve the covariance-bandpower discrepancy problem for the non-nulls. However, when the same $g_\ell$ was applied in null tests, the distribution of simulated bandpowers actually gets more discrepant with the covariances estimated. Limited by time, we chose to use a one time correction factor for the null spectra instead of the non-null $g_\ell$ factor.

It is also found that mode loss is not independent from the amplitude of the signal, so it would be different for nulls and non-nulls. Later, to best account for the mode loss, we compute the $g_\ell$ factor for nulls using 1000 simulations in both signal and noise, rather than signal-only simulations.

This iteratively solved $g_\ell$ factor replaced the one time correction factor and is now more consistent with the non-null pipeline. This procedure is also merged into the public XFaster code package.

Weighted bins

The weighted bins were introduced to compare our results to the NSI pipeline and make both of the pipelines more aligned with each other. By default, a flat binning operator was used when constructing $\tilde{C}_\ell$s. Weighted binning instead uses $D_\ell = \ell(\ell+1)C_\ell/2\pi$ within a bin. This changes the bin definition in the beginning of a null run, and hence would influence the transfer function, beam, and kernels calculations. Bandpower results from XFaster by default are calculated without the weighted bins but could be calculated with this option.

Dropping X3 in the analysis

After all the pipeline details were finalized, various null tests were run and compared with NSI pipeline results. In particular, we did individual focal plane null tests (X1, X3, X5) for 150 GHz, as the Kolmogorov–Smirnov test for the 150 GHz PTE distribution didn’t have a reasonable $p$-value. This was inspired by NSI pipeline null test results, where after dropping X3, our 150 GHz focal plane that has most systematics, the result PTE is significantly better.

After careful evaluation, we decided to drop X3 in our whole analysis for both null and non-null spectra. The final product of X1+X5 is labelled as 150a GHz. The direct comparison of the KS tests will be shown in section 2.3.3. The source of the null test failure of X3 is not fully understood. It is possibly due to the relative pickup from a combination of reaction wheel noise and MCE bad state. When we raised the level of scan turn-around velocity cutoff, the visible noisier stripe region in a X3 map is visually better, suggesting a reaction wheel related issue.
2.2. **XFaster Null Test Pipeline**

**Planck map subtraction**

In the last stage of null test development, simulated *Planck* maps were used as templates of the expected signal, instead of signal + noise simulations as described in 2.2.3. This was introduced to further capture expected residuals especially foreground signal which was not accounted for properly in our noise simulations, and appeared to be a dominant source in our residuals at large scales. The advantage of using such subtraction is that there is no ambiguity with regard to sample variance.

The subtraction was then done in the map space where we subtracted simulated half *Planck* maps from half data maps, instead of in the spectrum domain where we did spectrum subtraction at the end of null spectra estimation. We found that while null tests passed with signal + noise sims, *Planck* subtracted null tests also passed, and they are used in the result section of the published analysis papers.

**Null test pipeline**

As described in detail in the last section, the published results of XFaster null tests are finalized in the following steps:

First, we make two halves of SPIDER data maps, then make simulated planck maps with the same data splits, and subtract *Planck* maps from data maps to get rid of the expected residuals of CMB and foregrounds. In the meantime, 500 simulations of signal and noise maps are also made. The 90 GHz and 150a GHz(X1+X5) signal maps are then masked with point source removed, non-apodized "latlon" mask, fed through the XFaster spectra estimator, with weighted bin settings of $\Delta \ell = 25$ bin size, starting from $\ell_{\text{min}} = 8$ and end at $\ell_{\text{max}} = 407$ to have 16 whole bins. Signal and noise simulation maps are used separately to compute the filter transfer function and as an ensemble average to debias the covariance estimation.

Once we have the data null spectra and covariance matrices computed, we do the same for all 500 (signal+noise) simulated maps to compute 500 bandpowers and covariances. These end-to-end simulated bandpowers and covariances are used in statistical evaluations of the data result to determine whether we have passed null test.

2.2.4 **Pipeline Validation**

To validate this pipeline, we conduct a series of tests with simulated inputs to confirm that the ensemble averaged parameter estimates produced by XFaster match the input values used to generate the simulations, which, in null test’s case, is a flat zero. We also confirm that the error in the estimate must match the scatter of individual XFaster estimates over the ensemble.

To validate the XFaster bandpower estimation pipeline, we compute bandpowers for an ensemble of 500 CMB+noise simulations for both signal and null spectra. We verify that the average of the computed bandpowers matches the spectrum input and is therefore unbiased. These bandpower distributions are shown in Figure 2.13.
Chapter 2. SPIDER-1 Null Tests

To verify that the covariance computed by XFaster is accurate, we check that the scatter of the ensemble matches the covariance computed by XFaster for both signal and null simulations. We construct two distributions of $\chi^2$ values:

1. The $\chi^2$ of the spectrum for each of 500 realizations relative to the corresponding input model (fiducial $\Lambda$CDM for the signal ensemble).
2. The $\chi^2$ of each of 100,000 spectrum realizations, sampled from the average of the bandpower covariance matrices computed for each of the realizations in the signal and null map ensemble.

The second distribution forms the expectation for the first distribution. As shown in Figure 2.14, the two distributions are in good agreement.
2.3. **SPIDER-1 Null Test Result**

We have 30 (10 tests × 3 spectra, EE, BB, EB) null test spectra for each frequency (90 GHz, 150 GHz, Combined). As SPIDER-1 is a polarization focused experiment, the temperature related spectra TT, TE, TB were looked at in the pipeline development process but not shown in the results or used in the evaluations.
The results are presented in Figure 2.15, 2.16 and 2.17.  The labelled $\chi^2$ values are computed using full covariance matrix. Note that, we don’t include the sample variance in the null test spectra as they should cancel out for data from the same sky.

**Figure 2.15:** Three null tests of port and starboard, left and right scan and checkerboard detector pattern. The figure shows the comparison between the XFaster and NSI pipelines for the different frequency combinations 90 GHz, 150a GHz and all frequencies combined. A horizontal offset is added to NSI points for visual clarity. The $\chi^2$ values are computed independently for each pipeline and spectrum using the full covariance matrix. *Figure taken from* [26].

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5There’s one test that is not shown in this section due to code structure and limited space.
Figure 2.16: Three additional null tests of alternating days, inner and outer rows detector and alternating mux columns. The figure shows the comparison between the XFaster and NSI pipelines for the different frequency combinations. A horizontal offset is added to NSI points for visual clarity. $\chi^2$ values are computed independently for each pipeline and spectrum using the full covariance matrix.
Chapter 2. SPIDER-1 Null Tests

Figure 2.17: Three additional null tests of inner and outer radius, diagonal tiles and band center difference. Figure shows the comparison between the XFaster and NSI pipelines for the different frequency combinations. A horizontal offset is added to NSI points for visual clarity. $\chi^2$ values are computed independently for each pipeline and spectrum using the full covariance matrix.
2.3.1 $\chi^2$ test and PTE values

The $\chi^2$ distribution with $k$ degrees of freedom is the distribution of a sum of the squares of $k$ independent standard normal random variables. In the case where these assumptions are made:

1) All the binned bandpowers of a null spectra are almost independent,
2) All the null test results are independent splits,
3) All the spectra of a test (EE, BB, EB) are independent,

the statement that "one experiment passes a null test" might be described as "all the $\chi^2$ numbers that are calculated from the independent null tests are randomly drawn from a $\chi^2$ distribution." These assumptions need further discussion to validate and might not be true.

The first thing we did to evaluate null spectra was to compute a naïve $\chi^2$ number for each of the spectra in the $\ell$ range that we care most about ($\ell = 33 \sim 257$). Nine scientific bandpowers are used to compute this number:

$$\chi^2 = \sum_i b_i^2/err_i^2$$

(2.35)

where $b_i$ is the value of the bandpowers in each bin $i$ and $err_i$ is the estimated error bar (square root of the diagonal of the covariance matrix) for that bin. This equation gives us a naive $\chi^2$ value for a spectrum. However, in XFaster, the covariance matrix of the bandpowers is given for free at the end of the analysis. We could then easily introduce the correlations between spectra into the $\chi^2$ estimation:

$$\chi^2 = \sum_{i,j} b_i^T \cdot C_{ij} \cdot b_j$$

(2.36)

where $b$ is a vector of the bandpowers and $C_{ij}$ is the estimated covariance matrix of these bandpower values. $i, j$ iterate over the nine scientific bins. For each of the frequency 90 GHz, 150a GHz and 90×150a GHz, 30 $\chi^2$ numbers (10 independent tests × 3 spectra) are calculated. A simple way of visually checking if these numbers are randomly drawn is to compute a PTE number for each of the $\chi^2$s.

PTE values and Kolmogorov–Smirnov test

The probability-to-exceed (PTE) value is the probability of observing a test statistic that’s at least as extreme as the data in a $\chi^2$ distribution. Mathematically, it is the value of cumulative distribution function (CDF) for the appropriate degrees of freedom (in our case, nine) subtracting from 1. One can imagine that the larger the $\chi^2$ value is, the probability to observe that $\chi^2$ is smaller. For null test $\chi^2$ values that should be randomly drawn from a $\chi^2$ distribution, the PTE values are expected to be a uniform distribution from 0 to 1, which is visually more straightforward than a $\chi^2$ distribution when looking at a histogram. The PTE values from the 30 null tests are shown in Figure 2.18.
Chapter 2. SPIDER-1 Null Tests

Figure 2.18: XFaster null test results expressed as PTE values assuming a $\chi^2$ distribution for each of the bandpowers. Results are shown for each polarization spectrum as well as for each frequency band and for the combined data set “Comb”. The color scale extends from 0 (dark) to 1 (light) to make the extreme values visually apparent. For a suite of 10 null test for each frequency, the PTE values are expected to distribute evenly between 0 and 1. Figure modified from [10].

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<th>Alternating Mux Columns</th>
<th>Alternating Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 GHz</td>
<td>150 GHz</td>
</tr>
<tr>
<td>EE</td>
<td>0.62</td>
</tr>
<tr>
<td>BB</td>
<td>0.33</td>
</tr>
<tr>
<td>EB</td>
<td>0.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Early/Late Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 GHz</td>
</tr>
<tr>
<td>EE</td>
</tr>
<tr>
<td>BB</td>
</tr>
<tr>
<td>EB</td>
</tr>
</tbody>
</table>


Now 30 PTE values are calculated from 30 null tests, it is possible to construct a statistical value to evaluate whether these are drawn from a uniform distribution. We use the Kolmogorov–Smirnov test (K-S test) to do that. The K-S test is a nonparametric test that quantifies a distance between the empirical distribution function of the PTEs and the cumulative distribution function of the reference uniform distribution. The distance is then plugged into the K-S probability function to calculate a probability value. This higher level $p$-value tells us how likely the PTEs values are drawn from a flat distribution.

The K-S test $p$-values for the 30 $\chi^2$ number are 0.03, 0.09 and 0.57 for the 90 GHz, 150a GHz and combined frequencies in Figure 2.19. As we deliberately chose the null splits
that show potential issues in our data, a non-zero passing criteria is considered conservative and strict. A non-zero $p$-value shows that the PTEs are somewhat reasonably distributed if the assumptions are true. We will revisit these assumptions in the next section.

### 2.3.2 Null test correlations

While to zeroth order the correlations between different spectra and null splits are negligible, during the evaluation of null tests we decided that these correlations should be considered to make our null test result more reliable, as correlations between tests could be well studied by intensive testing on simulations.

#### Spectra correlation

In an ideal full sky observation, the E modes and B modes of CMB polarization are orthogonal, hence the EE and BB spectra should be independent. However in a partial sky the E mode could leak into B mode due to the non-orthogonal bases of polarization, and the filtering of the time stream data would also distort the sky in a way that introduces false B signals. The coupling kernel $K_{\ell\ell'}$ was introduced to mitigate this effect. These
Chapter 2. SPIDER-1 Null Tests

effects are studied in simulations and could be corrected in the null tests as XFaster estimates a covariance matrix that has correlations between different spectra. See Figure 2.20 for an example.

![HL x HL Correlation matrix](image1)

**Figure 2.20:** Correlation matrix between simulated null spectra of High/Low band center null tests (tagged as "HL"). The sub-block diagonal terms between EE and BB show correlations of the bandpowers. This figure is a visual representation of the correlations only. The correlation coefficients are not used in the analysis.

This correlation is successfully handled by the covariance matrix output of XFaster.

**Data-splits correlation**

Another correlation that we didn’t consider at first is the test correlation. When we do half data splits of a full detector set, different ways of splitting data are first considered to be independent, and ideally there could be a large number of ways of splitting data to mitigate over these chance correlations. However, it is not true as some splits are more correlated than others.

![IO x RA Correlation matrix](image2)

**Figure 2.21:** Correlation matrix computed from simulated null spectra of Inner/Outer rows (tagged as "IO") and Inner/Outer Radius (tagged as "RA") null tests. The diagonal terms between the same spectra show correlations of the bandpowers. This figure is a visual representation of the correlations only. The correlation coefficients are not used in the analysis. The 90 GHz block is a sub-block of Figure 2.22.
2.3. Spider-I Null Test Result

For example, consider in an extreme case while the half-data sets for the two null tests only have one detector swapped, then the systematics shown up in one null test would almost certainly show up in another null test, the results are then highly correlated. This is tested to be true for two of our null tests, Inner/Outer Focal Plane Rows and Inner/Outer Focal Plane Radius, while the half data sets overlaps by 75% to each other.

A way to look at these correlations is to build covariance matrices from simulated bandpowers, like shown in Figure 2.20 and Figure 2.21. In Xfaster the simulated maps generated for different data-splits with the same simulation-index use same random seeds, which means that correlations of different null tests, while being a complete geometric feature and is independent from the data, is already included in the simulation maps.

We used 500 pairs simulation maps for the null tests and the spider null data produced a total number of 9 bins * 3 spectra * 10 tests = 270 bandpowers for each frequency, a well defined $270 \times 270$ test-to-test correlation matrix can be derived from the 500 simulation. See Figure 2.22 as an example.

![90GHz correlation coefficient matrix](image)

**Figure 2.22**: Correlation coefficient computed between simulated null spectra of all 10 tests, three spectra and nine bandpower points for the 90 GHz. The dimension of this matrix is $270 \times 270$. The two-letter labels are tags for 10 different tests. The scale is saturated at $\pm 0.25$ for a clear show of the off-diagonal correlation lines. Each square shows one pair of test-test correlation, where the DT (diagonal tiles test) x PS (port startboard test) and the RA x IO (Figure 2.21) test correlations are visible in the diagonal lines. This figure is a visual representation of the correlations only. The correlation coefficients are not used in the analysis.
One can tell from the high level simulated correlation matrices that there are non negligible correlations between spectra and different tests. Thus the assumptions we made in section 2.3.1 need to be reconsidered, and higher level statistical evaluations about passing null tests should also be made.

2.3.3 Higher level statistical tests

As the correlations exist in our null test data, whether the $\chi^2$ numbers we computed are randomly drawn from a standard $\chi^2$ distribution is not a good way to define the passing criteria of null tests. We can instead construct a better underlying distribution from the simulations. We consider the 500 simulated bandpowers that should have same underlying correlations in them, and then do high level tests to compare our data against these simulated $\chi^2$ number distributions. To evaluate "how our data resembles simulations given the known correlations", we perform two statistical tests, outlier and distribution tests as described next.

Outliers test

While the correlations exist in the spectra and tests hence exist in the $\chi^2$ we draw, we still use the 30 $\chi^2$ numbers as statistics that represent the bandpowers. Instead of evaluating the distribution of these directly, we also compute 30 $\chi^2$ numbers for each one of the 500 simulations.

The outlier test is to compute the fraction of simulations that have the largest $\chi^2$ value that’s at least as high as the data’s largest $\chi^2$ value:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>90 GHz</th>
<th>150a GHz</th>
<th>Combined frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of outlier simulations</td>
<td>0.38</td>
<td>0.34</td>
<td>0.78</td>
</tr>
</tbody>
</table>

This test is essentially a higher level significance test, while we are inferring the distribution of the largest $\chi^2$ number in a 30 $\chi^2$ draws that are correlated using the 500 simulations. By counting how many simulations have a more unlikely largest $\chi^2$, we are getting a number of how likely it is that our data’s largest $\chi^2$ to be drawn. It resembles the $\chi^2$ test p-value in statistical meaning.

Distribution test

The distribution test is a series of higher level analysis on the $\chi^2$ distributions with the simulations. The step-by-step procedure is the following:

1. Take the full covariance matrix that XFaster outputs for data bandpowers.
2. Run 5,000 realizations of bandpowers using that full covariance matrix.

3. Calculate 3 $\chi^2$ numbers for the EE, EB, BB spectra respectively for each of the realizations using the sliced inverse of the covariance matrix$^6$.

4. Compute empirical cumulative distribution function (CDF) from the 15,000 $\chi^2$.

5. Perform Kolmogorov–Smirnov test comparing the 30 data $\chi^2$s to the simulated distribution function. Compute a K-S test $p$-value for the data.

6. Repeat step 1~5 for the 500 simulations to get 500 K-S test $p$-values.

7. Compute the fraction of simulations that have K-S test $p$-values lower than data.

The covariance matrix has correlations between EE, BB and EB built in it, hence the CDF constructed in step 4 will have the correlations between EE, BB and EB. Then, by comparing the data to 500 sims in step 7, the correlations between different tests are considered. See Figure 2.23 for a result of this procedure.

The distribution test is a better test for correlated null tests than a normal $\chi^2$ distribution test in the sense that the simulations have the test correlations built in. Instead of trying to correct for the correlations, constructing a higher-level distribution test helps deciding whether we pass a null test by telling us "how likely is it to have 30 $\chi^2$ numbers distributed like our data, given all the known correlations". A reasonable fraction is the single highest level $p$-value here that determines whether we pass our null test:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>90 GHz</th>
<th>150a GHz</th>
<th>Combined frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of outlier simulations</td>
<td>0.07</td>
<td>0.21</td>
<td>0.56</td>
</tr>
</tbody>
</table>

**Table 2.2**: Distribution test that probes the shape of the null statistics across all tests, accounting for correlations among similar null splits. Each value is the fraction of simulations that has worse distributions than data. These values are not including X3, one of the 150 GHz focal plane.

To complete the discussion of dropping an entire 150 GHz focal plane (X3) in the analysis, Figure 2.24 shows the 150 GHz result with X3 failed the null test.

### 2.3.4 Conclusion

Based on the results of null tests, data from one of the 150 GHz receivers were dropped from the present analysis; its data are excluded from all other results. This receiver was uniquely susceptible to noise correlated with the reaction wheel angle. Because all other receivers pass the Inner/Outer Focal Plane Row null test, we have confidence that the same systematic issues do not affect the rest of the data used for this analysis.

Combining the two tests results in Table 2.1 and Table 2.2, our null tests are considered to have passed both in the distribution and outlier $\chi^2$ tests.

$^6$The difference between using the slice of the inverted covariance matrix and the inverse of sliced covariance matrix is found to be negligible. We decided to use the sliced inverse to make sure the correlations between spectra are included.
FIGURE 2.23: Illustration of null statistics computed from the combined data set (all frequencies). (top) Histogram of all null test bandpower $\chi^2$ values and expected distribution of drawn $\chi^2$s from the covariance matrix. The red histogram consists of 30 $\chi^2$ values, (3 polarization spectra $\times$ 10 tests). The expectation histogram (*dashed line*) consists of 5000 random bandpower draws from each covariance matrix for each test, used to compute a total of 150,000 $\chi^2$s. A K-S test is performed between the data and expectation distributions, resulting in a *p-value* of 0.54. (middle) Histogram of the maximum bandpower $\chi^2$ value from 500 end-to-end simulations. The maximum $\chi^2$ of the data is 18.2, corresponding to a PTE of 0.78 given the ensemble of max- $\chi^2$ values. (bottom) Histogram of the K-S test *p-values* from the same set of 500 end-to-end simulations. The *p-value* = 0.54 of the data (*red line*) corresponds to a PTE of 0.55 given the ensemble of KS tests. Together, these tests indicate that the combined data set passes its suite of null tests.
2.3. SPIDER-I Null Test Result

Figure 2.24: Illustration of null statistics computed from the 150 GHz (X1,X3,X5) data set. (top) Histogram of all null test bandpower $\chi^2$ values and expected distribution of drawn $\chi^2$s from the covariance matrix. A K-S test is performed between the data and expectation distributions, resulting in a $p$-value of 0.000 (Fail). (middle) Histogram of the maximum bandpower $\chi^2$ value from 500 end-to-end simulations. The maximum $\chi^2$ of the data is 29.402, corresponding to a PTE of 0.082 given the ensemble of max-$\chi^2$ values. (bottom) Histogram of the K-S test $p$-values from the same set of 500 end-to-end simulations. The $p$-value = 0.000 of the data (red line) corresponds to a PTE of 0.000 given the ensemble of KS tests. Together, these tests indicate that the 150 GHz data set that includes X3 failed its suite of null tests.
Chapter 3

SPIDER-2 Cryogenic System Integration

The SPIDER-2 cryostat, nickname **Llorothaag**\(^1\), is a balloon-borne cryogenic payload that will be flying from McMurdo Station, Antarctica, following it’s sister Theodosia’s 16 days flight (SPIDER-1, see Figure 3.1).

\(^1\)An ancient spider goddess. I encourage you to google it.

**Figure 3.1:** A 16 days flight of SPIDER-1’s payload. The cryostat was flown from a balloon and flew in the stratosphere (36km altitude) of Antarctica in the path shown in the photo. The receiver benefits from being above the atmospheric emissions.
Lloro’s design resembles Theo in most aspects, and was refined in some features to be optimized for a longer flight with a larger liquid Helium tank, a more compact center cabling aperture, and most importantly, three new telescope inserts.

With heavy referencing to the previous cryostat Theo, we have integrated Lloro in a series of cryogenic runs, and have characterized it’s cryogenic performance, thermal behavior and mechanical stability by using a bespoke housekeeping system. In section 3.1, different stages of the cryogenic system are introduced. The history of the characterization, cryogenic runs, is introduced in section 3.2, and performance and monitoring of the cryo-system are introduced in section 3.3.

A detailed, complete introduction to the SPIDER-1 cryostat can be found in [11].

3.1 The Cryogenic System

Cryostat Lloro hosts three stages of cryogenics: A 4 K main tank that directly provides cooling for the six inserted receivers (inserts), a 2 K superfluid stage that cools the $^3$He refrigerators inside the inserts, and a sub-Kelvin stage that directly cools the focal plane unit. See Figure 3.2 for a complete view of the cryostat. These three stages form an open-vent path for helium gas that gradually vapors out as the inserts heat up from the thermal and optical radiation through the apertures. The flow path for gaseous helium is designed to make maximal use of the cooling power provided by the liquid in the main tank. The internal capillary system in between the 4K and 2K stages provides a steady 2 K thermal bath for the sub-Kelvin $^3$He fridges, allowing a steady cryo-environment for the focal planes. These stages will be introduced in detail in this section.

3.1.1 4 K+ Stages

In a balloon flight, the cryostat is designed to face an ambient temperature ranging from 250 K to 300 K. The stability of the temperature gradient from 4 K to ambient is important in the designing of a cryostat to keep the loss of liquid helium as low as possible.

Outer shell and top dome

The outer shell of the cryostat is made from aluminum alloy, placed at ambient temperature of around 300 K on the ground or around 250 K in the stratosphere, and white painted to reduce thermal absorption in flight and to prevent electrical shorts. See Figure 3.2. The shell consists of four pieces. From top to bottom, first, the top dome which has six apertures that holds the ultra-high molecular weight polyethylene(UHMWPE) vacuum window buckets. Second, the main body, a cylinder that has all the hermetic flanges where cryo cables connect through, and where multi-channel electronics (MCE) crates are mounted at. Third, the donut ring, where the fill line, vent line and pumping pipes connect out. Four, the bottom dome, a one-piece metal that functions as a mechanical closure.

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$^2$The cryogenic system is sometimes shortened as cryo-system in this and next chapter.
3.1. The Cryogenic System

Figure 3.2: A cross section of the SPIDER-2 cryostat design with two inserts visible in the drawing. The vacuum vessel (spaces between the outer shell and the main tank (MT)) is separated into three separate cryogenic stages by vapor-cooled sheids 2 (VCS-2) (dark red) and VCS1 (light red) that are at 30 K and 130 K respectively. The main and the superfluid tanks (MT and SFT) which hold regular liquid helium and superfluid helium are colored in light and dark blue respectively. Five plumbing lines exist at the bottom: the main and superfluid tank fill and vent lines and the VCS vent line. Figure modified from [11].
All of these four pieces are vacuum sealed through customized o-ring flanges, and are tested to be vacuum tight in each cryogenic runs, see section 3.2.

**Vacuum vessel, VCSs and MLI**

While in cryo-operation, a $10^{-6} \sim 10^{-5}$ torr level vacuum is maintained between the outer shell and the 4 Kelvin main tank (MT), of which the volume in between is called vacuum vessel (VV). There are two intermediate stages of vapor-cooled shields (VCS1 and VCS2) in the VV, mechanically supported from the main tank and vacuum vessel respectively. These two thin layers of aluminum 1100 (chosen for its high thermal conductivity) shells serve as radiation stops, and are cooled by negative thermal feedback from liquid helium vapor routed through heat exchangers, to maximize the use of cooling power provided by the liquid in the tanks.

In addition to minimizing thermal conduction, aluminized mylar multi-layer insulation (MLI) between the stages reduces thermal radiation on the main tank, which, under vacuum circumstances, is the dominant thermal loading. The MLI blanket is made with 6.4 $\mu$m thick Mylar, coated with a 35 nm thick aluminum layer, and separated by 0.1 mm thick polyester sheets. The layer construction of the MLI was optimized for minimum pump down time and maximum radiation shielding[15], resulting in 16 and 52 layers respectively between VCS2 - VCS1 and VV - VCS2.

**Main tank MT**

The main cylinder tank, penetrated completely by six inserting ports and one center port, is the dominant weight contributor to the whole cryostat. See Figure 3.3.

It is a tank for liquid helium with a center port reduced compared to SPIDER-1 for more storage volume, hence longer flight duration. Its sole purpose is to hold 1300 L liquid helium for the cryostat, and to ensure the inserted receivers are submerged in a relatively uniform 4 K environment. The MT, and the superfluid tank (SFT) in the following section, are made from Al-5083, chosen for its strength after welding.

There are three plumbing fixtures attached to the main tank that can be seen vaguely from Figure 3.2. All of them are made of 304 stainless steel due to its low thermal conductivity and suitability for welding. The MT fill and vent lines are 3/4 inch diameter plumbing. The VCS vent line however, is 1/4 inch outer diameter, and is routed through stages of heat exchangers on the VCSs to provide sufficient cooling power for the 4 K and beyond stages, being the highest flow impedance among the three that connects the MT to the outside.

These vent lines are positioned on the cryogenic tanks such that vapor can exit the cryostat when it is tilted through a 22-49 deg elevation range while full of liquid. During flight, the MT fill and vent lines are sealed so that all of the helium vapor from the MT is routed through the VCS heat exchangers, and vented out through the VCS vent line.

There are 7 explosion-bonded thermal contact pads on the bottom of the main tank, to provide direct thermal contacts with the cryogen inside. Heat straps run between these pads and 4 K stages of the fridges inside the insert to provide direct cooling for the cryo-pumps in the fridges.
3.1. The Cryogenic System

3.1.2 2 K Stage and the Capillary System

An intermediate temperature stage between the regular 4 K environment and sub-Kelvin science temperature is required for the $^3$He fridges to operate. In order to provide a cooling bath that is lower than 4 K for the $^3$He fridges, a superfluid tank (SFT) was custom designed and built for our system, and the cooling power of that SFT is provided by a system of capillaries which connects the main tank to the superfluid tank.

Superfluid tank SFT

SPIDER’s SFT was designed to have minimized weight while maximizing the use of superfluid helium. Figure 3.4 shows a zoom in of the SFT from the cryostat CAD model.
Chapter 3. SPIDER-2 Cryogenic System Integration

Figure 3.4: The superfluid tank and capillary assembly are mounted to the bottom of the main tank. The capillary assembly is located just below the SFT ring and connected to both tanks using flexible 1/8 inch bellows tubing. Thermal contact pads are welded into a ring that sits below the main volume. The CAD model is a collective work of the Spider collaboration.

As shown in the figure, the SFT has a ring-and-nose shape with a large (0.45 m²) surface area that accumulates superfluid coming through the capillary at the bottom of the ring, connected with the main tank. The design of this special shape is driven by two factors:

First, by centering the SFT ring with the MT bottom, we are using superfluid ⁴He with high thermal conductivity as the thermal link between the ³He fridges and the superfluid itself. The inserts are cooled via a series of thermal contact pads around the circumference of the ring. To reduce the thermal boundary resistance, which is the dominant thermal impedance between the liquid helium bath and instruments, these contact pads are made from explosion-bonded aluminum-to-copper. These pads are connected to custom-made copper heat straps, which are fabricated by folding 0.005 inch thick high purity copper shims into a stack of 18 layer assembly.
3.1. The Cryogenic System

Second, the special properties of superfluid helium drive the nose design of the SFT. The large surface area of the SFT nose makes the superfluid surface always lie in the top of the SFT assembly, ensuring the ring remains full over the full range of elevation angles.

The SFT is a passive assembly that is fully dependent on the 4 K main tank, through the connection via the capillary system.

**Capillary assembly**

The purpose of the capillary system is to provide continuous cooling power of approximately 60 mW to counter the steady state loading from the inserts. The design has no mechanical valves or other moving parts, driving the superfluid through solely from the pressure differences created by pumping on the SFT vent.

The general design principles of the capillary system are based on DeLong et al.\[32\] where they describe a two stage $^4$He cryogenic system for a dilution refrigerator. The full assembly and one capillary unit diagram is shown in Figure 3.5.

**Figure 3.5:** Left The capillary assembly. Four capillaries connect the 4.2 K main tank box (bottom) to the 1.6 K SFT box. The double volume structure is supported by two 1/32 inch thick G-10 flexures. The thermal load conducted through these flexures is negligible compared to the cooling power from the superfluid. Inside the MT box, stainless steel Mott filters\(^3\) preceding each capillary prevents ice and other dirt from entering and clogging these high impedance lines. Right A cutaway diagram of a capillary unit. The capillary itself is wound around a hollow teflon spool and brazed into a brass puck on either end to mate it to the VCR glands, which then mate to the fitting on the assembly boxes. The stainless steel spring ensures that the unit has structural support while freely fitting between boxes. **Figure taken from [11].**

\(^3\)https://mottcorp.com/.
Chapter 3. SPIDER-2 Cryogenic System Integration

The capillary in each unit is a 304 stainless steel tube with 0.035 inch I.D. and 0.06 inch O.D. Each capillary is approximately 14 inches in length. Each single unit can be made with a wide range of capillary lengths without altering the overall design, which allows us to make a large set of units with varying flow impedances and so choose the optimal flow rate. The number of capillary capsules in Lloro was optimized between what is sufficient for the cooling power needed from the inserts, and what doesn’t cause liquid waste by adding too much thermal loading on the main tank, which could shorten the flight time.

SPIDER-2’s capillary assembly is shorter than SPIDER-1’s, and is thermally isolated from the MT through G10 fiberglass laminate. This change allows us to heat the capillaries more quickly and with less power, which makes it easy to clear ice plugs if any appear. (See section 3.2 for discussions over ice plugs.)

3.1.3 Sub-Kelvin Stage and the $^3$He Cryo-fridge

The ultimate goal of the cryo-system is to provide cooling for the TES detectors and SQUID readout system inside the inserted telescope. To achieve the desired low thermal fluctuation and phase transition temperature of the TESes, the focal plane units (FPU) are cooled to <500mK through the $^3$He absorption fridge.

![Figure 3.6: A schematic diagram of the $^3$He miniature fridge.](image)

The fridges are provided by Chase Research Cryogenics. The pump and the still are the two main sections of the refrigerator which are connected by thin-walled stainless steel tubes through a phase changing section - the condensation point. Operator cycles the fridge by controlling the heaters in the pump and the heat switch, which then controls the adsorb / release of the helium atoms. The cooling power of the pump and the condensation point are provided by MT and SFT respectively, and the still provides cooling power for the focal plane unit through oxygen-free high thermal conductivity copper (OHFC) heat strap.
3.1. The Cryogenic System

As shown in Figure 3.6, each individual $^3$He fridge per telescope is mounted on the base plate of the insert, with the fridge pump connecting the 4 K base plate through a heat switch inside the fridge. The condensation point of the fridge is connected to the 2 K auxiliary post inside the insert, which connects to the end of the heat strap outside the insert. The heat straps then link with the thermal pads on SFT.

$^3$He adsorption fridge

The $^3$He adsorption fridge works under the simple principle of $^3$He gas-liquid phase transition. The pump contains an adsorbent material - activated charcoal, with a large surface area onto which helium gas atoms are adsorbed when the surface is cold enough. The pump is outfitted with a heater and a gas-gap heat switch that links the pump to the 4K bath provided by MT. The heat switch is a smaller version to the pump, where it also has adsorbent inside and would release/adsorb gaseous helium while heated or cooled.

The still is connected to the mK focal plane assembly up in the insert, running through a single flexible oxygen-free high thermal conductivity copper (OFHC) strap.

Fridge working cycle

In a flight situation, the fridge’s steady state has the heat switch is closed. The heat switch heater is turned on so that gas inside the switch is a thermal link between the pump and the base plate. The thermal load from the focal plane unit (FPU) makes the helium liquid in the still constantly boil off, and gas atoms get immediately adsorbed onto the charcoal, as the pump is kept at 4 K. When the still runs out of liquid, the fridge needs to be thermal cycled to be in good use again.

The steady state of the fridge can hold as long as 50 hours, as cryoruns shows (see section 3.2), but the fridges can be forced to cycle in order to control the working schedule and to avoid simultaneous cycling. The cycling of a fridge takes 1.5 - 2 hours.

Figure 3.7 gives a temperature measurement of one fridge cycling. To start a fridge cycle, the heat switch needs to be open (heat switch heater turned off) to isolate the pump from the 4K bath. After a couple minutes, the pump heater is turned on, and it is heated above at least 20 K to release the adsorbed helium atoms. The pump heater is kept at a servo mode, to keep the pump at a temperature range where it’s constantly beyond the charcoal adsorption point, but not too high to create too large of a thermal load. The condensation point is kept below the boiling temperature of $^3$He, so that the desorbed gas condenses there and falls into the still$^5$. Notice that while the pump is heated, the heat switch is in it’s open state (not-heated), to isolate the pump from the 4K bath.

Once there forms a certain amount of liquid in the still, the pump heater is turned off. The heat switch is then closed (with heat switch heater on), to immediately cool down the pump by connecting it to the 4K bath. This makes the pump quickly adsorb the

$^4$https://www.chasecryogenics.com/.
$^5$Hence in insert operation, it is important to make sure that the orientation of the pumps is correct in each insert so that the still falls below the condensation point.
Figure 3.7: Temperature data as an example for a two hour fridge cycle. At the beginning of the fridge cycle, heat switch temperature drops immediately as the switch opens, and pump temperature rises as being isolated from the base plate. The adsorbed gas atoms then get released into the system. Atoms that hit the condensation point get dropped into the still, meanwhile, they create loading onto the SFT through the condensation point. After around 40 minutes, as the pump heater turns off, and the heat switch closes, the pump connects to the 4K bath and gradually cools down. As cryo-pumping going in the gas/liquid mixture, the temperature of the still is constantly brought down due to pressure drop, and the liquid creates sub-K temperature in the still and stabilizes there. Figure modified from [12].

remaining gas in the connection, hence driving the pressure down to cool the liquid in the still. The still keeps cooling until the evaporation rate equilibrates with the pumping rate, drives the 2K liquid helium to mK temperature, and remains at this temperature until all the helium atoms are warmed up through the optical/electrical load on focal plane assembly.

Note that once the heat switch is closed, the fridge enters its steady state where the pump remains cold and the heat switch remains closed.

3.2 Cryogenic Runs

With every functioning part of the cryostat briefly introduced, this section will focus on the cryogenic runs we did to characterize this system. A "cryorun" is a ground testing procedure which typically lasts 2 to 3 month, where various tests are done on the system in cryogenic situations. Some system measurements that can only happen on the ground and before the final flight, such as the Fourier transform spectroscopy (FTS) measurement, beam maps, polarization angle testing and detector optical efficiency measurement are usually performed in these cryogenic runs.
In between the cryogenic runs, the empty cryostat is being integrated and is getting asymptotically closer to match the final flight environment, where it’s being filled with cables, electronics and inserts. These cryoruns are also essential in training operators to get familiar and comfortable with the cryo-system and getting them flight ready.

### 3.2.1 Cryorun Protocol

A cryogenic run follows a precise protocol to safely pump down, cool down, keep cold, and warm up while optimizing the use of all equipment and cryogens. The cryogenic operation team should always follow a protocol in practice runs, as balloon deployments are often constraint with intensive and limited time schedule. For that a standard operation procedure (SOP) for Lloro was written and followed strictly by operators during a cryorun. This subsection is a brief pedagogy of the SOP.

**Pumpdown.** After closing up the cryostat with top and bottom domes, a pumping manifold is set up for the vacuum vessel to pump down the cryostat. Ever since the delicate shader filters were installed, a needle valve and flow meter system is used while pumping to control the speed of pumping so that it doesn’t go too fast to wrinkle the filters. We make sure the pumping speed is less than 25 SLPM, which is tested to be a safe upper limit for the shader filters.

The pump down of the system consists of three stages: 1) Atmosphere pressure to turbo safe pressure with a Triscroll dry pump; 2) A turbo pump brings a 0.1 Torr level vacuum to $10^{-3}$ Torr level; 3) Leak check to make sure the system is vacuum tight before any cryo-filling happens.

As water and other gas molecules accumulate in the vacuum vessel when the system is idling and open, the pump down usually takes several backfills of dry N2 gas and re-evacuation to bring down the system to a relatively clean vacuum. See Figure 3.8 for a comparison plot.

**Leak check.** We do a thorough leak check as soon as the system is brought down to a pressure that is suitable for leak checking. so that if a leak was found the system could be brought up to room pressure and the leak could be fixed. During a leak check, the helium leak checker made by LACO is connected to one of the pump out ports of the vacuum vessel with readout being displayed in the real time reading program KST2. The leak checker should not be in parallel with the turbo during leak check, as the turbo pump has a larger or comparable pumping power than the turbo pump inside the leak checker which influences the result. Two operators are required for a leak check due to the size of the cryostat being large for a single person to completely monitor: One operator would monitor the real-time helium background and control the pace of helium spraying; another sprays helium to all the vacuum seams where there could be a leak.

---

6 The detailed, step-by-step procedure can be found in Lloro Standard Operating Procedure document.
7 https://lacotech.com/
8 https://kst-plot.kde.org/
Chapter 3. SPIDER-2 Cryogenic System Integration

Figure 3.8: An example second stage pumpdown plot from cryo run08. First stage refers to the pressure period before 10 Torr. The labels are tagged as the times of the pumpdowns, for example, "PD8" refers to the eighth pumping and purge cycle in a run, where all pump downs are lined up at the time when they reached 10 Torr. As the number of pump and purge cycles go up, the ultimate pressure goes down until it matches a pressure that's lower than the upper limit of a turbo pump operating pressure, which is at least lower than $10^{-1}$ Torr. The drastic change of pressure decreasing speed happening at $10^{-1}$ Torr was due to the change from a scroll pump to a turbo. This plot uses run06’s final pumpdown as an anchor comparison for it’s low ultimate pressure achieved. The unphysical pressure drop at 275 min for this curve was due to gauge shifting in the duo-gauge that was used to readout the pressure.

Different leaking seams would have different responses in the helium background, due to the size of the leak and the mean free path of a helium atom from the seam to the pump out port. One always first checks for the leak checker manifold before opening the leak checker to the system. The potential leaking seams in the system include all vacuum window flanges and window seams, top dome flange, bottom dome flange, donut ring flange, six MCE hermetic flanges and six ConFlat flanges for housekeeping cables.

See Figure 3.9 for an example of a leak event.

After the system is tested to have no leaks, it pumps with the turbo for at least 48 hours before any filling of the cryogens.
3.2. Cryogenic Runs

Figure 3.9: An example plot for the helium background when a leak happens. The helium background drifted from a very good $4\times10^{-10}$ to $1.6\times10^{-9}$ mbarL/sec when operators spray helium around one of the MCE flange bolts, indicating a small leak in the system. Absolute helium background values are proportionally scaled with the pressure so is usually not taken for scientific meaning and abrupt changes are signals of leaks. Leaks in a vacuum system affect the cryo-system where gas heat conducting creates additional thermal load to the cryogenic tanks.

LN2 filling. The heat capacity, temperature and price of the liquid helium (LHe) prevents a cryo system being cooled with LHe directly from 300K. For this reason a natural choice is to cool down the system to an intermediate 77K stage with the much affordable liquid nitrogen (LN2)\textsuperscript{9}.

Right before the filling of LN2, we do a last leak check to make sure the system is vacuum tight in a noticeable level of the leak checker. The main tank is pumped out and purged with gaseous helium at least twice to make sure the tanks are clean. A gas flow test of the capillary system is done to make sure we have enough working modules of the capillaries.

Flow tests happen both at 300K(pre LN2 filling) and 77K stage(pre LHe filling). Each flow test is a 30-45mins valve off of the SFT, to let atmospheric pressure helium gas in the MT gradually fills up a vacuum SFT. The pressure change in the SFT is almost linear due to the size difference and steady gas flow in the capillaries. The flow rate is then compared with previous runs that are deemed to be healthy, and further analyzed

\textsuperscript{9}The unit prices for liquid helium and liquid nitrogen are often analogized to a fine bottle of wine and cheaper than milk, indicating the price difference due to difference in rarity and costs to produce.
through a semi-empirical thermal model\(^\text{10}\). Based on the performance, operators choose
to either proceed with cryogen filling or further investigate the capillaries behavior.

The SFT is then over-pressurized to at least 5 psi higher than the atmosphere, and the
capillaries are heated on until the superfluid starts accumulating to prevent any possible
nitrogen, water, or oxygen plugs in the modules. All the other heaters in the system
including the heat switch heaters are turned off to prevent any additional loading\(^\text{11}\).

The liquid nitrogen can be filled all at once to make the procedure easier and faster. The
pressure in the main tank will be high due to the intensive boiling off of the liquid, and
will only stabilize when the system is cold enough. This process requires constant watch
of the cryo operators. During this stage, thermal acoustic oscillation (TAOs) happens in
the venting manifold, which produces a significant amount of heat\(^{[33]}\).

**LN2 backfill.** Once the system is cooled and stabilized at 77K, the excess LN2 in the
main tank needs to be pushed out of the system for the liquid helium fill later. We
pressurize the main tank and connect the fill line to a LN2 dewar to push out the LN2
rapidly. After this process, the LN2 that’s below the surface of the fill line will con-
tinue to boil off for a couple hours, giving preparation time for the liquid helium filling.
Once the tank becomes empty, the system will gradually warm up, so it is important to
prepare for the filling of liquid helium right after the boiling off.

**LHe filling.** As in filling LN2, before the liquid helium filling, we pump and purge the
main tank with helium gas. The over-pressurized SFT is evacuated and pumped out to
do the 77K flow test. After the flow test, we pressurize the SFT to be 5.5 psig again.

The filling of liquid helium should be paced precisely to maximize the use of the cooling
power provided by the 4K liquid. The pacing should make sure that the 17.5 psia safety
valve at the MT vent be kept close, otherwise the cold gas is not routing through the
system but rather getting straightly dumped into the recovery system.

Once the temperature of the sub-Kelvin system gets closer to the asymptotic value, we
turn on the cryo-fridge pump heater. This makes the thermal connection between the
sub-K system and the 4K system as the fridge pump might be isolated below certain
temperatures. This process will then also decrease the load on the SFT, making it cools
down faster.

**Superfluid and sub-Kelvin operations.** Once we have sustained liquid helium in the
main tank, it is safe to start pumping on the SFT to draw super fluid into the tank. We
evacuate the SFT by slowly opening the SFT vent valve to the pump, in order to prevent
any large perturbations on the system which could cause an explosion. Once the SFT
is pumped out, temperature of the SFT drops significantly faster, and the SFT starts to
accumulate superfluid around 15-20 hours after starting pumping on it. Once we have
steady superfluid in the SFT and the sub-K system is sufficiently cold as 2K, one could

\(^{10}\)Details of this model can be found in: *Characterizing the Thermal Performance of SPIDER II Capillaries* - J.
van der List, experimental project, which will be included in his thesis.

\(^{11}\)The heat switch is essentially open due to the high temperature that connects everything in the \(^3\)He
fridge.
3.2. Cryogenic Runs

start initial fridge cycling as described in section . All of the cryo system is then cooled down and in a steady state.

Steady state and warm up. The length of a cryorun depends on the detector testing plan made before the run. During the steady state, fridges are cycled every 30-40 hours, depending on the fridge algorithm. The boiling off of the LHe in the main tank is slow and steady, which usually only requires a helium fill every couple days. In the steady state, operations are then shifted from cryo focus to various testings of the detectors and other integrations.

When we end a cryorun, the liquid in both of the tanks will boil off. During this process, various outgassing happens in different stages of the system. It is important to keep monitoring the pressure change, which correlates with temperature changes as gas brings in thermal conduction. Once the system is warm enough, it is safe to put a sufficient amount of gas into the vacuum vessel to make the warming up faster.

3.2.2 Lloro Cryoruns and Testings

Cryostat Lloro arrived at Princeton on Feb 21th, 2017. Between Feb 2017 and Aug 2020, ten cryoruns were performed on Lloro for system integration, cryogenic testing, modification and optimization. Table 3.1 shows a list of testing and operations that happened in these ten Lloro cryoruns. The length of a cryorun listed here varies based on a combination of the allocation of the helium situation, the predetermined schedule of testing and the different problems that we encountered.

<table>
<thead>
<tr>
<th>Pre-insert integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run01</td>
</tr>
<tr>
<td>• Sanity check of cryostat. No obvious leak from the tanks to vacuum vessel at cryogenic temperature.</td>
</tr>
<tr>
<td>• VCS stable temperatures and empty flow rate of the VCS vent are measured.</td>
</tr>
<tr>
<td>Run02</td>
</tr>
<tr>
<td>• Capillary system tested.</td>
</tr>
<tr>
<td>• SFT load curve taken.</td>
</tr>
<tr>
<td>• Windows and window buckets of 1/8&quot; thickness installed.</td>
</tr>
<tr>
<td>• Housekeeping cabling system installed (Lloro HK, Insert HK, Half wave plate cables).</td>
</tr>
<tr>
<td>• Vacuum getter installed in VV.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Insert integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run03, Run3.5, Run04</td>
</tr>
<tr>
<td>• Four and a half inserts are installed, with Port1 being a spare baseplate and Port2 without the optical lenses.</td>
</tr>
<tr>
<td>• Ran MCE continuity check (Instrument Backplane checking. See chapter 4, section 4.2.2).</td>
</tr>
</tbody>
</table>

---

12It keeps happen while this thesis is being written, but what the literature covers is enough to explain all operations for a flight ready cryostat and the description will stop at run 10.

13This was checked because Theo had helium leak from the tanks to vacuum vessel.
Chapter 3. **SPIDER-2 Cryogenic System Integration**

- Installed optical filter stacks.
- Adjusted and installed half-wave plates on all six ports.
- Fixed misalignments between inserts and MT in both radius and z-axis directions.
- These three runs had touches in the bottom where the VCS1 touching MT, significantly load the SFT causing the superfluid disappears as soon as accumulating. See Appendix A
- Y (280 GHz) focal planes running hotter than the Xs (90 GHz and 150 GHz).

<table>
<thead>
<tr>
<th>Run05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed VCS touch and successfully sustained super-fluid in the SFT for the first time.</td>
</tr>
<tr>
<td>Ran MCE continuity check.</td>
</tr>
<tr>
<td>Successfully tuned SQUIDs and TES detectors on transition.</td>
</tr>
<tr>
<td>Tested for window loss/reflection in 280 GHz focal planes.</td>
</tr>
<tr>
<td>Took X6 FTS data with high pass filter on.</td>
</tr>
<tr>
<td>Fridge cycle algorithm enhanced.</td>
</tr>
<tr>
<td>Lloro and inserts housekeeping inventory.</td>
</tr>
<tr>
<td>Y focal planes running hotter than the Xs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full 6 inserts installation including three Y focal planes at 280 GHz.</td>
</tr>
<tr>
<td>Fixed touches in the Y inserts.</td>
</tr>
<tr>
<td>Performed optical efficiency test of X1, X6, Y4 and Y5.</td>
</tr>
<tr>
<td>Continuity and housekeeping checking.</td>
</tr>
<tr>
<td>New 1/16&quot; UHMWPE windows and window buckets development.</td>
</tr>
<tr>
<td>Fridge auto cycling settled.</td>
</tr>
</tbody>
</table>

**Loading issue of the 280 GHz**

<table>
<thead>
<tr>
<th>Run07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y3 sent to UIUC for lab testing.</td>
</tr>
<tr>
<td>Y focal plane internal loading assessment.</td>
</tr>
<tr>
<td>Continuity and housekeeping checking.</td>
</tr>
<tr>
<td>Noise level analysis of focal planes.</td>
</tr>
<tr>
<td>Normal resistance measurements of TESes in the Y FPUs.</td>
</tr>
<tr>
<td>Optical path RF background testing.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity and housekeeping checking.</td>
</tr>
<tr>
<td>First FTS analysis of Y focal planes.</td>
</tr>
<tr>
<td>&quot;Golden wok&quot; testing on the Y focal planes.</td>
</tr>
</tbody>
</table>

---

14 Starting Run07, we have found that the 280 GHz focal planes were not able to be biased on science transitions (The AlMn TES), suggesting a loading issue which is the main debugging elements of these runs.

15 Will be introduced in detail in the next chapter.

16 The "golden wok" is a test where a gold-plated wok shape mirror was installed at the aperture for internal loading assessments. The wok is optimized in curvature for better focus, and gold-plated for better reflection.
3.3. Cryo-system Performance

The stability and performance of the cryo-system require a set of electronics and firmware to control, monitor and analyze. For which, we allocated thermometers to different stages of the system, and adopted a housekeeping system that was designed for recording the temperature data of the thermistors, as well as managing the thermal heaters for temperature control. The housekeeping system is introduced in section 3.3.1.

These thermal data can be viewed in real time through KST-2\textsuperscript{18}, and are stored and analyzed for cryogenic system analysis and future enhancement. For example, the fridge cycle monitoring, steady-state gas flow, cooldown procedure comparisons and weight loss are all archived and comparable for different ground testings through this system. See section 3.3.2.

Various abnormal behaviors and issues were also analyzed and addressed during ground testing. Appendix A discusses these in detail.

### 3.3.1 House Keeping System

SPIDER’s housekeeping data acquisition system (HK-DAS) was designed in accompaniment with the BLASTbus[34] detector readout system to perform temperature control and monitoring.

---

\textsuperscript{17}Run10 was a short, practice run that happened during the global COVID-19 pandemic.

\textsuperscript{18}The fastest real-time large data-set viewing and plotting tool implemented in python.

| Run09 | • Normal resistance measurements of TESes in Y3.  
• 280 GHz loading investigation.  
• Scientific archival FTS measurements of all FPUs.  
• Water vapor pump out loading test of 280 GHz.  
• Upper limit on edge filter harmonic leaks assessment.  
• Dynema window insertion test. |
| Run10\textsuperscript{17} | • Material insertion chop tests.  
• RFI coupling hypothesis discussion and analysis.  
• Y5 black poly/golden wok test. |

**Table 3.1:** Measurements and tests in Lloro’s cryogenic runs. These operations include regular sanity check, specific run goals and debugging of specific problems happened in previous runs. The insert testing, which will be further explained in the next chapter, is also listed here. Blue text indicates significant abnormal cryo behaviors that were fixed latter. We do Lloro housekeeping continuity checking, insert housekeeping continuity checking and instrument backplane (IB) checking at every temperature stage of every run to make sure the electrical system is functioning properly and is not shorted at any stage since a large amount of metal is used in the system. These tests will be explained further in the next chapter.
Chapter 3. **SPIDER-2 Cryogenic System Integration**

The Housekeeping electronics crate is physically mounted on the top dome flange, outside of the cryostat, and connected to the six ConFlat™ flanges on the outer shell body via lab-made room temperature cables.

This system reads out and controls the adsorption refrigerators and a variety of thermometers and heaters both in the inserts and in Lloro, by providing analog circuits for amplifying cryogenic thermometry and powering heaters. It also contains analog-to-digital converters (ADCs) for these amplified cryogenic signals.

**Lloro housekeeping**

Two kinds of thermistors are installed all over Lloro.

Lakeshore\(^\text{19}\) DT-670 silicon diodes are used for monitoring temperatures down to about 1K. The forward voltage drop across a diode has a standard temperature dependence under a constant-current bias. The standard temperature calibrations from Lake Shore Cryotronics were used to calibrate these diodes, and temperatures larger 10K were extrapolated out through the calibration curve.

Additionally, high-current heaters are installed near critical areas. Heaters on the capillary, SFT and the bottom of the main tank are used during the cooldown procedure to heat and purge the tanks of residual gases. They are also of use if ice plugs occur in the capillaries.

See Table 3.2 for a complete set of the diodes and heaters installed throughout cryostat Lloro. This set of channels listed are routed to a dedicated preamplifier board and read out at 8.4 Hz sample rate.

<table>
<thead>
<tr>
<th>Main Tank</th>
<th>VCSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main tank bottom low</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank bottom mid low</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank bottom mid</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank bottom mid high</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank bottom hi</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank top low</td>
<td>diode</td>
</tr>
<tr>
<td>Main tank top high</td>
<td>diode</td>
</tr>
<tr>
<td><strong>Main tank getter</strong></td>
<td>diode</td>
</tr>
<tr>
<td>VCS1 bottom</td>
<td>diode</td>
</tr>
<tr>
<td>VCS1 top</td>
<td>diode</td>
</tr>
<tr>
<td>VCS2 bottom</td>
<td>diode</td>
</tr>
<tr>
<td>VCS2 top</td>
<td>diode</td>
</tr>
<tr>
<td><strong>VCS1 flexure</strong></td>
<td>diode</td>
</tr>
<tr>
<td>VCS1 heat exchanger</td>
<td>diode</td>
</tr>
<tr>
<td>VCS2 heat exchanger</td>
<td>diode</td>
</tr>
</tbody>
</table>

\(^{19}\)https://www.lakeshore.com/home.
### 3.3. Cryo-system Performance

<table>
<thead>
<tr>
<th>VCS1 filter</th>
<th>diode</th>
<th>diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCS2 filter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Superfluid Tank

<table>
<thead>
<tr>
<th>SFT bottom</th>
<th>diode</th>
<th>diode</th>
<th>SFT ring</th>
<th>diode</th>
<th>diode</th>
<th>SFT nosetop</th>
<th>diode</th>
<th>diode</th>
<th>SFT heater</th>
<th>25 Ω</th>
</tr>
</thead>
</table>

Three well calibrated diodes are installed at different heights of the superfluid tank to monitor superfluid liquid level. An individual heater for SFT is also installed.

### Capillary System

<table>
<thead>
<tr>
<th>Capillary SFT side 1</th>
<th>diode</th>
<th>diode</th>
<th>Capillary SFT side 2</th>
<th>diode</th>
<th>diode</th>
<th>Capillary MT side 1</th>
<th>diode</th>
<th>diode</th>
<th>Capillary MT side 2</th>
<th>diode</th>
</tr>
</thead>
</table>

Two pairs of diodes are installed in the capillary boxes, with each in the pair un-calibrated and the other calibrated one as a reference. Two heaters are installed on the capillary system to respond to any clogging happens in the capillaries.

### Table 3.2: Thermometers and heaters installed in the flight cryostat.

<table>
<thead>
<tr>
<th>Capillary SFT side heater</th>
<th>85Ω</th>
<th>Capillary MT side heater</th>
<th>85Ω</th>
</tr>
</thead>
</table>

The wiring is routed to four 25-pin D-sub hermetic connectors and collected to a pair of 50-pin D-sub connectors on a dedicated preamplifier board. The MT getter diode, filter diodes, heat exchanger diodes, flexure diode and spare diodes in the capillary boxes are biased and controlled through the ground readout box instead of the flight system, as labelled out in blue.

---

### Insert housekeeping

Each of the six inserts housed in the cryostat is also wired with diode thermometers, resistive thermistors, and heaters for monitoring and controlling the cryogenic environment of each focal plane.

Two types of thermistors are employed on each receiver: Lake Shore Cernox™ thin film resistors and neutron transmutation doping (NTD) germanium semiconductor thermistors. These thermistors are maximally sensitive at sub-Kelvin temperatures.

The Cernox thermistors are installed on each focal plane and adsorption refrigerator still for monitoring sub-Kelvin temperatures. The NTD thermistors are epoxied onto the back of each of the four detector tiles for monitoring the temperature of each tile independently. The NTD readout circuit incorporates a pair of 30MΩ bias resistors mounted onto the 300mK stage to reduce the Johnson noise contribution of the load resistors, and to avoid amplifying noise along the readout cabling. The NTD thermistors are much more sensitive than the Cernox thermometers, and are read out at the full ~120 Hz sample rate along with the detectors to enable post-flight correlation with bolometer data.
See Table 3.3 for a complete set of the diodes and heaters installed throughout each receiver.

<table>
<thead>
<tr>
<th>Truss</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>objective</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>truss</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>snout</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2K stop</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spittoon</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>eyepiece</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSA</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSA heater</td>
<td>200Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aux post</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>base plate</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fridge</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>condensation point</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>heat switch</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>heat switch heater</td>
<td>10kΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pump</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pump heater</td>
<td>200Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>still</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Focal Plane Unit</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>focal plane ring</td>
<td>diode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>focal plane Cernox × 2</td>
<td>Cernox</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wafer NTD × 4(Xs), or 2(Ys)</td>
<td>NTD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPU low current heater</td>
<td>500kΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPU high current heater</td>
<td>200Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>strap/300mK ring heater</td>
<td>500kΩ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3: Thermometers and heaters used in each insert. Heaters are installed to control the fridge cycling or incidents if ever happened. The 280 GHz FPUs are outfitted with two NTDs instead of four, due to different tile structure.

### 3.3.2 Thermal Measurements

The housekeeping system could be used to observe different kinds of thermal behaviour in the system. In the past ten cryoruns, housekeeping data were analyzed for different purposes.

**Thermal performance**

The temperature response of the cryostat to the filling of cryogens is essential in the pacing of the cryogenic filling. Operators decide when to fill the main tank, to draw superfluid, to cycle fridge, etc, based on the system response. An abnormal behavior could be caught if temperature performance deviates from what usually happens which needs debugging.
**3.3. Cryo-system Performance**

**LN2 fill.** In Figure 3.10 and 3.11, we space two fillings of liquid nitrogen to quickly cool down the system. As soon as the temperatures are stabilized at 77K, especially in the focal plane units where things are last to respond, we proceed with LHe filling.

**Figure 3.10:** Temperature profiles of different sections of cryostat responding to filling of liquid nitrogen. Time zero denotes the exact minute at which we started the fill. The labels are in a format that stands for ThermalDiode_diode location_Lloro_HouseKeeping. The response is straightforward where the main tank bottom reacts to the filling first as liquid starts to accumulate in the bottom of the main tank. SFT cools down together with the other part of MT due to metal thermal conduction. VCSs are overcooled first, and reached their temperature minima at around hour 40, and started to bounce back to their equilibrium temperature which are at 130K and 220K respectively for the LN2 fills. VCS2 top diode is not shown due to a housekeeping check of shorting to ground.
Figure 3.11: Temperature profiles of sections inside an X or Y insert responding to filling of liquid nitrogen. Time zero denotes the exact minute at which we started the fill. The labels are in a format that stands for ThermalDiode_diode_location_focal_plane_HouseKeeping. The base plates and fridges are cooled down almost spontaneously with the main tank bottom as they mount at MT bottom. The difference of the truss temperature in X and Y focal planes was due to the diode locations and the length difference of the trusses. The inserts start to equilibrate at around hour 125.

LIHe fill. The liquid helium fill is calculated precisely to maximize the amount of cooling power LHHe provides. Figure 3.12 shows the liquid helium fills that gradually drag down the temperature of the system. The first couple of fills before main tank bottom constantly sustain liquid are well segmented to maximize the cooling power of LHHe: each fill is arranged to be where the temperature decrease slows down.
3.3. Cryo-system Performance

**Figure 3.12:** Temperature profiles of different sections of cryostat responding to filling of liquid helium. Time zero denotes the exact minute at which we started the helium fill. After around 25 hours of liquid helium fill, the main tank bottom starts to sustain liquid. Starting hour 50, we turned on the fridge heater to connect different temperature stages, preventing sub-Kelvin stages from isolating. At around hour 60, we start pumping on the SFT.

The MT is constantly cooled at 4K as it’s roughly rotated at 45°. The top high diode is at the highest point of the main tank, hence runs higher than the other diodes in this configuration. The SFT stabilizes at superfluid temperature once the MT starts to hold constant liquid. VCSs are over-cooling at first, then stabilize at 40K and 130K respectively for helium operations. VCS2 top diode is not shown due to short to ground.

Figure 3.13 shows the temperature response of an insert to the filling of helium. We start pumping on the SFT as soon as we are able to sustain liquid at the bottom of the main tank.
Chapter 3. SPIDER-2 Cryogenic System Integration

Figure 3.13: Temperature profiles of sections inside an X or Y insert responding to filling of liquid helium. The base plates and fridges are cooled down almost spontaneously with the main tank. The fridge pump heater is turned to servo at hour 30-40 to prevent the FPU from thermally isolating. The 2K stages are cooled down along with the SFT after we start pumping, and the fridge cycles start by connecting the pump to the 4K stage at around hour 70.

Sub-Kelvin stage cooling and fridge cycle. After the fridge cycle starts, the Cernox sensors and NTDs start to respond to the fridge cycling command. See Figure 3.14. Cryostat enters a steady cryo state, where the temperatures are hardly affected by the filling operations that are only performed to sustain the liquid in the main tank.
3.3. Cryo-system Performance

**Figure 3.14:** A 280 GHz FPU response to the steady-state operation. Time zero denotes the start of the first liquid nitrogen fill. The fridge hold time could be as long as 75 hours before it warms up and the algorithm for each of the cryogenic fridge is being optimized individually to maximize this number. The circled region shows the FPU Cernox sensors running hotter than the 300mK stages in the insert, which is a constant thermal load onto the FPU.

**Cryo loading and expected flight durations.**

Besides temperature data, the cryo system also measures other aspects such as weight of the system, gas flow and cooling power of the SFT.

**SFT load curve.** The 25Ω SFT heater is powered individually, and is not integrated into the housekeeping system. This heater is used in Run2 to estimate the load of the SFT, as shown in Figure 3.15. Each cryo fridge requires around 5mW of power to cycle. This load curve shows that the SFT can easily handle a total load of ~30 mW without causing significant temperature drift to the SFT.
Figure 3.15: Load curve of the SFT. The SFT ring diode was having cross short with other channels during the test. Power is sent intermittently to the SFT while it sustains superfluid in the SFT bottom and ring, and the nosetop part is designed to keep boiled off helium. The power is increased each time SFT temperatures equilibrate. The maximal power that was added to the SFT was 42 mW, which is higher than the total power required by six cryo fridges cycle simultaneously.

**Flight duration and effective hours.** In addition to the flight housekeeping system, a ground electrical readout box was also made to take measurements of the weight and gas flow out of the VCS vent, see Figure 3.16. A healthy constant helium flow rate of 35 SLPM with five inserts (and was around 40 SLPM for six), and a weight loss of 0.8lbs/h (1.0lbs/h with six inserts) suggest how long a full tank of cryogen (1300L = 358lbs) could last. The cryostat will be cooled down and filled full before flight, which indicates around 15 days of total flight.

As discussed, the SFT could hold simultaneous cycling of six fridges, which takes around 3% of the total flight times. These measurements give a maximal estimation of around 14.5 day length of data.
3.4 Conclusion

In this chapter we introduced the integration, cryo testing and system performance of the SPIDER-2 flight cryostat that is scheduled to deploy. The cryostat is not only housing the six receivers, but also where our largest work effort is distributed. Many parts of the cryostat have been modified or built from scratch to be integrated with the system, and during cryoruns all the fits and modifications have been deemed to work and are flight ready. It’s thermal stability directly affects the data quality of the inserts and is therefore required to be carefully tested on ground. These data suggest that this cryostat is in a status that’s sufficient for a balloon integration and a scientific flight.
Chapter 4

Design and Performance of the SPIDER-2 Optical System

The optical path of SPIDER-2’s 280 GHz insert is slightly different from the first generation, due to its high frequency and the revised design of a second generation cryostat. The optical design was constrained to accommodate the smaller size of the 280 GHz focal plane and beam shape, with a target far-field beam size of 17 arcmin FWHM. The optical path of which is discussed in section 4.1.

There are six optical inserts in SPIDER2 cryostat, three of which are new 280 GHz telescopes designed specifically for Lloro, with the focal plane unit fabricated in the National Institute of Standards and Technology (NIST)[35]. The focal plane unit is described in section 4.2.

Over our four years of cryoruns described in the previous chapter, the system was characterized and enhanced to make of flight ready. Although many tests were done, I will focus on the Fourier Transform Spectrometer (FTS) data sampling of the 280 GHz as an example as it couples best to the optical sections of this chapter. Detailed spectra of two of the three 280 GHz focal planes were taken using a custom-designed Fourier Transform Spectrometer. The design and results are described in section 4.3.

4.1 SPIDER-2 Optical Path

The optical path before the focal plane units not only shapes the received signal but also determines the loading from the optical system, hence directly affecting the acquired data quality. Different kinds of thermal and optical loads should be considered carefully when choosing the appropriate material for the components in front of the detectors.

Figure 4.1 shows a complete optical chain for one of the inserted 280 GHz telescopes. The focal plane box is cooled through the $^3$He fridge, and the whole insert is embedded in the 4 K main tank to provide a 4 K environment for the elements inside the inserts. The 1/16” thickness ultra-high molecular weight polyethylene (UHMWPE) vacuum windows were adopted for the 280 GHz inserts, and the filter stack is carefully determined to reduce the thermal load from the optical elements, especially for an infrared system. Half-wave plates with 90 GHz, 150 GHz and 280 GHz are also made for the system.
Chapter 4. Design and Performance of the SPIDER-2 Optical System

4.1.1 UHMWPE Window Mounting, Testing and Characterization

SPIDER’s window requires material that maintains atmospheric pressure differences, maximizes the transmission of mm-wave radiation, and has an emissivity that doesn’t cause a heavy optical load on the sensitive detectors. A ultra-high molecular weight polyethylene (UHMWPE) material was used as one of the conventions in the vacuum-sustain window design, and is also used in SPIDER-1, due to its robustness and low dielectric losses.
4.1. **Spider-2 Optical Path**

Despite nice vacuum features, UHMWPE has a low friction coefficient with metal, making it difficult to hold the windows in place with clamping force alone, as the vacuum drags it down in the center as shown in 4.2. To provide sufficient gripping force, an aluminum clamp with sharp concentric teeth was made, which cut into the plastic material as shown in the figure.

![Diagram of window system](image)

**Figure 4.2:** Photo and CAD model of window, window bucket and the custom made window clamp. The upper photo shows deformation of a UHMWPE window after pressure. UHMWPE's high impact strength allows for the use of very thin sheets as windows which minimizes absorption losses without sacrificing strength. *Figure taken from [9].*

**Window selection for the 2nd generation.**

All plastic deforms when held in a vacuum. SPIDER1’s window was 1/8" thickness, with a diameter of 16.22 inches. The deformation of such a window is around 1.75 inches in z-axis, and such deformation has been tested to be of little consequence in light ray analysis with Zmax modelling. As the 280 GHz FPU is more sensitive to the in-band loading of the plastic, various tests of the thickness of the windows were done to find the thinnest for the SPIDER2’s 280 GHz instrument. The 1/16” thickness UHMWPE was chosen as the window material for the 280 GHz inserts. Such a window deflects around 2.25” in z-axis measurements. Windows were water cut made with 16 holes circular pattern and then AR coated with according thickness. Anti-reflection Teflon coating glued with Low Density Polyethylene (LDPE) on both sides of according thickness enhances transmission at each given frequency. Due to the limitation of length in the axial direction, a standoff piece was also designed and machined to lift up the 1/16 inches thickness UHMWPE window so that the center of it doesn’t touch the shader filters described below.

See Figure 4.3 for a sketch and photo of our window system.

Windows are first installed onto a "bucket", a be-spoke aluminum piece designed to insert into the top dome, using torque wrench in a interleaved circular pattern to provide even torque for each one of the sixteen screws and is hold tight by the teeth clamp described above. This careful installation procedure is optimized to prevent any possible failure or even explosion during pumping down, which happened more than a couple times during the optimization of the process. Vacuum break and explosion could
Chapter 4. Design and Performance of the SPIDER-2 Optical System

Figure 4.3: Left. The bottom view of the top dome when it is on the crane waiting to be installed onto the cryostat. The window buckets are inserted into the top dome then vacuum tight down during installation. Filters can be seen from the bottom. Middle and right. A photo and a sketch of the window buckets installed. The 1/16" thickness window is installed with an additional stand-off aluminum piece to prevent the window from touching the IR shader filters.

cause fatal failure of the whole experiment therefore intensive testing of each window is required before any further installation.

Window leak, cold, shock testing and installation.

Before being installed on the cryostat, a final set of tests that are described next is performed on each of the window bucket systems.

Vacuum testing. The window bucket is installed on the window bucket tester, and the flight window is then pumped down through a needle valve to mimic a real pumpdown environment which protects the filters and provides steady pressure loss of the system. After pumping overnight, the window deformation is measured, and a leak check is performed on the system. In the SPIDER-2 system, all of the tested windows sustained a He background of around 5e-9 mbarL/cc in all of our pre-installation testing, after the volume between the window and an acrylic plate on top of the bucket tester is filled with helium gas. 1

Thermal cycling. One difficulty of ballooning is the cold ambient flight temperatures. To ensure the window could withstand flight conditions, liquid nitrogen was poured onto the window (a test piece) while under vacuum until the window equilibrated with the LN2 (77 K). This caused no vacuum failures. To further test the robustness of the system, a 5 lb hammer was dropped from approximately 2 feet above the window onto the center of the window while the window was still 77 K. The window was undamaged after this stress shock.

Installation. After passing leak testing, two of the window shader filters (introduced in the next section) are taped onto an aluminum filter plate which is then threaded on the tapped window bucket cryostat-side surface. Aluminum tape is routed around the plate

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1 In testing, the Helium background drifts up after aggressive filling of gas. The hypothesis being that helium atoms travel through the porous plastic cumulatively as time goes by. We have deemed this to be "leak-tight" if no spikes were seen in the leak checker. The time constant of this process is usually more than 10 min.
4.1. Spider-2 Optical Path

To provide light sealing and thermal connection. The window buckets are then installed onto the ports to perform its duty. We gradually tighten down the 1/4”-20 screws as the pressure drops to make sure the o’ring is pressed down evenly across its circumstance.

We keep a close eye on the window deflection during the entire cryorun to observe the healthiness of the window.

4.1.2 Filter System

Optical bandpass filters and thermal IR filters ("shaders") in the system were made in Cardiff University. The metal mesh filters are used widely in FIR and sub-mm wave instruments [37].

For the Spider system, low pass hot-pressed edge filters were used in many stages of the system to determine the final bandpass.

The stack of the filters for the 280 GHz were determined after many runs of testing and the filters available in the Spider collaboration. A combination of AR coated and uncoated filters were used in the system.

Metal mesh filters

Metal mesh filters are modelled by considering the grid as a lumped circuit in a free space transmission. See Figure 4.4. This analogy works well in the non-diffraction region while the wavelength is much larger than the size of the mesh grid.

In Spider, two kinds of metal mesh filters were used in the system. The first kind is the capacitive hot-pressed filters shown above. Ultraviolet photolithographic techniques are used to replicate metallic patterns over large areas with good control of the filter geometrical properties, which uses a thin dielectric substrate of polypropylene coated with a thin copper film. These single meshes were stacked together with plane parallel spacers to form the filter. Dielectric spacers are then fused (hot-pressed) together with the mesh sheets to make a solid disc filter. See Figure 4.5 for an explanation sketch of the technology.
Figure 4.5: A exploded view of a multilayer hot-press filter. The metal meshes are patterned onto supporting dielectric sheets, which can then be sandwiched with dielectric spacers for fusing together. Figure taken from [37].

The second type is the thermal filters, "shaders" [38]. In a large-aperture cryogenic system such as ours, the multi-grid filters would heat up in the central area and re-emit because of the dielectric material which causes heavy IR loading onto the detectors. Hence a thermal "shader" filter is designed to mitigate this thermal effect. These filters use ultra thin substrate that reflects most of the incoming NIR power and has near-unit transmission in the FIR. Several shaders can be stacked together as required.

See Figure 4.6 for photos of both kinds of filters used in the system.

Figure 4.6: Photos of "shader" filters (Left) and hotpress filters (Right). Photo Credit: Lorenzo Moncelsi, talk, Metal-mesh technology: a past and present view.

Temperature testings and SPIDER-2 filter stack

In SPIDER-1, a single hot-pressed filter was used at the VCS1 stage in each of the receivers. As we have more hot-pressed filters in stock, a combination of two filters can provide better band shape and further reduce out-of-band loading.
4.1. SPIDER-2 Optical Path

In on-ground test cryoruns, thermal diodes were placed on several locations of the half-wave plates (HWP), including the rotors and the center of sapphires (introduced in the next section) to measure the thermal effects of different combinations of two hot-pressed filters. See Figure 4.7.

![Figure 4.7: Raw temperature data comparing diodes at HWP rotor (Left) and center of sapphire (Right). Each temperature line is a different combination of two hot-press filters from different ports and different runs. The other optical path before the half-wave plates are identical. We read the temperature until the system equilibrates with liquid helium, and use the data to decide the flight combination of filters. Figure is just for visual example and the result are listed out in Table 4.1.](image)

A steady state temperature was measured for each combination of the stack to find an optimal filter stack for the system. See Table 4.1.

<table>
<thead>
<tr>
<th>Filter Combination (Left: Skyside)</th>
<th>Steady State Temperature, descending sorted</th>
</tr>
</thead>
<tbody>
<tr>
<td>15cm + Nylon filter</td>
<td>60 K</td>
</tr>
<tr>
<td>15cm single</td>
<td>45 K</td>
</tr>
<tr>
<td>15cm + 18cm (ARcoated)</td>
<td>38 K</td>
</tr>
<tr>
<td>18cm (ARcoated) + 15cm</td>
<td>30 K</td>
</tr>
<tr>
<td>18cm (ARcoated) + 12cm</td>
<td>30 K</td>
</tr>
<tr>
<td>15cm + 12cm</td>
<td>22 K</td>
</tr>
</tbody>
</table>

**Table 4.1:** Temperature measurements of half-wave plate rotors under different combinations of hot-pressed VCS1 filters. Each filter is labelled as the cutoff frequency in icms. A couple of center temperature of HWPs were sampled as a reference, and were shown to be 10-12 K higher than the motors in general.

Based on temperature data and the stock of hot-press filters, the following stack was determined for different frequencies, see Table 4.2.

4.1.3 Half-wave Plates (HWP)

To mitigate beam systematics and to increase polarization coverage, sky polarization modulation is provided by monochromatic half-wave plates. The 280 GHz HWPs are
1.66\,mm thick birefringent sapphires from Rubicon Technology with a 1/8\,mm Cirlex AR coating, which is similar to the 150 GHz HWP design \cite{39}. They are mounted skyward of the telescope’s primary lens to enable strong control of beam systematics.

A warm gear configuration driven by a cryogenic stepper motor is used to meet SPIDER’s need. In operation, the rotation mechanism rotates the HWPs at a targeting angle accuracy of \( \pm 0.1^\circ \), and turns smoothly at a minimum of \( 1^\circ\,s^{-1} \) while cold. See Figure 4.8 for a reference.

### 4.1.4 Lenses

The SPIDER lenses (objective and eyepiece) are machined from high-density polyethylene (HDPE). At millimeter wavelength the index of refraction of the HDPE is around 1.52. We bond an anti-reflection coating layer to the surface of each lens to suppress reflections of order 4\% at each surface. The AR coatings are sheets of porous Teflon manufactured by Porex\textsuperscript{2} that is optimized for the 280 GHz band by choosing the Teflon density such that the index of refraction is close to the ideal \( n_{AR} \). The sheet thickness is chosen to be as close to \( \lambda/4n_{AR} \) as possible, while being constrained by the availability of commercial materials. The same AR material is used to AR coat the vacuum windows described above. The selected 280 GHz AR material is 0.18\,mm thick and has an index

\textsuperscript{2}Porex Filtration Group, Atlanta, GA
4.2 280 GHz FPU and Readout

Radiation hits the 280 GHz focal plane after going through the components described in the previous section. The focal plane unit (FPU)[35] has a transition-edge-sensor (TES) bolometric array that is readout with a time division Superconducting QUantum Interference Device (SQUID) multiplexer[14]. The amplified data is further readout by the Multi-Channel-Electronics (MCE) system that is mounted on the room-temperature side of the cryostat.

of refraction near 1.31, and has been chosen with AR performance on all three optical materials in mind.

The HDPE lenses were fabricated by the Mechanical Engineering machine shop at the University of Illinois at Urbana-Champaign (UIUC) [36]. Measurements of the lenses shape and curvature fall within the 0.005 inch machining tolerance. The AR coats are bonded to the lens surfaces using a thin sheet of low-density polyethylene (LDPE) under vacuum to prevent the formation of air bubbles underneath the AR coat. The AR material is pre-stretched before bonding for the higher curvature lens surfaces to reduce wrinkling of the AR layer during the oven cycle.

Figure 4.8: Photograph of the 280 GHz HWP mechanism installed in the flight cryostat Lloro. The HWP stack is held in a 305mm clear diameter invar mounting ring attached to a rotor wheel and the main gear. The rotor wheel is held in a three-point bearing, while the main gear is driven by a cryogenic stepper motor turning a worm shaft. The worm shaft is spring loaded toward the main gear. Optical encoders verify that main gear is at a desired angle.

4.2.1 Detector Design and Cryo-readout

SPIDER2’s 280 GHz FPU uses NIST-developed, single-wafer feedhorn-coupled AlMn TES arrays[14], while the 95 and 150 GHz FPUs each supports four wafers of dual-polarization, slot antenna-coupled Ti TESes fabricated at JPL[40]. See Figure 4.9 for an integrated overview of the 280 GHz unit.

**Figure 4.9:** 280 GHz FPU assembly. (a) FPU design model. The feedhorn array (bright yellow) is visible in the center of the FPU and is surrounded by a 300 mK copper plate. SQUID multiplexing hardware folds behind the array by use of flexible cabling and is located within the gray box beneath the 300 mK plate. (c) Rear view of sensor array assembly. The detector array stack (light green) presses against the feedhorn array by using BeCu springs located under the 300 mK bracket (orange). (b)(d) Images of one fully assembled 280 GHz FPU ready for installation and back of the sensor array unit before bonding. The gold-plated copper heat straps are thermally sunk to the faceplate and bent into the box to cool down the internal components from the center. The superconducting NbTi cabling connects the first and second stage multiplexing SQUIDs (SQ1 and SQ2) to the 2 K SQUID Series Array (SSA) and warm readout electronics. The niobium box serves as both the outer layer of the packaging and as superconducting magnetic shielding. *Figure taken from [35].*
A 16×16 array of conical, corrugated feedhorns made of Au-plated silicon couples to a detector array with dual-polarization sensitivity via planar orthomode transducers (OMT), and connected to multiplexed TESes, as shown in Figure 4.10 and 4.11.

**Figure 4.10:** (a) The assembled 255-pixel feedhorn array. (b) Corrugated conical feedhorns zoom-in. (c) Feedhorn corrugation profile. 333 µm thick two-step etched silicon platelets are stacked and aligned together to form the corrugation slots. The stack is then Au electroplated to form a continuous metal surface. As shown in the profile, a 725 µm diameter circular waveguide that defines the low edge of the band is integrated into the detector end of the feedhorn. *Figure taken and modified from [14].*

The detector assembly consists of three silicon parts: waveguide interface, detector wafer and a backshort. The polarization sensitive probes are inserted into circular waveguides with a reflective backshort, see pixel details in 4.12.

**Figure 4.11:** (a) Detector array stack consists of three silicon layers. (b) The 16 × 16 detector wafer layout. The dual-polarization sensitive pixels are placed in a checkerboard pattern, where the adjacent pixels are 45° difference from each other, such that neighboring pixels in a scan measure Stokes I, Q and U. Figure (c) shows a zoom-in of this implementation. Details of the pixel architecture are presented in Figure 4.12. Heatsink pads exist on either side of the array and are also used as the mounting points for neutron transmutation-doped (NTD) thermometers used to monitor the detector wafer temperature. *Figure taken and modified from [14].*
Figure 4.12: Detailed structure of one pixel. Each detector comprises an integrated superconducting circuit with elements for polarization diplexing and power sensing. The circuit elements of a pixel are a planar orthomode transducer (OMT); a coplanar waveguide (CPW) to microstrip (MS) transition; a microwave cross-under; and two TES bolometers which contains niobium to gold microstrip transitions to deposit power in the bolometers. The bolometer contains two sensors wired in series: a 420 mK AlMn sensor for science observations and a 1.6 K Al sensor to extend the bolometer dynamic range for lab measurements, as the following FTS measurements will show. Figure taken from [14].

The detector array is readout in 16 columns at a time, and each detector column couples to a $1 \times 32$ time-division SQUID multiplexer chip. Detector wiring that exits the top and bottom of the wafer couples to the SQUID readout through superconducting aluminum flexible cables, which enable the readout modules to fold behind the focal plane. The feedhorns, detector arrays and SQUID multiplexers are fabricated in the NIST Boulder microfabrication facility [41] [42].

4.2.2 Warm Readout and Data Acquisition

The focal plane bias and readout are wired out to the warm electronics via custom cabling manufactured by Tekdata Interconnections Ltd. Within each insert, three unshielded NbTi twisted-pair cables connect the SQ1 and SQ2 amplifiers to the SSA and to the receiver baseplate. Three shielded 100-pin manganin twisted-pair micro-D cables then route the signals from the receiver baseplate out to the hermetic connectors on the vacuum vessel wall.

MCE crates

Outside of the cryostat, UBC designed MultiChannelElectronics (MCE) crates are mounted directly to the cryostat vacuum vessel\(^4\). Each insert is controlled by an independent

\(^4\)For a full description of the MCE and related publications: https://e-mode.phas.ubc.ca/mcewiki/index.php/Main_Page.
MCE crate, which then communicates to a dedicated MCE control computer (MCC) via optical fibers. The MCCs then communicate with the flight computers to monitor and record MCE data. The receiver data is acquired at a rate of 119.116 Hz, limited by the time constants of SQUID readout system.

Each MCE crate (we use 3MDM connector MCEs) contains 1 clock card, 2 bias cards, 2 address cards and 1 address card. See Figure 4.13.

The clock card is responsible for communicating to the outside world which includes fiber optical links to a computer and a Synchronization Box, incoming commands dispatch to other cards in the MCE rack, clock generation and distribution, and coordinate operation among cards. The address card takes charge of the row-addressing. It produces analog bias currents to select one row of SQUIDs at a time using the row-select lines. The bias cards provide bias voltages. For the 280 GHz, the resistors are replaced with suitable resistance to bias the 280 GHz detectors correctly. The readout cards provide the readout circuitry from the array of detectors.

Figure 4.13: A photo showing the 3MDM type MCE in SPIDER. From left to right are: address card, two bias cards, two readout cards and one clock card.
Instrument backplane checking

The pin-to-pin connection from inside the FPU to the MCE backplane are checked using an additional instrument backplane board (“IB checker”). This card is a GPIB card with the same footprint as all plug-in cards, and can be used to measure impedances of the cryostat interface and identify shorts and openings inside the cryostat and/or the MCE. SPIDER uses a modified python package to do IB checking. This checking is performed whenever inserts are at a different configuration, including before and after insert assemble, insert sleeve installation, bench, cryostat, 300K vacuum, 77K. We usually do not perform any IB checking process after the system gets down to 4 K since the checking procedure could trap magnetic flux inside the SQUIDs after superconducting temperature. The TES and SQUID tuning will instead be performed as detector connection checking.

4.2.3 TES and SQUID Multiplexing Readout

Once the cryo-system gets to the sub-Kelvin stage for the focal plane, the first step toward a properly biased bolometer array is tuning the SQUID readout to maximize both gain and multiplexing bandwidth.

TES

A transition-edge-sensor (TES) is a type of cryogenic energy sensor that exploits the strongly temperature-dependent resistance of the superconducting phase transition. It is typically achieved from a superconducting thin film weakly heat-sunk to a bath at much lower temperature than the transition temperature $T_c$. When supplied with a voltage bias, a TES sensor can operate in its transition such that small changes to the TES temperature (from the absorbed power) lead to large changes in the TES electrical resistance. See Figure 4.14.

The voltage bias and sharp response curve of resistance vs temperature makes it an ideal sensor for temperature changes in mK. It also makes the TES Joule power dissipation oppose changes in the incident power, which could maintain the TES at a nearly constant temperature through negative feedback.

SQUID

Superconducting QUantum Interference Devices (SQUIDs) are sensitive magnetometers used to measure subtle magnetic fields based on superconducting loops containing Josephson junctions. In a single DC SQUID, two Josephson junctions form a superconducting loop in parallel. See Figure 4.15.

An input current splits evenly into the two branches. When a small external magnetic field is applied to the superconducting loop, a screening current $I_s$ begins to circulate the loop that generated the magnetic field, to cancel the applied external flux. This makes

\[^5\] IB checking guide and python package can be found on spiderwiki; co-written by Xue Song and Stevie Bergman
4.2. 280 GHz FPU and Readout

Figure 4.14: Thermal circuit and response curve of a typical TES device. A weakly thermally sunk heat capacity absorbs power $P$ which is to be measured. Variations in the absorbed power change the heat capacity’s temperature, which is measured by a TES operating under strong electrothermal feedback. The plot of resistance vs temperature illustrating the negative feedback. Because of the voltage bias, an increase in the temperature produces an increase in the resistance, leading to a decrease in the Joule heating power supplied by the bias. This loop makes the current through the TES nearly proportional to $P$.

A current difference in the two branches. Once the current in either branch exceeds the critical current $I_c$ of the Josephson junction, a voltage appears across the junction.

As the through flux increases in the loop, the screening current in the junction would change periodically, since Josephson phase of a super conductor requires the flux inside the loop to be maintained as integer times of the flux quanta, and the screening current generated would always prefer a lower energy state. This makes the voltage across the junction (when biased higher than superconducting phase, $2I_c$) also changes periodically as Figure 4.15 shows. The period of the change equals flux quanta $\Phi_0$.

This periodic curve is called the modulation curve in SQUID tuning, and the tuning procedure would always want to lock the SQUID at both the largest amplitude, and the largest slope on the curve to maximize sensitivity.

Combination

In a SQUID-TES readout system, the TES is operated in series with the input coil, which is inductively coupled to a SQUID series array (SSA). A change in TES current manifests as a change in the input flux to the SQUID, whose output is further amplified and read by room-temperature electronics.

See Figure 4.16 for a demonstration of this mechanism.
In multi-detectors system, a single channel at certain row and column location on the detector wafer is readout in a multiplexed fashion. See Figure 4.17. For more details of this multiplexed readout, see Reference [43].
4.2. 280 GHz FPU and Readout

Figure 4.17: The multiplexed readout chain for a single channel located at row \( r \) and column \( c \). A TES bias \( I_B \) is provided in series for all channels in the same column (all rows in one column share the same value) while the first stage SQUID (SQ1) bias \( I_{SQ1} \) is a boxcar function provided in series for all channels in the same row. In this manner the SQ1 within a column are coupled sequentially to the corresponding second stage SQUID (SQ2). A third stage SSA for each column provides impedance matching to warm electronics. This multiplexing over rows and columns reduces the wire count required for readout. Figure taken from [12].

Tuning

To tune the three stage SQUID and TES system, we apply bias to each stage sequentially to lock the SQUIDs and TESes at their maximum performance points from SSA, SQ2, SQ1 to TES. The SQUIDs are locked at a point where the modulation amplitude is maximum, and the slope is downward, see Figure 4.18.

The negative feedback line allows this lock to stabilize around this point during readout. Although in the case where a flux jump happens, the flux jump counter is also read out and stored via the readout chain. We use a pre-written auto tuning system to control and monitor the tuning curves[44].

Once the SQUIDs are tuned, we search the TES bias range from the largest current stepping down to take I-V curves for the detectors. See Figure 4.19.

After the TESes are biased, the system is then fully tuned up. Bias steps with a small current (around 200 ADUs or 2 \( \mu A \)) are regularly sent to the TESes to monitor the health of the detectors and also to be used as calibrations to the noise level analysis. The value of the bias step current is chosen as a small fraction of the bias current to not affect the thermal response too much.

If no particular test is done, the detectors are usually kept biased for the entire fridge cold stage with the observation port light sealed, to get archival dark noise data. These data are often hours or days long, with a bias step sent every 10 minutes or so to calibrate the temperature drift of the bath.

The next section will be introducing one of the particular measurement FTS which measures the spectrum of the 280 GHz detectors.


4.3 Fourier Transform Spectrometer Measurements

Fourier-transform spectroscopy is used in the field to measure the bandpass of the detector optical path using the relative coherence of two splits of a radiative source. The spectra measurements in SPIDER are taken in space domain, with the raw data to be Fourier transformed into the actual spectrum. In this section I introduce the FTS spectra measured and analyzed from the 280 GHz instrument.
4.3. Fourier Transform Spectrometer Measurements

Figure 4.19: Different I-V curves for one detector on Y5 (280 GHz) with different bath temperature of the TES island. The slopes indicate different electrical responses of the TES to the bias current due to its superconducting phase. A working detector should be locked at its phase transition range, with the resistance to be much higher than the shunt resistor to maintain voltage bias.

4.3.1 FTS Design

A customized FTS was made for SPIDER-I’s spectra measurements (Figure 4.20) by previous graduate student Anne Gambrel and Jon Gudmundsson[19]. It is further enhanced in this generation for better control of the scanning and pointing process. Specifically, the output mirror is enhanced with programmed stepper motors and a new python-based controlling program developed by Corwin Shiu.

The source we use with this FTS is a heating element that’s encapsulated in two concentric steel cylinders that are wrapped in insulation and mounted to the breadboard by a steel bracket. The element is controlled by a transformer to adjust the temperature of the heat source so that it still gives a good signal-to-noise ratio for the detectors as the cover or the breadboard of the FTS heat up. The temperature of the source is high enough in the region where Rayleigh-Jeans law is a good approximation.

The linear stage for the mobile rooftop mirror is a Velmex BiSlide E01 with 0.21m of travel. To take interferograms of the system, the mirror position is controlled by running programs in Cosmos operating system. Multiple scripts are written to take scans over the peak, the white light fringe (center envelope), and the science mode where taking a full scan. To prevent aliasing, the scan speed is tuned so that sampling is higher than Nyquist lower limit. The scan speed can be adjusted lower to take even finer scanning.

The orientation of the output mirror is controlled through two stepper motors to move in two axes, to cover as many detectors as possible. The whole FTS mechanism is covered by a carbon fiber case with eccosorb inner surface to reduce stray light.
Figure 4.20: The design of FTS. Source light reflects through the collimator and splits at the beam splitter. Half of the split light is modulated by the mobile rooftop mirror (blue), with the phase being scanned over the liner stage by interfering with the other half (red). The output light reflects at the output mirror, illuminates a few detectors on the focal plane. Figure modified from [19].

4.3.2 Data Acquisition, Processing and Spectra

In cryorun Run08, rough FTS measurements of a couple of detectors on two of the 280 GHz (Y4 and Y5) were taken.\(^6\) In this first round of FTS measurement, the environment was not radio frequency silent, and the data was coarsely analyzed to get a first impression of the spectra of 280 GHz.\(^7\) In cryorun Run09, precise, flight environment comparable data of Y4 and Y5 were taken, as backups where limited time could be spared for FTS measurements in deployment.\(^8\) The paradigm for testing and analysis is detailed as follows.

FTS hardware setting

Y3 and Y5 had exactly the same filter stack when the FTS data were taken. As discussed in section 4.1, starting skyside, the FTS source light goes through a 1/16” UHMWPE

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\(^6\)The confusing labelling scheme is due to hardware mixing and changes across different cryoruns. You may find the FPU referred to as Y3 in other literature. In this section, “Y4” in the text and figures represents the “Y3” FPU fabricated in NIST, sitting in a "Y4" truss.

\(^7\)These data can be found internally on spider wiki: flight cryostat development, Run08

\(^8\)The complete data set could be found internally on the lab computer and spider wiki.
window, 9 shaders, AR coated 18icm, uncoated 12icm edge filters to hit the 4 K stage. It then gets polarization modulated through the 280 GHz HWP, and finally goes through a 12 icm and 10.5icm edge filter, a 3/32” Nylon filter inside the insert to hit the FPU. We added an additional output polarized wire grid after the FTS output mirror before the window for enhancing polarization of the source. The edges of the FTS mirror before the FPU were Al-taped down to prevent RF leak with an eccosorb stop piece made to further reduce stray lights.

To correctly acquire the data under cold conditions, we tuned the three stages of SQUID (SSA, SQ2, SQ1), then biased the TESes on Al transition for lab testing, as scientific AlMn TES is too sensitive for a room temperature, radio noisy environment. The high-bay was as radio silence as possible by turning the wifi and all bluetooth signal off.

The standard scan speed of the mobile mirror was 2mm/s, with a couple of 0.667mm/s fine scans taken for Nyquist sampling check.

Detector signal-to-noise is sensitive to the pointing angles of the output mirror and the polarization angle of the input source light. To maximize the results, 32 pointings × 4 polarizations (45° segmented) = 128 scans were taken of each FPU as the detectors are four direction oriented on the focal plane (For a reminder, see Figure 4.11).

All 128 scans are round trip scans where the white light fringe was gone through twice during each scan.

**FTS science data analysis paradigm**

A complete code package was written to implement the analysis of the FTS data. For each pointing and polarization combination, certain detectors that pass a defined signal-to-noise ratio get selected for further processing. See Figure 4.21. Interferograms were analyzed in a symmetric base that centers at the white light fringe peak, which is picked out by convolution with predicted interferogram. The signal-to-noise ratio is then defined as the absolute peak value of detrended TOD over the standard deviation of the signal masked out noise time-stream. The noise timestream is attained by masking out (230-320 GHz range) in the Fourier domain. Only detectors that have a SNR above a threshold of 20 are analyzed to get the interferogram. Because of this method, some sensitive detectors have more interferograms selected than the others.

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*Filter stacks were changed between run09 and flight condition.*
Figure 4.21: A combination of four scans as an example of detector selection working in FTS data analysis. Each plot of the four is a full view of all 512 detectors (a full focal plane) with 16 columns vs 32 rows, where scanning timestreams with white backgrounds are selected based on a defined signal-to-noise ratio. These four plots are the same FTS pointing, so the same region of detectors are illuminated. One pointing illuminates roughly a ninth of the detectors on the FPU. These four plots are scans under four different HWP polarization angle, where each angle is aligned with a fourth of the detectors on one tile (For a reminder, see Figure 4.11). In one same pointing, different polarizations reject according detectors that are perpendicular to the HWP polarization angle - the mute grids are regularly patterned, suggesting detectors that are perpendicular to the HWP polarization are not scanned. This is a side proof of precise half-wave plate control. The double scan can be seen in the time-stream that is selected.
Spectral bandpasses are reported as $F(\nu)$ normalized to unity, which is the characterized response of a single-moded detector to a beam filling source. This is natural as it is the signal that is directly measured through the optical system for a source that’s Rayleigh-Jeans (the spectral intensity of the source $I_\nu \propto \nu^2$):

$$s = \int dv F(\nu) I_\nu = \int dv \lambda^2 F(\nu) \nu^2 = \int dv F(\nu)$$  \hspace{1cm} (4.1)

where $\lambda^2$ is the throughput in the single-moded full sky limit required by Liouville’s theorem.

Accordingly, the band center and bandwidth are defined as

$$\text{bandcenter} = \frac{\int v * F(\nu) dv}{\int F(\nu)^2 dv},$$  \hspace{1cm} (4.2)

and

$$\text{bandwidth} = \frac{\left[ \int F(\nu) dv \right]^2}{\int F(\nu)^2 dv}. \hspace{1cm} (4.3)$$

The bandwidth is defined as the width of a fictitious rectangular spectrum such that the power in that rectangular band is equal to the power associated with the actual spectrum over positive frequencies\(^{10}\). The integral is chosen between a reasonable range (100-1000 GHz) where the 1/f noise is avoided in computing band statistics.

### 4.3.3 Spectra Results and Discussions

The FTS analysis not only shows features of the detector array but also deems the functioning of all optical components from the window down to the detector membrane level. It is a lab characterization of the 280 GHz optical pipeline.

#### Single detector spectra

Different analyses on the spectra were done, and scans of one detector were combined to produce a single spectrum per detector. An example of one well-scanned detector can be found in Figure 4.22.

These spectra show a successful implementation of the 280 GHz optical system\(^{11}\). They are useful for future band analysis, and are grouped to study the detector uniformity of the FPUs.

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\(^{10}\)The reported spectral response, bandwidth and bandcenter formulae follow private notes: Spectral definitions and Conversion from $\Delta T_{CMB}$ to Jansky, W. C. Jones. The spectra are reported under the assumption that the source is both uniform and beam filling, and the detectors are single-moded.

\(^{11}\)The single detector spectra can be found on spiderwiki. Log-scale plots were also generated to further capture the spectrum feature.
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Figure 4.22: One spectrum example of one detector at row 21, column 01 on Y5 FPU. Spectrum reported as $\lambda^2 F(\nu)\nu^2$ - direct response to a Rayleigh-Jeans source. This particular spectrum is averaged over 22 scans, with bandcenters and bandwidth computed accordingly. The lower band edge is reported at the 10% response of maximum. The imaginary part is plotted out as noise level indications and is reduced over multiple scans. Only the center 10 cm of the interferogram is shown in the figure as a zoom-in of the center fringes.

FPU uniformity

In run09’s FTS scanning, 55.8% of the "Y4" FPU and 93.32% of the "Y5" FPU have successful data taken. An averaged spectrum was computed for each FPU. See Figure 4.23.
Uniformity of the detector array are also measured through statistics of the bandwidth, bandcenter and band loweredge, see Figure 4.24 and 4.25.

These data show the very different band statistics and performance between two 280 GHz FPU. The bands are defined through the sharp feedhorn cutoff at the lower edge, and Y4 has a uniform 5 GHz lower performance than Y5 on that front. Y4’s bandcenters are also uniformly 5 GHz lower than Y5, suggesting the difference comes mainly from the lower band.

At the upper edge, a series of hot-pressed filters define the band and give a similar band for Y4 and Y5. A similar 315 GHz dip (corresponding to the 10.5 icm filter) happens on both of the 280 GHz spectra.

Beyond that, the uniformity of Y5 is excellent, and the whole FPU yield (good detector ratio) is 93%. Y5 is placed at one of the bottom ports for a longer hold-time during flight due to its better uniformity.

4.4 Conclusion

In this chapter we have detailed the optical system of each 280 GHz receiver, the focal plane unit and the readout system of the detectors. This system is integrated into the cryo-system that was introduced in the previous chapter, and different measurements were taken as the system gets close to it’s flight ready state. The optical system has been tested to work, and I used the FTS measurements to demonstrate one of the important hardware work performed in lab testing, where all FTS data would contribute to related band analysis such as null test. This successful test is also a side proof that the whole integrated cryogenic and optical system is ready for a flight. The other important testing data such as noise analysis, RF response, ”chop” testing and optical efficiency testing are all analyzed in similar fashion and will be important supplementary materials for the final flight data.

The global pandemic has delayed the scheduled SPIDER-2 flight and made hardware works in this document seem insufficient. This thesis will not be able to include preliminary data directly from SPIDER-2, however the work will keep being updated.

The second flight with the 280 GHz receiver will provide strong information over the galactic foreground emission, further enhance CMB polarization data quality provided by the two flights combined, and provide new constraints over the primordial tensor-to-scalar ratio $r$. 
Figure 4.23: Averaged spectra of all selected detectors for FPU Y4 and Y5. Spectra reported as $F\lambda^2 F(\nu)\nu^2$ - direct response to a Rayleigh–Jeans source. Vertical lines indicate the 10% response lower cutoff of the band. The band center and bandwidth are reported in the text.
FIGURE 4.24: Band statistics of Y4. Rows and columns that are turned off were because of shorts found through IB checking or SQUID tuning issues. Grey detectors suggest unsuccessful aluminum biasing or noisy detectors that don’t pass the SNR threshold.
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Figure 4.25: Band statistics of Y5. Rows and columns that are turned off were because of shorts found through IB checking or SQUID tuning issues. Grey detectors suggest unsuccessful aluminum biasing or noisy detectors that don’t pass the SNR threshold.
Appendix A

Cryo and Insert Troubleshooting and Discussion

Among various on-the-ground testings, a large portion of the effort was to debug fatal behaviors which prevented the cryostat from flight ready. Some of these are abnormal features that are worth attention or effort to mitigate over, the others require more careful investigations. I’ll list some of the features that we have seen, investigated or debugged.

Thermal acoustic oscillations (TAOs)

Thermal acoustic oscillations can occur in cryogenic systems when there is a large thermal gradient along the length of a gas filled tube which is closed at the warm end[33]. Which in our case happens when the filling of LN2 causes cold gas flow through a long series of KF tubes that are constrained at several joints that are high impedance.

This kind of thermal behavior is visible in the venting manifold where the vacuum pipes are oscillating as a visible acoustic wave, causing mechanical energy load on the system. See Figure A.1.

Despite its mechanical energy wasting, TAOs only happen in the liquid nitrogen filling stage, and the flight configuration will be free of a venting manifold that consists of large temperature gradients to prevent this behavior.

VCS touch in Lloro, closed

In run03, we were not able to sustain superfluid in the SFT and the SFT is requiring two triscroll pumps working in parallel to be able to get superfluid at all. See Figure A.2.

We investigated the problem in different tests, including a series of flow tests, capillary unclog baking, quick turn around run opening the top[1]. These all enhanced the performance of the system to second order and helped the operators to have deeper understanding of the cryo system but didn’t really fix the problem. The system was then completely opened up, and we found that the VCS1 stage pie wedges were touching the superfluid tank.

[1] Technical details and discussions of these can be found in the spider wikipedia and elogs.
Appendix A. Cryo and Insert Troubleshooting and Discussion

**Figure A.1:** A pressure response of the thermal acoustic oscillations happened in the MT. With an emptied SFT, starting around minute 7, the pressure in the main tank started an oscillation around 0.3 psi width. As the pressure continuously drops down, the valve closing happens around 17 min which perturbed the system and reduced the amplitude of the oscillation.

**Figure A.2:** A temperature profile of the system while liquid cannot sustain. SFT temperatures are higher than the superfluid phase transition temperature, and all cryo stages are running hotter than what they should be.

To prevent the VCS1 pie wedges touching the SFT, three long G-10 poles were made and mounted at the bottom of the main tank to support the VCSes from deforming inward. The length of the poles were chosen to be not long enough to reach the VCS1 at its normal state to avoid any actual thermal contact, but can prevent it from deforming if some potential perturbation of VCS1 leads to that.
Capillary plugs, closed

In conjunction with the VCS touch in run03, a capillary N2 plug was also found when thermal cycling of the capillaries changes the flow rate in a flow test. Plugs of the capillary can be of various nature, where the impurities in the gaseous helium could be nitrogen, oxygen, or hydrogen molecules which cools down to solid state at superfluid helium temperature. Based on different types of plugs, the capillary heaters were heated up to different temperatures to melt down the "ice" and pressure cycled to vent the impurities outside of the system. While an ice plug could be solved in an emergency, it would significantly slow down the cooling down schedule and burden the liquid helium budget which could be fatal when deploying the instrument.

To prevent plugs in future runs, the standard operation procedure includes a series of operations to make sure nothing other than ultra high purity (UHP) canisters of helium gas will be in the system. UHP canisters of helium are used to over pressurize the SFT to at least 5 psi higher than the atmospheric pressure as well as maintain an active helium gas flow outside of the SFT. This constant outflow is to make sure the chemical potential of other source of gas is low enough that it’s unlikely for them to get inside the system through gas exchanges\(^2\).

A flow test model and procedure is also come up with and is performed multiple times during a cool down to make sure the capillaries are healthy at different stages of temperatures.

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\(^2\)Discussion of gas equilibrium and chemical potentials is out of scope of this document, and is only the most favored theory behind this operation.
**Ongoing 280GHz FPU loading investigation**

Since run07, we have found 280GHz detectors are not able to get on AlMn(science) transition due to possible overloading on the ground. The detectors were able to get on transition when covered up at different stages inside the cryostat. However, at high frequencies, a light measurement in the lab is hard due to significant noisier environment than the float altitude. A few detectors with lower optical efficiencies were able to get on transition, and their performance are used as calibration for the loading investigation.

Several tests were proposed to address this issue and to break down the loading budget into various sources. Different tests of radio frequency(RF) load were measured, including installing high pass filter, bluetooth environment pulse test, etc. Filter stacks and HWP temperatures were optimized to decrease thermal loading from the optics. The optical efficiency, saturation power and normal resistance of each single detector are measured (Figure A.4).

![Figure A.4: A example plot showing measured normal resistance of Y5 detectors (previously called Y7). These values were helpful in calibrating the optical efficiency measurements from a IV curve. Credit to Corwin Shiu, Princeton University](image-url)

The loading from the 280 GHz UHMWPE window is also measured and estimated. *This issue is still under investigation as this thesis is being written.*
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