Building and Flying the E and B Experiment to Measure the Polarization of the Cosmic Microwave Background

by

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Abstract

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The E and B Experiment (EBEX), a balloon-borne polarization sensitive microwave telescope, will map the cosmic microwave background (CMB) over a 420 deg$^2$ patch of sky with 8’ resolution. The observing area and resolution provide sensitivity to an angular power spectrum from $\ell = 20$ to 1500. This will allow EBEX to observe the primordial B-mode signal predicted by inflation on a scale of about $\ell = 100$ and the anticipated lensing B-mode signal at smaller angular scales. Simulations show that EBEX will detect the primordial B-mode signal if the tensor to scalar ratio, $r$, is 0.1, or it will reduce the current upper limit to 0.02. This limit assumes that errors due to foreground subtraction are below detector noise, and it does not include systematic uncertainties.

During the EBEX $\sim$ 14-day Antarctic long duration science flight the instrument will observe with 1432 transition edge sensor (TES) bolometric detectors in three frequency bands centered at 150, 250, and 410 GHz. This broad frequency coverage will provide valuable information about foreground emission from thermal dust. The polarimetry and signal modulation are achieved using an achromatic half wave plate (HWP) rotating on a superconducting magnetic bearing and a fixed wire grid polarizer.

In this thesis we discuss the EBEX science goals, instrument design, integration, and characterization. We provide an overview of the June, 2009, engineering flight
from Ft. Sumner, NM, and a summary of the results from the flight. Additionally, we provide a detailed analysis of scan synchronous temperature signals in the warm optics and a preliminary analysis of bolometer data taken during galactic crossings in the engineering flight.
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Chapter 1

CMB Polarization Science

1.1 The Standard Cosmological Model

Data from CMB and other cosmological probes have allowed us to formulate a standard cosmological model of our Universe, also referred to as concordance cosmology or ΛCDM. The model describes our present day Universe as expanding at an accelerated rate, with flat spatial curvature, and filled with significant densities of baryonic matter, cold dark matter (CDM), and dark energy, and small amounts of radiation and neutrinos. The standard model also predicts an epoch in the late Universe when the first stars turned on, called reionization. Numerous observations, including those of the CMB, provide strong evidence for initial conditions of nearly, if not perfectly, scale invariant density perturbations that grew into the structures we see today, including galaxies, clusters of galaxies, and voids. Although data from a host of experiments support the standard cosmological model, the field of cosmology lacks a specific, well-supported description of the dynamics in the early Universe, and a mechanism to generate the seeds of the density perturbations that grew into the Universe we observe today.
1.2 The Temperature of the CMB

1.2.1 A Blackbody with Anisotropies

The CMB is a relic of the early Universe, emitted during the epoch of last scattering at a redshift of $z \simeq 1100$ when the Universe was about 380,000 years old. In the hot Big Bang\textsuperscript{1} picture, at the beginning of this epoch the Universe was fully ionized, and it was filled with a photon-baryon\textsuperscript{2} plasma in which the photons were tightly coupled to the free electrons. As the Universe expanded and cooled, the free electrons became bound to nuclei, referred to as recombination \textsuperscript{56}, and the photons free streamed across the Universe from all locations in all directions. The present-day temperature of the CMB, about 3 K, reflects the temperature of the Universe at last scattering, taking into account the redshifting of the photons between the surface of last scattering and today and the present day recessional velocity.

The existence of a background radiation with a temperature of a few Kelvin was predicted by Alpher and Herman as early as 1948 \textsuperscript{2}, and the CMB was first discovered by Penzias and Wilson in 1965 \textsuperscript{49} \textsuperscript{12}. The Cosmic Background Explorer (COBE) satellite, launched in 1989, provided a platform for two important measurements of the CMB. First, the Far Infrared Absolute Spectrophotometer (FIRAS) performed a precise measurement of the CMB spectrum, showing that it is very nearly a perfect blackbody over three orders of magnitude in frequency with a temperature of $2.725 \pm 0.001$ K \textsuperscript{45}. The discovery of the blackbody spectrum of the CMB had a number of important implications, including suggesting that the observable Universe was in thermal equilibrium at the time of last scattering despite the fact that vast regions of the Universe were out of causal contact at that time. Second, measurements by the Differential Microwave Radiometer (DMR) showed that, although the

\textsuperscript{1}In the hot Big Bang theory, the Universe began in a hot, dense state and it cooled through time by expansion.

\textsuperscript{2}Although baryons are typically considered matter made of quarks, in cosmology baryonic matter also includes electrons.
temperature of the CMB is remarkably uniform across the sky, anisotropies in the temperature exist to the level of $1 \times 10^5$.

1.2.2 The Temperature Power Spectrum

Over the past 20 years, CMB experiments have aimed to characterize the subtle variations in the smooth temperature field. In order to describe the CMB temperature anisotropies on the curved surface of the celestial sphere in the direction $\hat{n}$, it is convenient to expand the temperature signal in the spherical harmonic basis:

$$T(\hat{n}) = \sum_{\ell,m} a_{T,\ell m} Y_{\ell,m}(\hat{n}). \quad (1.1)$$

The two-point correlation function provides a statistical measure of the temperature anisotropies across angular scales. We consider a temperature field that is isotropic and homogeneous on large scales and Gaussian. The assumption of isotropy allows us to average the $Y_{\ell,m}$ modes over all azimuthal angles specified by the values of m. Gaussianity, homogeneity and isotropy of the CMB imply that the strength of the fluctuations on each angular scale on the sky, $\ell$, can be characterized by a single number corresponding to the standard deviation of the Gaussian distribution of the amplitudes of the fluctuations at that $\ell$. We define the two-point correlation function in temperature as:

$$C_{\ell,TT} = C_{TT} = \frac{1}{2\ell + 1} \sum_m <a_{T,\ell m}^* a_{T,\ell m}>. \quad (1.2)$$

Note that $C_{TT}$ depends only on the angular size, $\ell$.

---

3 We postulate that our solar system is not located at any special place in the Universe, so that on large scales the Universe is isotropic and homogeneous.

4 Recent measurements of the temperature anisotropies by a number of experiments indicate that the distribution of temperature fluctuations are close to or perfectly Gaussian; for example see Komatsu et al., 2010 [38].

5 Angular separation decreases with increasing $\ell$. At most values of $\ell$, the angular separation $\Theta$ can be approximated as $\frac{\pi}{\ell}$. 
1.2.3 Temperature Anisotropies at the Surface of Last Scattering

Current CMB measurements, in addition to probes of structure in the late Universe\(^6\), suggest that the anisotropies in the temperature of the CMB were generated by density perturbations that were present at early times. Current data indicates that these density perturbations, which existed on all spatial scales, were nearly, if not completely, scale invariant\(^7\)\[^{38}\]. Possible mechanisms for generating these density perturbations are discussed below in Section 1.3. The power spectrum of the temperature two point correlation function, \(C_{TT}\), reflects the dynamics at the last scattering surface where the photon-baryon fluid was gravitationally driven by the density perturbations, in addition to the dynamics in the late Universe and the composition of the Universe throughout cosmic history.

Although the shape of the temperature power spectrum contains a wealth of features, we will not detail them here, but rather describe how the temperature anisotropies observed on small and large scales formed under distinct conditions at the surface of last scattering. On smaller scales, where the density perturbations lay inside a common causal horizon, the perturbations evolved and drove oscillations in the photon-baryon fluid. The gravitational potential in over dense regions provided a compressive force, driving the fluid into the potential wells. On the other hand, the photon pressure that built in the hot, compressed fluid acted as a restoring force. The angular frequency of these so-called acoustic oscillations was determined by the sound speed in the fluid. As time passed and the causal horizon increased, oscillations were excited at larger and larger scales, where the oscillations at each scale were synchronized in time, although spatially incoherent. Consequently, the temperature anisotropies observed on small scales resulted from two distinct mechanisms: red or

\(^6\)For example, the correlation of galaxies observed today by the Sloan Digital Sky Survey (SDSS) \[^{14}\].

\(^7\)Scale invariance implies that the power in the perturbations at each angular scale, encoded in the width of the Gaussian distribution, \(C_{\ell,TT}\), was identical.
blue shifting of the photons by the Sachs-Wolfe effect\[\text{[53]}\] as the photons exited the local gravitational potential, and the presence of hotter and cooler regions that were generated by acoustic oscillations in the photon-baryon fluid\[\text{[9]}\].

The signature of acoustic oscillations in the power spectrum is formed because, at the time of last scattering, the common phase of the oscillations at each scale was locked in when the photons free streamed from the surface of last scattering. The time of last scattering determined whether that particular mode was in a compressive phase, a rarefactive phase, or some intermediate phase. As a result, some of the oscillatory modes show more extreme temperature differentials in the temperature power spectrum than others.

Regions on the sky that are separated by large angular scales today lay outside of a common causal horizon during recombination. Consequently, anisotropies on large scales had not yet evolved significantly before last scattering. The structure of the temperature power spectrum on large scales primarily reflects the presence of over and under dense regions, and their associated gravitational potentials, present at last scattering creating temperature anisotropies by the Sachs-Wolfe effect.

1.2.4 Temperature Anisotropy Measurements to Date

The CMB temperature anisotropies have been measured to high precision by a host of recent experiments including WMAP \[\text{[40]}\], the Arcminute Cosmology Bolometer Array Receiver (ACBAR) \[\text{[51]}\], QUEST at DASI (QUaD) \[\text{[19]}\], the South Pole Telescope (SPT) \[\text{[43]}\] and the Atacama Cosmology Telescope (ACT) \[\text{[62]}\].

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\[\text{[5]}\]The Sachs-Wolfe effect describes the gravitational red shifting of photons when they climb out of potential wells at the surface of last scattering.

\[\text{[9]}\]This picture oversimplifies the dynamics; for example, on smaller scales the anisotropies were washed out by a number of mechanisms, disregarded here for pedagogical reasons.
1.3 The Inflation Paradigm

We digress from our discussion of the CMB to give a brief overview of inflation since inflationary models provide a description of the dynamics in the early universe and a mechanism to produce the density perturbations at last scattering. In the inflationary paradigm, during the first fraction of a second after the Big Bang the Universe underwent an accelerated expansion in which space-time was stretched at superluminal speeds; the Universe is believed to have increased exponentially in size by a factor of at least $10^{26}$ in less than $10^{-34}$ seconds [3].

The paradigm provides solutions to three classic problems in cosmology\footnote{For a pedagogical discussion of inflation see Dodelson, 2003 [13], Liddle and Lyth, 2000 [41], and a review by Baumann et al., 2009 [3].} First, the relic problem describes the absence of a detection to date of relics, such as magnetic monopoles, expected to be generated by the breaking of gauge symmetries at extremely high energies in the early Universe. Second, the flatness problem describes how the Universe appears to be spatially flat even though flat space is unstable, requiring extreme fine tuning of the initial conditions. These two problems are solved by inflation since the exponential expansion of Universe dilutes both the density of relics and the curvature of space. Finally, the horizon problem arises because we see striking uniformity in the temperature of the CMB across the sky despite the fact that many regions of the Universe were out of causal contact during the epoch of last scattering. Inflationary theories solve the horizon problem by providing a mechanism to push regions of the universe that were once in causal contact outside of the horizon, allowing for uniformity in the CMB at last scattering.

In the simplest inflationary models, inflation is driven by a slowly changing potential energy, $V(\phi)$, of a scalar field, $\phi$, referred to as the inflaton. In order for accelerated expansion to occur, the potential energy must dominate over the kinetic energy: $V \gg \dot{\phi}^2$. To insure this condition is maintained throughout inflation, the rate of change of the kinetic and potential energies must also be constrained: $|\ddot{\phi}| \ll |V'|$,\footnote{For a pedagogical discussion of inflation see Dodelson, 2003 [13], Liddle and Lyth, 2000 [41], and a review by Baumann et al., 2009 [3].}
where $V' = \frac{dV}{d\phi}$. These conditions are summarized in constraints on the slow roll parameters, $\epsilon$ and $\eta$:

$$\epsilon \approx \frac{M_{pl}^2}{2} \left( \frac{V'}{V} \right)^2, \quad |\eta| \approx M_{pl} \left| \frac{V''}{V} \right|$$  \hspace{1cm} (1.3)

Quantum mechanics predicts the existence of microscopic fluctuations in the metric and the inflaton during inflation. The superluminal expansion that occurred during inflation stretched the small-scale quantum fluctuations to astronomical sizes, while simultaneously driving nearby regions out of causal contact. The initial spectrum of fluctuations in the metric and the inflaton can be decomposed into scalar, vector, and tensor components. This decomposition is useful since the perturbations produced by the different fluctuations evolved independently in the linear regime, and they have different physical manifestations at the surface of last scattering. Additionally, it should be noted that the perturbations on different scales also evolved independently in the linear regime. Since vector perturbations are diluted by the expansion of space before the epoch of recombination and are not expected to be significant at the surface of last scattering, they will not be addressed below.

The scalar perturbations produced density fluctuations. The power spectrum of the initial scalar fluctuations can be written in an approximate power law form with linear and quadratic terms:

$$P_s(k) = A_s(k_\star) \left( \frac{k}{k_\star} \right)^{(n_s(k_\star)-1+\frac{1}{2} \alpha_s(k_\star) \ln(k/k_\star))}.$$  \hspace{1cm} (1.4)

The scalar spectral index, $n_s$, provides a measure of the tilt in the initial spectrum of fluctuations; a value of $n_s=1$ describes fluctuations with the same power on all scales, $k$. The rate of change of the scalar spectral index with scale, referred to as the running of the spectral index, is parametrized by $\alpha_s$. $k_\star$ is the arbitrary scale at

$^{11}M_{pl}$ is the reduced Planck Mass.

$^{12}$Vector perturbations can be significant in some models, like those that predict cosmic strings.
Tensor fluctuations produced gravitational waves that propagated from the inflationary era, to the epoch of last scattering, and to the present day. The power spectrum of the tensor fluctuations can be written as:

\[ P_s(k) = A_t(k_*) \left( \frac{k}{k_*} \right)^{n_t(k_*)}. \]  

(1.5)

where in this case, due to convention, \( n_t = 0 \) corresponds to scale invariance.

Different inflationary models predict different relative amplitudes of the scalar and tensor perturbations. It is useful to define the tensor to scalar ratio parameter,

\[ r \equiv P_t/P_s. \]  

(1.6)

In some cases \( r \) is defined as the ratio of the tensor to scalar power spectral amplitudes at a given scale, \( k \): \( r = \frac{A_t}{A_s} \mid_k \). In Section 1.6 below, we discuss how data from CMB polarization experiments can be used to constrain or rule out inflationary models or alternative models to inflation.

1.4 Polarization of the CMB

The CMB can become polarized when the photons Thomson scatter off of free electrons. Figure 1-1 shows photons from hot and cold regions incident on an electron. Relative to the observer looking into the page in the \( \hat{n} \) direction, the electron surrounded by such a temperature anisotropy pattern can only re-radiate the hot photons with a vertical polarization, and the cold photons with a horizontal polarization, producing a net vertical polarization at the observer.\(^{13}\) The figure shows that a net polarization will be observed today if a quadrupolar anisotropy in temperature is

\(^{13}\)Note that if the anisotropy were formed from bright and faint regions rather than hot and cold regions the output radiation would also be polarized.
Figure 1-1: Linear polarization produced by a quadrupolar anisotropy in temperature as seen by the electron. The blue lines indicate the possible polarization of a hotter photon incident on a free electron while the red lines indicates the possible polarization of a cooler photon incident on a free electron. \( \hat{n} \) shows the direction of observation, with the observer looking into the page, and the quadrupolar anisotropy lies in the page. Figure based on Hu and White (1997) [32].

The two epochs in our cosmological history when both free electrons and quadrupolar anisotropies were present are recombination and reionization. Below we focus on the generation of polarized CMB at the surface of last scattering since the signal imprinted on the CMB during reionization appears at large angular scales that are inaccessible to EBEX [15].

[14] For a pedagogical discussion with varied treatments see Lin and Wandelt (2004) [42] and Hu and White (1997) [32]. For a more formal discussion see Zaldarriaga and Seljak, 1997 [65].

[15] Although large angular scales can be measured by balloon-borne experiments, it is more difficult to contend with systematic effects on such large scales. Additionally, EBEX was designed to be sensitive to intermediate and small scales to allow for measurement of both the gravitational wave and lensing B-mode signals.
1.4.1 Polarization Generated by Scalar Perturbations

At the surface of last scattering, motion of the photon-baryon fluid is driven by density fluctuations which were produced by primordial scalar perturbations. Gradients in the velocity of the photon-baryon fluid produce quadrupolar temperature anisotropies in the CMB in the rest frame of free electrons \[31\]. Polarization is produced when these CMB photons scatter off of the free electrons as described in Figure 1-1.

On large scales, the fluid velocity is driven by the combined effects of the thermodynamic temperature at the surface of last scattering and the redshifting of photons climbing out of the gravitational potential wells from the Sachs-Wolfe effect. Hu and White (1997) \[32\] define an effective temperature differential across the sky:

\[
\left( \frac{\Delta T}{T} \right)_{\text{effective}} = \Delta T_T + \Psi, \tag{1.7}
\]

where \(\Psi\) is the gravitational potential and \(\Delta T_T\) describes the temperature differentials that exist on the surface of last scattering, described above in Section 1.2.3. Just as with thermodynamic temperature, the effective temperature differentials will drive the photon-baryon fluid from hot effective temperature regions to cold ones.

On smaller scales, the polarized signal still depends on gradients in the fluid velocity, but the dynamics of the photon-baryon fluid are complicated by the changing pressure, and therefore temperature, of the photons as they undergo acoustic oscillations. This results in a periodic reversal in the direction of the effective temperature gradient \[32\].

1.4.2 Polarization Generated by Tensor Perturbations

The mechanism by which the tensor perturbations generate a quadrupolar anisotropy at the surface of last scattering is surprisingly straightforward, compared with the scalar perturbation case. Figure 1-2 shows how, as a gravity wave propagates through space it stretches and compresses space, distorting the green dotted circle of test
Figure 1-2: Quadrupolar isotropy produced by a gravitational wave traveling in the vertical direction. The distortion of the green dotted circle of test particles shows that, at the gravitational wave extrema, space is compressed or stretched. Both Figure based on Hu and White (1997) [32].

particles. Photons traveling through a region which is compressed or stretched will be blue or red shifted, and appear hotter or colder, respectively. If a gravity wave propagates in the $\hat{k}$ direction with some component along the observer’s line of sight direction, $\hat{n}$, then CMB polarization will be observed. The degree of polarization will depend on the amplitude of the gravitational wave and the absolute value of the dot product $\hat{n} \cdot \hat{k}$.

1.5 CMB Polarization Formalism

The goal of developing the formalism below is to parametrize the polarization field so that it informs us about the constituents and dynamics of our Universe over evolutionary history. We want to build a set of mathematical tools that we can use to describe the variations in the CMB polarization field on the spherical surface of the celestial sphere, as discussed above for the temperature anisotropies in Section 1.2.2.
Additionally, we want to relate the quantities directly measured by our experiments to the constituents and dynamics of our Universe. Below we generally follow the approach of Lin and Wandelt (2004) [42] and Zaldarriaga and Seljak (1997) [65].

1.5.1 The Q and U Stokes Parameters

The Q and U Stokes parameters can be used to describe the polarization of the CMB on the sky in a particular direction, \( \hat{n} \).

Definitions

The real part of an electromagnetic plane wave can be written as:

\[
E_k = \hat{x}\mathcal{E}_x \cos(kz - \omega t + \phi_x) + \hat{y}\mathcal{E}_y \cos(kz - \omega t + \phi_y).
\] (1.8)

In the most general case the wave can be elliptically polarized, where the shape of the ellipse is described by \( \beta \), the ellipticity angle, and the angle between the semi-major axis and the x-axis is \( \chi \). The Stokes parameters for the wave are then defined as

\[
I \equiv \mathcal{E}_x^2 + \mathcal{E}_y^2 = \mathcal{E}_0^2
\]

\[
Q \equiv \mathcal{E}_x^2 - \mathcal{E}_y^2 = \mathcal{E}_0^2 \cos 2\beta \cos 2\chi
\]

\[
U \equiv 2\mathcal{E}_x\mathcal{E}_y \cos (\phi_y - \phi_x) = \mathcal{E}_0^2 \cos 2\beta \sin 2\chi
\]

\[
V \equiv 2\mathcal{E}_x\mathcal{E}_y \sin (\phi_y - \phi_x) = \mathcal{E}_0^2 \sin 2\beta.
\] (1.9)

The parameter I provides a measure of the total intensity, Q and U provide the linear polarization intensity and direction, and V provides the circular polarization intensity and direction. Since circular polarization is not produced by Thomson scattering of unpolarized light, below we discuss only the Q and U parameters.
Figure 1-3: One convention for defining Q and U.

Rationale for Using Q and U to Describe the Polarization Field

It can be convenient to work with Stokes parameters since they are linear in intensity\(^\text{16}\), where the electric field is quadratic in intensity. Additionally, Q and U are natural parameters for describing the polarization measured by our instruments in a given pointing \( \hat{n} \) on the sky. However, Q and U require the definition of a fixed coordinate frame, one convention of which is shown in Figure 1-3. In the case of polarized CMB signal observed on the sky, Q and U are defined in the tangent plane to the celestial sphere in the observing direction, \( \hat{n} \). Note that Q and U are defined over \( \pi \) radians since polarization can be represented by headless vectors, not vectors.

\(^{16}\)Optics calculations make use of both the Jones calculus and Mueller calculus where transformation matrices act on Stokes vectors.
1.5.2 E-Mode and B-Mode

In Appendix A.2 we demonstrate that we can define two quantities E and B from Q and U using spin-weighted spherical harmonics:

\[
\begin{align*}
\tilde{E} &= a_{E,\ell m} Y_{\ell m}(\hat{n}) \\
\tilde{B} &= a_{B,\ell m} Y_{\ell m}(\hat{n})
\end{align*}
\] (1.10)

Unlike Q and U, E and B are scalar quantities and they have definite parities; E has positive parity and B has negative parity. Additionally, different physical mechanisms at the surface of last scattering produce E and B polarization patterns, referred to as E-modes and B-modes.

E-modes and B-modes refer to non-local patterns in the polarization field on the celestial sphere. Figures 1-4(a) and 1-4(b) shows how E-modes are curl-free patterns while B-modes are divergence free. The opposite parity of E and B with respect to reflections around a line through the center of the pattern into the page is evident. It can be shown (see for example Kamionkowski et al., 1997, [36], and Zaldarriaga and Seljak, 1997 [65]) that scalar perturbations at the surface of last scattering will only produce E-modes; no handedness is present in the scalar perturbation to produce a B-mode component. On the other hand, the quadrupolar anisotropies produced at the surface of last scattering by gravitational waves, if they were present, would produce both E-modes and B-modes in roughly equal strength. The decomposition of the polarization field into E and B allows us to use the B-mode signal to search for evidence of gravitational waves at the surface of last scattering, providing strong evidence in support of inflation. Although an E-mode signal is also produced by gravity waves, this signal will be dwarfed by the higher amplitude E-mode signal produced by scalar perturbations.

\footnote{The tilde notation on E and B indicates the a factor of \( \sqrt{\frac{\ell+2}{\ell-2}} \) is absorbed in the unique components.}

\footnote{Note that the E and B nomenclature is reminiscent of the electric and magnetic fields in electromagnetism which are similarly curl-free and divergence-free, respectively.}
1.5.3 Lensing of the Primary CMB by Foreground Matter

The polarization field produced at the surface of last scattering is predicted to be altered by gravitational lensing of the CMB photons by foreground matter at late times. The CMB photons are deflected in random directions by large scale density perturbations encountered between the surface of last scattering and the observer. The net effect on the polarization field is to mix power between E and B modes; see for example Zaldarriaga and Seljak, 1998 \cite{66}. The lensing B-mode signal appears at small scales in the power spectrum because the structures described by the gravitational potential are not very correlated on large scales. Lensing of the CMB temperature signal has been observed at low significance by cross-correlating WMAP data with tracers of large scale structure, including luminous red galaxies, quasars and radio sources; for example see Smith et al., 2007 \cite{58} and Hirata et al., 2008 \cite{28}. However, lensing of the polarization signal has not yet been observed.

The degree of lensing provides a measure of the integrated gravitational potential along the line of sight. Lensing is particularly powerful because it provides a measure of both the geometry of the Universe and the growth of structure, and it can measure

Figure 1-4: \(a\): Curl-free E-mode patterns formed, around hot and cold regions. \(b\): Divergence-free B-mode patterns.
structure at high redshifts, among the deepest of cosmological probes. Consequently, the shape and amplitude of the lensing signal can constrain cosmological parameters such as the neutrino mass, $m_\nu$, which can damp the growth of structure, the dark energy equation of state, $w$, which dictates the degree to which growth of structure is suppressed, and the curvature of space.

While much can be learned from the lensing signal, its presence will contaminate the already weak gravitational wave B-mode signal, if it exists. In order to reconstruct the lensing and gravitational wave B-mode components separately the measured B-mode signal must be de-lensed. This is achievable because the lensed B-mode signal is highly correlated with the un-lensed E-mode signal, where the shape of the correlation is defined by the lens potential, $\phi$. However, in practice de-lensing of the B-mode signal is challenging [57]. To de-lens the B-mode signal, the deflection operation performed by the lens potential is inverted to recover the un-lensed E-mode and B-mode. An estimator for the lens potential is created using the measurements of the lensed E-mode and B-mode; see for example Hirata and Seljak, 2003 [29]. At lower signal to noise, lens reconstruction can be performed by constructing an estimator of the lens potential using the lensed temperature signal or cross correlation of the lensed E-mode and B-mode, as has been tested on simulated data for EBEX.

1.5.4 Power Spectra of the Polarized CMB

We have defined three quantities, $a_{T,\ell m}$, $a_{E,\ell m}$ and $a_{B,\ell m}$, with which we can compute six auto-correlations and cross-correlations: $C_{TT}$, $C_{EE}$, $C_{BB}$, $C_{TE}$, $C_{TB}$, and $C_{EB}$. However, since B has negative parity, $C_{TB}$ and $C_{EB}$ will vanish, assuming no parity violating processes in the early Universe. The $C_{TB}$, and $C_{EB}$ cross power spectra may still be computed in order to provide checks on instrumental effects, and also to subtract the primordial signal from lensing of the CMB polarization field, described above in Section 1.5.3. It should be noted that the amplitude of $C_{BB}$ provides a measure of the tensor to scalar ratio, $r$. 
Figure 1-5: Theoretical curves for E and B signals (assuming $r = 0.1$) and predicted data points with error bars for a 14-day EBEX flight, in red, and 1 year of Planck data (in blue). The green dashed lines show the pixel noise for EBEX and Planck for the specified observing duration, and the pink and blue dashed lines show the anticipated B-mode power spectrum from foregrounds in the EBEX CMB patch based on the WMAP three-year data [47], labeled with the observing frequency in GHz.

Figure 1-5 shows the power spectrum of the E and B modes with the usual normalization factor of $\sqrt{\ell(\ell + 1)/2\pi}$. The black curves show theoretical power spectra for both $C_{EE}$ and $C_{BB}$, assuming $r = 0.1$, in addition to predicted data points with error bars for an EBEX 14-day flight, shown in red, and 1 year of Planck data in blue. Both the E and B curves show power at large scales that is generated during reionization. At intermediate and small scales the E pattern is dominated by the scalar perturbations, showing peaks that reflect the presence of the acoustical oscillations.

The B pattern, on the other hand, reflects the contribution of two sources: gravitational waves at the surface of last scattering and the lensing of E-modes to B-modes.
The peak in the power spectrum at $\ell=100$ is determined by the size of the horizon at the surface of last scattering, where the peak location corresponds to the wavelength of the gravitational wave that entered the horizon around that time. The gravity wave contribution to the B-mode signal is highly suppressed at small scales by decay of the gravitational waves once they enter the horizon.

While the lensing B-mode signal is weak on large scales, it is comparable in amplitude to the gravitational wave B-mode on intermediate scales and it dominates the B-mode signal at small scales. The shape of the lensing signal mirrors that of the small scale E-mode signal, where the acoustic peak structure is smeared out.

1.5.5 Polarization Observations to Date

E-mode polarization was first detected by the Degree Angular Scale Interferometer (DASI) experiment [39], and it has since been detected by a number of experiments. Notable recent measurements include the detection of the first peak in the E-mode power spectrum by The Background Imaging of Cosmic Extragalactic Polarization (BICEP) [9] experiment and the 2nd peak in the E-mode power spectrum along with the oscillatory structure of the spectrum at smaller scales by the QUAD [5] experiment.

Neither the gravitational wave nor the lensing B-mode signal has been detected. Current data shows that the B-mode signal is at least an order of magnitude weaker than the E-mode signal (for example see Komatsu et al., 2010 [38]). The current upper limit on $r$ from WMAP data alone is 0.36, constrained mostly using temperature, rather than polarization, data. The upper limit is reduced by using WMAP data along with other CMB and non-CMB data sets which provide an upper limit of 0.33 and 0.24, respectively [38].
1.6 Constraining Models of the Early Universe Using CMB Polarization

Different inflationary models predict different values for the spectral indices and their variation with k, the amplitudes of the scalar and tensor power spectra, and the slow roll parameters. For example, in the simplest inflationary models with single fields and small $V'$, the slow roll parameters can be related to the spectral indices through consistency relations: $n_t = -2\epsilon$, $n_s - 1 = 2\eta - 6\epsilon$, and $r = 16\epsilon$, to lowest order in $\epsilon$ and $\eta$. Departure from these relations may result from the presence of multiple fields during inflation. Since different inflationary models predict varying values of r, CMB polarization experiments can be used to distinguish between, and therefore allow or rule out different classes of inflationary models. Additionally, in the simplest inflationary models the value for r provides the energy scale at which inflation occurred: $V^{1/4} \propto 10^{16} r^{1/4}$ Gev.

A measurement of or better constraints on r can also allow or rule out alternative models to inflation. For example, Ekpyrotic models, which provide an alternative to the inflation paradigm yet still resolve the problems that inflation addresses, predict a Universe that has undergone a Big Crunch before the Big Bang. These models predict an insignificant amplitude of gravitational waves, so a detection of the gravitational wave B-mode signal could rule out these models.

1.7 Sources of Polarized Foreground Contamination

CMB observations are affected by at least three distinct diffuse galactic foregrounds: free-free emission, synchrotron radiation, and dust emission. Free-free emission, known as bremsstahlung radiation in the particle physics community, is produced by electron-ion scattering and is not polarized, so it will not be discussed further.
below. Synchrotron radiation is produced by acceleration of free electrons in a galactic magnetic field and polarized dust emission is produced by warm interstellar dust grains that align in the galactic magnetic field. A number of data sets suggest a fourth diffuse galactic foreground component, possibly from spinning dust grains or an unaccounted for synchrotron component, that may be significant at EBEX observing frequencies; for example see Gold et. al, 2010 [21], and Kogut et. al., 2009 [37].

Dust emission and synchrotron radiation have distinct scaling with frequency. Figure 1-5 shows the anticipated B-mode power spectrum of polarized synchrotron radiation at 150 GHz in dashed blue and of polarized dust emission at 150, 250, and 410 GHz in dashed pink. The figure indicates that dust will contribute significantly to the EBEX B-mode signal at all frequencies, however synchrotron is expected to be negligible. The lowest EBEX observing frequency was chosen in part to allow for significant exposure to only one polarized foreground.

Current knowledge of the polarized dust foreground at the EBEX observing frequencies is limited. Finkbeiner et al. [17] provides full sky maps of the dust flux over a large frequency range[19] however the maps contain no polarization information. The Archeops experiment detected the polarized dust signal at 353 GHz with a 13' beam and found a polarization fraction of 4 to 5% in regions around the galactic plane [4]. Finally, WMAP foreground measurements at lower frequencies, with a maximum at 94 GHz, can be scaled up to higher frequencies (see for example Gold et al., 2010 [21].

Although many current CMB experiments observe in a region near the south celestial pole with an especially low amplitude of polarized foreground emission, the sensitivity of current and future CMB experiments is high enough that efficient foreground subtraction from the raw data will be necessary to measure the gravitational

\footnote{Finkbeiner et al. used data from the Diffuse Infrared Background Experiment (DIRBE) instrument on the COBE satellite and the Infrared Astronomical Satellite (IRAS) to create full-sky maps at 100 \( \mu m \) and maps of flux ratios of 100 \( \mu m \) to 240 \( \mu m \). They then extrapolated the flux maps to a wide range of frequencies using a variety of models, including a two-component model which includes silicate and carbon-dominated grains with different amplitudes and spectral indices [17].}
wave and lensing B-modes. Current foreground subtraction techniques, including the parametric separation technique\textsuperscript{20} can be significantly improved with better models of the galactic magnetic field, the spatial distribution of dust, and the alignment and shape of the grains, many of which are not currently fully understood.

### 1.8 EBEX Science Goals

- **Detect the primordial gravitational wave signal:** EBEX will provide a detection of the gravitational wave generated B-mode signal if $r = 0.1$, about one-third the value of the current upper limit \textsuperscript{38}. If the B-mode signal is not detected, EBEX will improve the upper limit on $r$ by roughly an order of magnitude to about 0.02, and rule out a class of cosmological models, described in Section 1.6.

- **Detect the B-mode signal produced by lensing:** If the amplitude of the B-mode lensing signal is as expected, EBEX will constrain the lensing amplitude within 6.5\% up to about $\ell=900$, including anticipated uncertainties due to foreground subtraction. The lensing B-mode measured by EBEX may constrain the dark energy equation of state \textsuperscript{1}, and EBEX data used along with WMAP and Planck data is expected to constrain the difference between neutrino mass species, $\Delta m_\nu$, to 0.16 and 0.056 eV, respectively.

- **Characterize the Polarized Dust Foreground:** EBEX will characterize the polarized dust foreground at 150, 250 and 410 GHz at intermediate scales by reconstructing the foreground signal over the EBEX CMB patch. Figure 1-6 shows power in antenna temperature plotted against frequency at a scale of $\ell=100$, where the gravitational wave B-mode signal is expected to peak, if it exists. The plot shows that EBEX should make a high signal to noise detection of the dust foreground signal, and it emphasizes the low dust flux in the EBEX CMB patch compared to a larger area of sky. Simulations show that, using a parametric separation technique (for example see \textsuperscript{20}See Stompor et al. 2009 \textsuperscript{61}, and Stivoli et al. 2010 \textsuperscript{60}, for example.)
Figure 1-6: Power in antenna temperature versus frequency, at a scale of $\ell=100$ where the gravitational wave B-mode signal is expected to peak, if it exists. The power spectra of the anticipated synchrotron (blue) and dust (pink) signals are shown for a large region of the sky outside WMAP’s P06 mask (dotted) and in the anticipated EBEX CMB patch (dotted). The black curve shows the theoretical CMB B-mode signal for $r=0.1$. The blue and yellow bars show the Planck and EBEX noise for 1 year of data and a 14-day flight, respectively.

Eriksen et al., 2006) [15], the error on the foreground removed CMB B-mode signal will increase by 6 to 30% of the sampling error and instrument noise in the absence of foreground subtraction. Additionally, in the simulation the power spectrum of the dust signal was recovered.$^{21}$

$^{21}$This simulation does not take into account instrumental effects, and it assumes a constant polarization fraction across the CMB patch and a single, scale independent, spectral index.
Chapter 2

Instrument Overview

2.1 Summary of the Instrument

The EBEX instrument, shown in Figure 2-1, is a microwave telescope mounted to an aluminum platform called a gondola. The $\sim 6,000$ lb instrument will map the polarization of the cosmic microwave background (CMB) while suspended from an enormous Helium balloon at the top of the stratosphere over Antarctica. The EBEX cryostat, which houses the receiver, maintains $\sim 1500$ bolometric detectors at a few hundred mK. The instrument will observe at 150, 250, and 410 GHz with a resolution of 8’ at all frequencies. The bolometer signals are frequency multiplexed and read out by superconducting quantum interference devices (SQUIDs). The polarimetry is achieved using a half-wave plate (HWP) modulator and a wire grid analyzer. The attitude control system (ACS) provides telescope boresight pointing and control of the gondola. In this chapter we provide an overview of scientific ballooning, a review of the design principles on which EBEX was built, and an overview of coordinates on the gondola and on the sky. In Chapter 3 we discuss each EBEX subsystem in detail.
2.2 Scientific Ballooning

The Columbia Science Balloon Facility (CSBF) provides support for NASA-funded balloon projects. Balloons are launched from North America for short flights with a typical duration of 24 hours or less, and from Sweden, Australia and Antarctica for flights lasting up to about 30 days. The balloon, which is made of 0.8 mil thick polyethylene film, is filled with Helium gas and at stratospheric altitudes it extends hundreds of feet in diameter [11]. The science payload is carried to the top of the stratosphere to roughly 115,000 ft in two to three hours. When observations with the
payload are complete, or if the balloon drifts to a forbidden altitude or location above the earth, the flight is terminated by separating the balloon from the payload. The payload returns to the earth’s surface on a parachute and it is recovered by CSBF personnel. EBEX was launched from Ft. Sumner, NM, in June, 2009, to complete an engineering flight. A launch is planned during the Austral summer of 2011/2012 from Antarctica for the EBEX long duration science flight.

![Figure 2.2: Atmospheric transmission in the zenith direction at the South Pole, one of the driest ground-based observing sites. The curve is produced using the atmospheric model from [55], assuming 0.3 mm of perceptible water vapor. The three EBEX frequency bands are shown shaded in blue. (Figure courtesy of JoJohannes Hubmayr).](image)

Observing the microwave sky from the top of the stratosphere affords many advantages over ground-based observation. The balloon platform allows for observation at high frequencies, limiting significant foreground exposure to a single foreground, dust, discussed in Section 1.7. Figure 2-2 shows that water vapor in the atmosphere attenuates the millimeter wave signal at higher frequencies at even the driest ground-based observing sites, such as those at the South Pole and the Atacama desert in Chile. Observing at high altitudes also minimizes the drifts in signal that are present in ground-based measurements resulting from atmospheric instability in time and at
different observing zenith angles. Although satellites provide even better atmospheric transmission and other advantages, a balloon-borne project typically costs about three orders of magnitude less than a satellite.

Antarctica is an ideal launch site for stratospheric balloons. The high altitude polar vortex winds typically provide circumpolar flight trajectories at relatively constant latitudes. This keeps the payload over land and, in some cases, carries the payload close to the launch site near McMurdo base at termination, simplifying the recovery process. The polar summer environment provides relatively constant temperatures throughout the 24 hour diurnal cycle, minimizing the contraction of the balloon at night. This allows the balloon to maintain a relatively constant altitude, and thus a relatively constant atmospheric loading on the detectors, and it lessens the loss of helium in each diurnal cycle, allowing for long flight durations. The 24 hour presence of the sun during the polar summer also enables the payload to receive relatively constant power from solar panels.

2.3 EBEX Design Principles

The EBEX design was driven by the need for a high sensitivity microwave polarimeter with a low susceptibility to systematic effects and a sensitivity to a wide range of scales on the sky. Table 2.1 highlights the fundamental design principles in EBEX and how the hardware or scan strategy meets the requirements.

2.4 The EBEX Long Duration Flight

2.4.1 Observations

During the long duration science flight in Antarctica EBEX will map a 420 deg$^2$ patch near the southern celestial pole. The patch location was chosen for it’s relatively low dust emission, with an expected mean brightness on the order of 3 µK. Additionally,
<table>
<thead>
<tr>
<th><strong>Design Principle</strong></th>
<th><strong>Hardware Implementation or Scan Specification</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Map the CMB (power spectrum peaks at 160 GHz)</td>
<td>Use a majority of detectors at 150 GHz</td>
</tr>
<tr>
<td>High Sensitivity</td>
<td>Use 1500 low noise detectors and low noise read out electronics</td>
</tr>
<tr>
<td>Sensitivity to lensing B-mode signal</td>
<td>Primary mirror diameter of 1.5 m</td>
</tr>
<tr>
<td>Sensitivity to primordial B-mode signal at ( \ell = 100 )</td>
<td>Scan patch size of 410 deg(^2)</td>
</tr>
</tbody>
</table>
| Only one foreground is significant at the observing frequencies | 1. Choose frequency bands at 150 GHz and above  
2. Work on a balloon platform high in the atmosphere |
| Reconstruct dust foreground signal | Observe over three frequencies to get leverage over a large spectral range |
| Minimize cross-polarization in warm optics and allow for a large focal plane to accommodate many detectors | Use Gregorian MizuguchiDragone Design |
| Reject polarized systematics | Use a half-wave plate to modulate the polarized signal |
| Reconstruct pointing to 9\(^\circ\) | Use redundant high precision star cameras and sets of three fiberoptic gyroscopes |

Table 2.1: Summary of the EBEX design principles and corresponding hardware and scanning specifications
for a few hours per day EBEX will scan bright polarized sources to allow for post-flight calibration. Candidate calibration sources that will be accessible during the Antarctic flight include RCW38 and Centaurus A.

2.4.2 Scan Strategy

While mapping the EBEX CMB patch the instrument will perform azimuth slews with a 20° peak-to-peak amplitude. The scan speed of about 1deg/s allows for about 4 measurements of Q and U per 8' beam size. After roughly two azimuth scan periods the instrument will step up in elevation by about \( \frac{1}{3} \) of a beam, with the azimuth adjusted to maintain a constant RA. After about four hours the scan will be repeated, where the starting elevation will be adjusted to match the starting declination of the previous scan.

The resulting coverage on the sky is shown in Figures 2-3(a) and 2-3(b). Figure 2-3(a) shows that in repeated 4 hour scans of a single 150 GHz detector, the CMB patch is approached at different angles, resulting in cross-linked scans. Over the 14-day flight, about 24,000 pixels will mapped with relatively uniform coverage across the patch. Figure 2-3(b) shows that, at 150 GHz, each pixel will be sampled about \( 10^7 \) to \( 10^8 \) times. The predicted errors on the EBEX measurements, shown in Figure 1-5, are based on this type of scan strategy and sky coverage.

2.5 An Overview of Coordinates

Different coordinate systems are convenient to describe the orientation of the gondola in three dimensional space and the angle of the microwave telescope boresight on the sky. Figure 2-4(a) shows the horizontal coordinates that describe the three rotational axes of an object such as an airplane, called azimuth, elevation, and roll. The azimuth is defined along the gravity vector pointing down from the zenith towards the earth, and the elevation and roll are defined relative to the object—the elevation axis extends
along the left/right direction and the roll axis extends along the front/back direction. Typically, 0° azimuth is at North with azimuth increasing in the Eastward direction, and 0° elevation is at the horizon with elevation increasing for angles above the horizon. Figure 2-4(b) shows the conventions for front, back, left, and right on the EBEX gondola for defining azimuth, elevation and roll.

A number of coordinate systems can be used to describe the angular position of an object on the sky. Equatorial coordinates are defined as projections of the earth’s latitude and longitude lines onto the celestial sphere surrounding the earth. Figure 2-5(a) shows that right ascension (RA) is a projection of the earth’s longitude and declination (Dec) is a projection of the earth’s latitude. The roll is the angle described by rotations around the vector pointing from the telescope to the celestial object. Galactic coordinates, shown in Figure 2-5(b), are defined relative to the galaxy as viewed from the location of the solar system. In the figure the solar system is located at S and the galactic center is in the direction of G. The galactic latitude, b, describes the magnitude of the angle above or below the galactic plane, ranging from +90° to -90°, and the galactic longitude, l, describes the angle within the galactic plane, from
Figure 2-4: *a:* The horizontal coordinate system conveniently describes the orientation of an object in three dimensional space using azimuth, elevation, and roll. *b:* A drawing of the EBEX gondola showing the conventions of front, back, left and right.

$0\degree$ to $360\degree$.

The horizontal coordinates, azimuth, elevation, and roll, are related to the equatorial and galactic coordinates using the local sidereal time (LST$^1$) and the latitude on earth from which the celestial object is observed.

---

$^1$Local sidereal time defines the passage of time relative to the stars, not the sun, providing a more consistent measure of time.
Figure 2-5:  
a: The equatorial coordinate system describes the pointing angle of the millimeter wave boresight on the sky in right ascension (RA) and declination (Dec), where RA is a projection of the earth’s longitude and Dec is a projection of the earth’s latitude. The earth is shown in blue embedded in the celestial sphere, shown in black. 
b: The galactic coordinate system describes the pointing angle of the millimeter wave boresight on the sky in b, the galactic latitude, and l, the galactic longitude. The solar system is located at S and the galactic center is in the direction of G.
Chapter 3

The Instrument

3.1 Gondola

3.1.1 Overview and Design Drivers

The EBEX gondola was designed at Space Sciences Lab (SSL) at the University of California at Berkeley. After assembly at SSL in the Fall of 2007 the gondola was shipped to Nevis Labs for integration with the attitude control system hardware. The gondola is shown with and without the sun and ground shields, called baffles, in Figures 3-1(a) and 3-1(b). The design of the EBEX gondola was driven by CSBF requirements, the most significant of which are listed below, and functionalities required in the instrument, summarized in Table 3.1:

Some Columbia Science Balloon Facility (CSBF) Structural Requirements [10]:

- The gondola structural members must be able to sustain a load of 10 times the gondola weight in the vertical direction, and 5 times the gondola weight in the horizontal direction and at an angle 45° to the horizontal direction.
- In a multi-cable suspension system the breaking strength of each cable must be at least 5 times the payload weight divided by the sine of the angle between the cable and the horizontal direction.
Figure 3-1:  
(a) The EBEX gondola, including the inner frame (top) painted in white emissive paint and the outer frame (bottom). The cryostat weight dummy is mounted in place of the actual cryostat.  
(b) The gondola with baffles in place while hanging from the launch vehicle.
• The weight of the EBEX hardware must be less than 6,000 lb.
• The gondola structure must fit into a specified envelope so that it can hang from the launch vehicle without obstruction.

3.1.2 Gondola Frame Structure

Outer Frame

The outer frame table, shown in Figure 3-1(a), is constructed from four sections of I-beam which are joined together using L-shaped aluminum brackets. Pins and bushing installed in the beams and brackets help to insure the table sides are square with one another and coplanar. The trunnion legs, each made from two sections of aluminum c-channel and a top rectangular panel, are mounted to the inner frame table.

Support beams for the reaction wheel and motor and the Support Instrument Package (SIP), the CSBF electronics, were added to the outer frame table at Nevis Labs. In choosing the beam shape and size we aimed to maximize the allowed stress on the beam and minimize the deflection of the beam under load while also minimizing its weight. Both I-beams and c-channels were considered because of their especially high second moments of inertia per unit weight. Given the sizes of stock readily available an I-beam was chosen. Figure 3-2 shows the four I-beams bolted to the outer frame table, with the inner pair of beams supporting the reaction wheel and motor and the outer pair of beams supporting the SIP (not shown in the photo).

1The gold color of many of the gondola pieces results from chemical treatment with Alodine which produces a hard non-reactive surface, preventing further surface oxidation. Although the treatment was not necessary and it was not readily available from all machine shops, given its low additional cost the treatment was performed since it allows paint to adhere more easily to the aluminum surface.

2The second moment of inertia describes the resistance of a beam to deflection or bending due to loads perpendicular to the beam.
<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Design Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>The inner frame structure needs to rigidly support a roughly 2,000 lb cryostat over many elevation angles</td>
<td>Use segments of opposing pairs of c-channel that are joined by aluminum sheet on the top and bottom to provide rigidity and strength; see Figure 3-3(a).</td>
</tr>
<tr>
<td>Flexibility to view incoming microwave beams ranging in elevation angle from 15° to 68° to allow for scanning of the desired patch of CMB and calibration sources</td>
<td>Implement a linear actuator with motor.</td>
</tr>
<tr>
<td>Gondola can scan in azimuth</td>
<td>Build a high torque motor into the rotator housing and a reaction wheel on the outer frame table; see Figures 3-6 and 3-7.</td>
</tr>
<tr>
<td>The inner frame tower must be rigid enough so that the secondary mirror does not slump relative to the cryostat or the primary due to large changes in elevation</td>
<td>Add shear panels to the inner frame tower and the primary mirror support and add aluminum angle pieces to attach the primary mirror support to the inner frame tower; see Figure 3-1(a).</td>
</tr>
<tr>
<td>Placement of the primary and secondary mirrors must be adjustable so that one can easily configure a focused warm optical system</td>
<td>Mount the mirrors to hexapods and write an algorithm for setting the positions of the hexapod legs; see Figure 3-1(a).</td>
</tr>
<tr>
<td>The gondola is balanced at all inner frame elevation angles</td>
<td>Design the gondola so that the inner frame is balanced when the cryostat is full of cryogens and all electronics boxes and mirrors are mounted to the inner frame.</td>
</tr>
<tr>
<td>Top surfaces of the two trunnion legs are aligned relative to one another so that the trunnion pins, which support the entire inner frame, sustain minimal load due to misalignment</td>
<td>Insure the outer frame table is completely square, and the trunnion legs are mounted flat to the table using pins and bushings at all points of intersection of independent metal components in the table and trunnion legs.</td>
</tr>
<tr>
<td>Provide protection of the instrument at landing to minimize damage</td>
<td>Build protection hardware such at quills, a roll bar, and a support for the triangle spreader; see Figure 3-5(b).</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of the EBEX gondola design requirements and associated implementations.
Figure 3-2: View from below of four I-beams installed in the outer frame table. The inner pair of beams supports the reaction wheel motor (shown with reaction wheel motor plate, motor and wheel installed) and the outer pair of beams supports the SIP (not shown here).

**Inner Frame**

Since the inner frame structure supports the optics and cryostat, it was designed to be relatively low weight but extremely strong and rigid so the optical alignment is maintained at all elevation angles. The base of the inner frame is an octagon structure, shown in Figure 3-3(a), built from opposing pieces of c-channel and aluminum sheet. The octagon supports a tower structure, shown in Figure 3-1(a), made out of aluminum box beam pieces. A u-shaped primary mirror support is mounted perpendicular to the base of the tower. The rigidity of the tower structure is provided by thin aluminum panels which add shear support, and two pieces of aluminum angle that connect the far side of the primary mirror support to the middle of the tower. The inner frame elevation angle ranges from fully upright to 37° down from the vertical. The corresponding incoming microwave beam angles into the primary mirror range from 68° to 15°.

The outer frame connects to the inner frame at the trunnion bearing assembly.
Figure 3-3:  

(a): The octagon with the two opposing trunnion pins installed.  
(b): Bushing and block (part of the trunnion bearing assembly). The alignment pins in the bottom of the block are visible.

The assembly includes a pair of hard anodized aluminum cylindrical pins, shown installed on the left and right sides of the octagon in Figure 3-3(a), and a bronze bushing fitted into a stainless steel block that mounts to the top of the trunnion legs on the outer frame, shown in Figure 3-3(b). It is critical that the trunnion leg tops are aligned with each other and the gondola, as described in Appendix B, to minimize stress on the trunnion pin and bushing. Since the trunnion bearing assembly is not sealed, allowing debris to migrate from the environment around the gondola to the space between the pin and bushing surfaces, protection hardware was installed to prevent debris from entering the assembly.

**Baffles**

Baffles made from foam, aluminized mylar, and thin pieces of aluminum angle, shown in Figure 3-1(b), provide shielding of the telescope from radiation from the sun and the ground.
3.1.3 Suspension Hardware

The EBEX suspension hardware, included in Figure 2-1, provides an interface between the EBEX instrument and the CSBF cabling and balloon, referred to as the flight train. The outer frame table hangs from an aluminum triangle spreader bar by four light-weight Spectra plasma ropes\(^3\) each connected to a turnbuckle and shackles at both ends to provide fine adjustability of the rope lengths. Three other turnbuckles and shackles connect the triangle spreader bar to a ring mounted to the rotator, shown in Figure 3-4. A universal joint, shown in Figure 3-4 is connected to the top of the rotator to allow the system to relax in the vertical direction regardless of the angle of the CSBF flight train due to the presence of external forces such as wind. The interface to the CSBF hardware occurs at the truck plate which is connected to the top of the universal joint, shown in Figure 3-4.

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\(^3\)5/8” diameter rope from Helinets, http://www.helinets.com/ropestrengthspecifications.html
3.1.4 Protection Hardware

In order to minimize damage to the payload on landing we implemented three types of protection hardware, shown in Figures 3-5(a) and 3-5(b). Additionally, CSBF attaches four crush pads made out of corrugated cardboard and wood to the base of the gondola legs to absorb impulse on landing, visible in the bottom of Figure 3-5(a).

![Figure 3-5: The EBEX protection hardware. (a) Roll bar to protect the primary mirror. (b) Triangle support to prevent the rotator and triangle from crashing into the inner frame tower on landing.](image)

1. A roll bar, shown in the top left of Figure 3-5(a), is made out of pieces of aluminum box beam joined together by rivets in aluminum plates. It surrounds the primary mirror in the event that the gondola lands on its front.
2. Quills, shown in the bottom left of Figure 3-5(a), made out of aluminum box beam were installed on each side of the gondola to absorb impact in any landing configuration. The strength of the quills is bolstered by the presence of a steel cable, not easily visible in the photo, which runs from the front quill to the back quill.

3. A triangle support, shown in Figure 3-5(b), made out of four pieces of aluminum angle was installed to prevent the triangle and rotator from impacting the inner frame tower, including the secondary mirror, on landing. The back two pieces of the support are connected to the outer frame table and the front two pieces are connected to the front quills. The connection made by the triangle support pieces between the triangle spreader and the outer frame table is rigid, so vertical slots were machined into the base of the support pieces to allow for the extension of the ropes when the gondola is hanging.

3.1.5 Control Hardware

The Rotator

The EBEX rotator is comprised of a cylindrical aluminum housing which supports a shaft with a pair of thrust bearings and a high torque motor to contribute to the azimuthal control of the gondola. The two bearings are installed on an aluminum shaft, as shown in the left panel of Figure 3-6 and the shaft is placed in the rotator cylindrical housing, shown in the middle panel of Figure 3-6. Bearing races are installed on the top and bottom of the cylinder, and the bearings are preloaded by plates bolted to the ends of the cylinder that apply pressure to the races, shown in the right panel of Figure 3-6. A high torque brushless motor\textsuperscript{4} built into the base of the cylindrical frame drives the shaft from below via a coupler, providing large bursts.

\textsuperscript{4}Kollmorgen F7925A, http://www.danahermotion.com
Figure 3-6: The EBEX rotator. *Left:* The rotator shaft with two thrust roller bearings installed. *Middle:* The rotator shaft and bearings in place in the cylindrical rotator housing. *Right:* The top plate of the rotator before it has been secured to the cylindrical housing to pre-load the bearings. A similar plate is bolted to the bottom of the cylindrical frame. A bearing race, not visible in this photo, is placed between the roller surfaces and the plates.

of torque when the gondola requires large accelerations. A slip ring\textsuperscript{5} is built into the rotator housing to allow for signals to travel from the CSBF electronics on the gondola to other CSBF electronics installed along the flight train.

**The Reaction Wheel**

Fine control of the gondola azimuth is provided by a reaction wheel, shown in Figure 3-7, driven by a high torque motor similar to that in the rotator. The reaction wheel design was optimized for a maximal moment of inertia to weight ratio. The wheel is constructed from 12 stainless steel segments that fit together to form a 5 ft outer diameter ring, as shown in the assembly drawing in Figure 3-8. Two thin aluminum disks mount to the top and bottom of the ring, and the disks are held together by a central hub. The wheel is connected to the motor using bolts that pass through the

\textsuperscript{5}A slip ring allows electrical signal transmission between two objects that rotate relative to one another.
hub and screw into the rotor.

Figure 3-7: Photo of the reaction wheel.

Figure 3-8: Assembly drawing of the reaction wheel
1. **Search for warping in the wheel**: To assess the degree of warping in the wheel, if any, we placed the wheel and motor assembly on the floor of the high bay. We mounted a dial indicator such that it measured the height of the top and bottom of the reaction wheel surface above the floor. We rotated the reaction wheel in a stepped fashion and recorded the dial indicator position for various angular positions. Then we placed the dial indicator at various radii on the bottom of the wheel and repeated the rotations. The results of the tests are shown in Figures 3-9(a) and 3-9(b). Figure 3-9(a) shows the deflection follows a somewhat sinusoidal pattern over a full rotation on both the top and bottom of the wheel with the same phase on both surfaces. Figure 3-9(b) shows that the deflection is greatest at a larger radius, which is expected from a warped wheel. The plots show that at the wheel edge the peak to peak deflection of the dial indicator is about 140 mils. The tolerance on the flatness of the surface of the aluminum disks that encase the mass segments was specified at 10 mils. Given the tolerance on the disk surfaces and the systematic pattern in the surface deviation, the wheel shows a small amount of warping.

2. **Search for the reaction wheel rotation frequency in gondola pendulations**: With the gondola in a dynamically balanced configuration, we rotated it slowly in positive and negative azimuthal directions. We produced plots of the wheel rotation speed versus time and power spectra of the fiberoptic rate gyroscopes to search for the presence of the rotational frequency of the reaction wheel in the gondola motion. The power spectra did not show the wheel frequency.

   Although the dial indicator measurements do show warping in the wheel, the dynamic measurements indicate that the warping and other possible imperfections in the wheel do not result in measurable pendulations by our high precision fiberoptic gyroscopes. Thus, we concluded that the wheel is sufficiently balanced for use on EBEX.
Figure 3-9: Evaluation of the EBEX reaction wheel using a dial indicator to measure the surface of the wheel. 

(a) Measurements of the top and bottom of the wheel at a constant radius show a sinusoidal type variation, with the top and bottom surfaces in phase, suggesting warping of the wheel.

(b) Measurements of the bottom of the wheel at three radii show more displacement of the dial indicator at higher radii, as expected in a warped wheel.
The Elevation Actuator

The elevation of the inner frame is controlled by an actuator driven by a brushed motor. The actuator connects to the inner frame at the outer edge of the primary mirror support, and to the outer frame at the trunnion leg.

3.1.6 Gondola Balance

As the gondola scans in the azimuth direction, if it is dynamically unbalanced it will experience a torque in the radial direction. This torque can produce wobbling and excitation of various normal modes of the gondola, resulting in unwanted pendulations.

The gondola was designed so that it will be balanced when all of the EBEX components are mounted. However, fine tuning of the balance will always be required since changes in the design of various subsystems will result in deviations from early models of the instrument. Since balancing generally requires adding weight, or in some cases redistributing weight, there is a limit to how well we can control the balance of an out of balance system. In order for the gondola to be dynamically balanced, the following conditions need to be met:

1. The Inner frame must be balanced in the elevation direction so that the gondola does not change its balance when the inner frame moves in elevation. This requires that the inner frame center of mass lie on the elevation axis, which is defined as the line connecting the center of the two trunnion pins. The center of mass is shifted by adding weight to either the inner frame tower or the base of the cryostat. The balance can be verified by changing the inner frame elevation angle through the full range of motion and measuring the corresponding tilt of the outer frame table; no tilt in the table will be measured for a perfectly balanced inner frame.

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7Pittman 14207, www.ametektip.com
balanced inner frame. Since the inner frame has no degree of freedom in roll, it does not need to be independently balanced in the left/right direction.

Three-dimensional computer aided drawing (CAD) simulations of the gondola show that as the Helium and Nitrogen cryogens boil off, the inner frame center of mass will shift by about 3”. Thus during the flight the balance will shift by a small amount towards the bottom of the cryostat.

2. The inner frame and outer frame together must be balanced in elevation and roll

3. The rotator and reaction wheel must be level such that rotator shaft and the axis through the reaction wheel hub are aligned with the gravity vector, ensuring that the system is being driven in azimuth along a principal axis of the gondola. This can be verified using a digital level or clinometer on the rotator and the outer frame table.

Although achieving the inner frame balance is straightforward and verifiable, balancing and leveling the outer frame, while independent conceptually, are coupled in practice. If the gondola is balanced, the rotator should be level regardless of the reaction wheel angle. And ultimately, the gondola is balanced and level, the desired configuration, if both the rotator and the reaction wheel are level. Achieving this state is iterative. Adjustments can be made to the turnbuckles that are connected to the ropes between the outer frame table and the triangle spreader, and weights can be added or shifted on the battery table.

3.1.7 Addressing Design Errors

Two significant errors made during the design process resulted in less than optimal performance of the original gondola, as described below.
Inner Frame Imbalance

An error in the three-dimensional CAD model for the gondola resulted in an incorrect specification for the attachment point of the cryostat to the octagon, and consequently, the position of the cryostat relative to the elevation axis. As a result, the inner frame was excessively top heavy, and to dynamically balance it 650 lb had to be added to the base of the cryostat.

The inner frame was left unbalanced for the engineering flight since the EBEX weight budget could not accommodate the addition of 650 lb and there was not sufficient time before the flight to solve the problem with a redesign of the interface between the cryostat with the inner frame. There were two consequences to flying the payload with an unbalanced inner frame:

1. The gondola could not be dynamically balanced. The outer frame table was relatively level when the inner frame was upright, however, as the inner frame elevation angle decreased the outer frame table tilted downwards in elevation by about 1° over the full elevation range. The imbalance of the gondola at lower elevations had the potential to induce wobbling and pedulations during azimuthal scans. To assess the amplitude of pendulations that may be induced by the imbalance, azimuth scan tests were completed with the inner frame at high and low elevation angles, creating balanced and unbalanced gondola configurations, respectively. The amplitude of pendulations measured by the fiberoptic rate gyroscopes was not noticeably different in the two cases in either the gyroscope timestreams or power spectra. We concluded that we could fly the payload with an unbalanced inner frame without dynamical consequences. However, post-flight analysis suggests that, at times, the imbalance of the gondola coupled with a seized universal joint may have prevented the gondola from moving in azimuth as commanded, discussed in Section 5.3.9.

2. The unbalanced inner frame applied an increasingly larger compressive load on
Figure 3-10: Springs were installed between the back of the cryostat and the front of the outer frame table to counteract the large compressive forces of the top heavy inner frame on the elevation actuator at low inner frame elevations.

Additionally, springs with a high spring constant were mounted between the back of the cryostat and the front of the inner frame table, as shown in Figure 3-10. When the inner frame was upright the springs were neither stretched or compressed, so they applied no force on the gondola. However as the inner frame angle decreased, the higher load was perceptible in the high pitch noise induced in the actuator during motion at lower elevations. The actuator attachment on the outer frame table was moved from the front of the table to the side of the trunnion leg to provide a more advantageous angle for the actuator at lower inner frame elevation angles. CAD simulations indicated that the gondola would not overload the actuator even at the CSBF specified load of 10 times the gondola weight.

The springs used were stock springs used to control the motion of garage doors.
frame decreased in elevation, the springs applied an increasingly greater force, based on Hooke’s Law. This pulled the cryostat base forward to counter the increasing force of the top heavy inner frame down on the elevation actuator. The overall action of the springs was to reduce the loading on the elevation actuator at lower inner frame elevation angles.

We are currently redesigning the interface between the cryostat and the octagon and trunnion pins to allow for a balanced gondola in the long duration flight.

**Suspension Hardware Re-Design**

Due to another error in the CAD model of the gondola, the triangle support geometry and the locations of the attachment points for turnbuckles on the rotator ring, shown in Figure 3-4 did not allow the instrument to be dynamically balanced and level as described in Section 3.1.6. After attempting to work around the problem by adjusting turnbuckle lengths and redistributing mass, the hardware was redesigned. Subsequently, the entire instrument could be balanced, although it was only possible with the excess 650 lb mounted the inner frame.

**3.1.8 Instrument Weight**

The overall weight of the EBEX gondola was driven largely by the need to support a ∼2000 lb cryostat. During the design process it became clear that the final gondola weight would be close to or in excess of the 6,000 lb weight limit set by CSBF. During the final phases of the design, care was taken to design components for the minimum possible weight. Additionally, some components were redesigned or replaced with lower weight options. For example, the hexapod top and bottom plates, detailed in Section 3.3.4 were redesigned, the flat bottom lid of the cryostat was replaced with a much lighter domed design, and the steel suspension cables between the outer frame table and the triangle spreader were replaced with extremely lightweight ropes.\(^9\)

\(^9\)Each rope, including steel thimbles installed at each end, weighs 4 lb.
Also, before the flight an analysis with the CAD model of the gondola showed that a section of the octagon was not required to support the cryostat so it was removed. As a result, before the engineering flight the instrument weighed 5,885 lb, 12 lb lower than the predicted value in the weight tally spreadsheet we used to track the weight of individual components. Table 3.2 summarizes how the weight was distributed across the instrument in the engineering flight configuration based on the measurement of individual components.

We are currently implementing a number of measures to reduce the weight of the payload for the long duration flight. In the cryostat the cryogen tanks and the top plate are being replaced by thinner versions that reduce the weight of these pieces by a factor of two. On the gondola we are considering replacing some aluminum components with carbon fiber, such as the shear panels, we are producing even lighter weight hexapods, and we are redesigning some electronics boxes.
## Table 3.2: Summary of the weights of the EBEX components before the North American engineering flight, measured or estimated separately. The last two lines show the sum of the individual measurements and the measurement of the whole instrument before the engineering flight.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner frame</td>
<td>478</td>
</tr>
<tr>
<td>Outer frame</td>
<td>693</td>
</tr>
<tr>
<td>Reaction wheel and motor</td>
<td>351</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>100</td>
</tr>
<tr>
<td>Secondary mirror</td>
<td>50</td>
</tr>
<tr>
<td>Primary and secondary hexapods and brackets</td>
<td>120</td>
</tr>
<tr>
<td>Cryostat (with cryogens)</td>
<td>1839</td>
</tr>
<tr>
<td>Plasma ropes and turnbuckles</td>
<td>97</td>
</tr>
<tr>
<td>Turnbuckles between triangle and rotator</td>
<td>78</td>
</tr>
<tr>
<td>Rotator, universal joint and truck plate</td>
<td>304</td>
</tr>
<tr>
<td>Triangle spreader</td>
<td>168</td>
</tr>
<tr>
<td>Elevation motor and linear actuator</td>
<td>5</td>
</tr>
<tr>
<td>Baffles</td>
<td>313</td>
</tr>
<tr>
<td>Roll bar</td>
<td>52</td>
</tr>
<tr>
<td>Quills</td>
<td>116</td>
</tr>
<tr>
<td>Triangle support</td>
<td>80</td>
</tr>
<tr>
<td>Batteries</td>
<td>390</td>
</tr>
<tr>
<td>Electronics and associated mounting hardware</td>
<td>663</td>
</tr>
<tr>
<td><strong>Sum of individual measurements</strong></td>
<td>5897</td>
</tr>
<tr>
<td><strong>Measurement of entire instrument at once</strong></td>
<td>5885</td>
</tr>
</tbody>
</table>
3.2 System-wide Electronics, Software, and Power Delivery

3.2.1 Summary of Components

The EBEX electronics provide signal bias and read out, instrument control, communication between the ground and the payload, writing of data to disk, and power to the instrument. Below we summarize the contents of each of the primary EBEX electronics components that will be discussed in further detail in this section. An overview of the electronics is shown in Figure 3-11; the first two items on the list are provided by CSBF.

**Support Instrument Package (SIP):** The SIP, shown in Figure 3-11 in a green box labeled “CSBF SIP”, is furnished by CSBF and provides a link to the EBEX payload from the ground, allowing data downlink and commanding uplink. The SIP consists of computers, receivers and transmitters, and related electronics that are mounted to the payload to communicate with a satellite network and ground station receivers and transmitters.

**Science Stack:** The science stack, shown in Figure 3-11 in a green box labeled “CSBF Science Stack”, also provided by CSBF, contains electronics for sending a limited number of discrete commands to the payload from the ground.

**Flight Computer Crate:** The flight computer crate, shown in Figure 3-11 in a blue box, provides control of the payload, time synchronization of subsystems, and data logging to external hard disks. The crate contains a power module that provides the appropriate voltages to all of the internal electronics. The crate also houses two redundant computers, each of which is attached to a custom Peripheral Component Interconnect (PCI) card, a watchdog board, a timing board, two redundant network switches, and electronics that implement some of the discrete commands from the
science stack.

**Disk Pressure Vessel and Ethernet Network:** The disk pressure vessel, shown in Figure 3-11 in a blue box, provides on-board storage of all flight data. The vessel contains a network switch and laptop hard disks. Ethernet switches are also located in the flight computer crate, bolometer readout crates, and the half-wave plate (HWP) crate.

![Diagram of EBEX electronics subsystems](image)

Figure 3-11: Overview of the EBEX electronics subsystems. The colored boxes indicate the power domain for the ACS (blue), the cryostat electronics (red) and the CSBF electronics (green). The dotted line between the HWP and ACS crates indicate this link was only present during the engineering flight.

**Attitude Control System (ACS) Crate:** The ACS crate, shown in Figure 3-11 in a blue box, supports the ACS sensors and motors. The crate contains a power module that provides appropriate voltages for the ACS components, readout boards
that provide sensor signal read out and processing and control signal output, the
distribution of the Science Stack command signal lines, and electronics that implement
some of the discrete commands from the science stack.

**Motor Control Boxes:** The motor control boxes, shown in Figure 3-11 in three
blue boxes labeled “Elevation Mot. Controller”, “Reaction Mot. Controller” and
“Rotator Mot. Controller”, interface between the ACS readout boards and the motors
to provide the appropriate current to the motors. One motor control box is dedicated
to each of the three EBEX motors: the elevation motor, the reaction wheel motor, and
the pivot motor. Each controller box contains a commercial motor controller, and the
reaction wheel and rotator boxes contained a custom board to filter the pulse-width
modulated (PWM) control signal to an analog signal during the engineering flight.

**Cryostat:** The cryostat, shown in Figure 3-11 in a red box, provides mechanical
support and a low temperature environment for the receiver. It houses the bolometric
d Detectors and the SQUID boards used to amplify the bolometer signal before read
out in addition to signal modulation, polarimetry and re-focusing optics.

**Bolometer Power Crate:** The bolometer power crates, shown in Figure 3-11
in red boxes labeled ”Bolometer Power 1” and ”Bolometer Power 2”, contain power
modules that provide the appropriate voltages to all of the cryostat electronics, and
electronics that implement some of the discrete commands from the science stack.

**Bolometer Readout Crates:** The bolometer readout crates, shown in Figure 3-
11 in red boxes labeled ”Bolometer Readout 1” and ”Bolometer Readout 2”, provide
signal read out and control of the cryostat electronics. Each crate contains boards
that bias and read out the bolometers, boards that provide cryostat housekeeping\footnote{Housekeeping electronics provide monitoring of system health, including temperatures, pressures, currents and voltages.},
and timing boards which send the EBEX time stamp to each board.

**Half-Wave Plate (HWP) Crate:** The HWP crate, shown in Figure 3-11 in a
red box, controls the HWP motion and reads out its position. The crate contains a
commercial motor controller for driving the rotation of the HWP and two readout
boards for recording the angular position of the HWP.

**Power System** The power system provides a nominal 24 V to the instrument using non-rechargeable batteries in the engineering flight and a solar panel power system in the long duration flight. Figure 3.11 is color coded to reflect how the subsystems are allocated to the three power systems on EBEX, discussed in detail below in Section 3.2.7.

### 3.2.2 Flight Computer Crate

Figure 3−11 shows that the flight computer crate provides the interface to all EBEX signal read out electronics, the disk pressure vessel used for data storage, and the CSBF SIP which contains electronics for data downlink and command uplink. The crate houses two redundant computers\(^\text{11}\) with identical operating systems and software. Each computer runs the custom flight control program (fcp) that executes all of the interfacing between the computers and the other flight electronics; fcp was built by modifying the flight control program used by the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST) experimental team at the University of Toronto. Both computers read all system data and write it to external disks in the pressure vessel.

Only one computer, which is designated “in charge” by a watchdog board in the crate, executes commands to the EBEX electronics and communicates with the CSBF electronics; the “in charge” computer is designated by the electronics arbitrarily on bootup. The watchdog board monitors the health of the computers through receipt of a signal that is sent by each computer when fcp is running. If this signal is not received by the watchdog from a computer then the watchdog board reboots that computer; if the signal from fcp is not sent by the ”in charge” computer then the watchdog transfers control to the other computer. All serial signals that are input to the computer are routed into the watchdog card and then distributed to each

\(^{11}\)Ampro Mightyboard 800, http://www.ampro.com/products/MightyBoard/
computer. A custom PCI card, built by the University of Toronto electronics shop, is
attached to each computer to interface with the bus to the ACS crate and to properly
format the data for downlink and uplink, as discussed below. The flight computer
crate also contains a timing board which is part of the timing synchronization system
that will be discussed below in Section 3.2.6.

3.2.3 Ethernet Network and Disk Pressure Vessel

The ethernet network, shown in Figure 3–12 provides connectivity between the flight
computer crate and the bolometer readout crates, the HWP crate, the disk pressure
vessel, the star camera, and the sun sensor; during ground operation a connection
to a ground station is also provided. The EBEX network is built with Sixnet12 ring
switches which are connected to form a ring topology. The ring switches allow for
two connections to the network from each switch so for each subsystem there are a
minimum of two paths to any client on the network. This provides immunity against
a single point failure in the network caused by a damaged connector or cable.

During the engineering flight the disk pressure vessel held a pair of laptop hard
drives which communicated with the flight computers using the ATA over Ethernet
(AoE) protocol via an ethernet switch. Each flight computer simultaneously wrote a
copy of data to two separate disks to provide two redundant and independent copies
of the data. For the long duration flight two redundant vessels will be implemented
with additional disks to accommodate the higher data volume.

3.2.4 The Support Instrument Package (SIP)

Data Downlink and Command Uplink

While EBEX is in flight, two-way communication is facilitated between the payload
and the ground by the CSBF SIP, allowing for data downlink and command uplink.

12http://www.sixnetio.com
The SIP contains two independent computers that each connect to the serial inputs on both of the EBEX flight computers. One of the SIP computers is connected to the IRIDIUM satellite network and the other is connected to the TDRSS network, providing redundancy. The IRIDIUM and TDRSS satellites uplink and downlink data at 255 bytes every 15 minutes, and a higher rate TDRSS connection downlinks at 6 kilobytes per second. The computers are also connected to line of sight (LOS) data and video transmitters which provide downlink at 1 megabit per second. Throughout the ~ one day engineering flight when line of sight communication is always possible LOS transmitters are used. Additionally, CSBF provides modified electronics that interface with the science equipment as a SIP for testing, although the data link uses LOS transmitters in place of the satellite communications system. During the long...
duration flight the SIP provides the connection between the ground and payload via the satellite links, and LOS transmitters are also available during the first 12 to 24 hours of the flight, depending on the wind speed.

The data downlink from the flight computers and command uplink from the ground station computers requires the PCI board in the flight computer crate and an additional one in the ground station computer. The PCI board contains a biphase that, in the flight computer, combines the clock and data lines into a single data stream for radio transmission, and in the ground station computer separates the transmitted data stream into clock and data lines so it can be read into a computer. Data downlinked to the ground station computer is reformatted in real time using the custom *interloquendi* and *defile* software into the dirfile format for viewing by multiple clients.

Command strings can be uplinked to the payload using *ebexcmd*, a custom program running on the ground station. Because the satellite network provides low bandwidth and is not always reliable, multi-step commands are written as scripts initiated by a single command.

**Commanding Through the Science Stack**

CSBF also provides a science stack with a bank of 28 transistors that execute discrete commands. The signal line provided by the science stack is used to control a pair of latching\(^{13}\) and solid state relays. EBEX uses these commands as 14 pairs of on/off switches to execute power cycling for the entire system. The allocation of the commands to various subsystems during the engineering flight is shown in Table 3.3. Commands were allocated to large subsystems, or to smaller systems that had a higher probability of failing such as those with computers that are vulnerable to a single event upset from a cosmic ray.

\(^{13}\)Teledyne 422 series latching relays from http://www.teledynerelays.com. These relays have been shown to not switch under the shock from the parachute opening at the end of the flight.
<table>
<thead>
<tr>
<th>Number</th>
<th>Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flight Computer Crate</td>
</tr>
<tr>
<td>2</td>
<td>Disk Pressure Vessel</td>
</tr>
<tr>
<td>3</td>
<td>Network Switches</td>
</tr>
<tr>
<td>4</td>
<td>Video Transmitter</td>
</tr>
<tr>
<td>5</td>
<td>Data Transmitter</td>
</tr>
<tr>
<td>6</td>
<td>Cryostat Housekeeping</td>
</tr>
<tr>
<td>7</td>
<td>Cryostat Heaters</td>
</tr>
<tr>
<td>8</td>
<td>Bolometer Power Crate</td>
</tr>
<tr>
<td>9</td>
<td>Half Wave Plate Motor and Readout</td>
</tr>
<tr>
<td>10</td>
<td>ACS Readout boards and Some Sensors</td>
</tr>
<tr>
<td>11</td>
<td>Star Camera</td>
</tr>
<tr>
<td>12</td>
<td>Sun Sensor</td>
</tr>
<tr>
<td>13</td>
<td>Attitude Control Motors</td>
</tr>
<tr>
<td>14</td>
<td>Cryostat Valve Open/Close</td>
</tr>
</tbody>
</table>

Table 3.3: Science stack discrete on/off command allocation for the engineering flight

### 3.2.5 Signal Read Out Overview

The EBEX electronics provide signal read out and payload control for low noise bolometer and cryostat housekeeping systems and higher noise attitude control and gondola housekeeping systems. Three independent read out systems were implemented to achieve these functions since no single existing system could interface with all of the EBEX subsystems and each subsystem has very different requirements in noise and functionality. Considerable effort was conserved by using some pre-existing read out electronics and software that have been flight tested. The three independent read out systems are synchronized through the distribution of a timing signal, discussed in Section 3.2.6. The three systems are described below:

1. **Bolometer and HWP Readout**: The bolometers are biased and read out by digital frequency multiplex (DfMUX) boards, described in detail in Section 3.4.4. The encoder that records the position of the HWP is also read out by DfMUX boards located in the HWP crate. These signals travel to the flight
computer by ethernet over fibers to provide isolation of the low noise cryostat electronics from the noisier ACS system.

2. **Cryostat Housekeeping**: The cryostat housekeeping boards are located in the bolometer power crates and the bolometer readout crates. Housekeeping of the cryostat is performed using a variety of generalized custom readout boards with Embedded Local Monitoring Boards (ELMBs), daughter boards developed by the A Toroidal LHC ApparatuS (ATLAS) experiment and provided by the Weizmann Institute. These boards can read out analog and digital signals and also provide excitation for temperature and pressure sensors. During the long duration flight these boards will also provide housekeeping for the flight computer crate, the disk pressure vessels, and the power system. The signals on these boards travel over controller area network bus (CANBUS); the CANBUS interfaces with the flight computers via off-the-shelf CANBUS to USB converters.

3. **ACS and Gondola Housekeeping**: The ACS readout boards, developed at the University of Toronto, read out and control the ACS sensors and motors and provide ACS and gondola housekeeping. The signals from the ACS readout boards interface with the flight computers via a proprietary bus that connects to the PCI board in the flight computer crate; as Figure 3-11 shows, some of the attitude control sensors connect to the flight computers directly via ethernet and serial connections.

3.2.6 **Timestamping and Synchronizing Different Subsystems**

A timing system is required to synchronize the data from the three separate asynchronous data streams discussed in section 3.2.5. A diagram of the timing system is shown in Figure 3-13. Two identical time server boards, shown in green in Figure 3-13, are located in the flight computer crate and in one of the bolometer readout
Figure 3-13: A schematic showing the EBEX timing system.

The two time servers provide redundant independent time stamps of relative EBEX system time to each subsystem. The arbitrary EBEX time from the servers can be correlated with absolute time through a GPS heartbeat signal, shown in purple, that the GPS receiver sends to the time server once per second, and an absolute time stamp that the GPS sends to the flight computer each second; this functionality will be implemented for the long duration flight. Timing distribution boards, shown in orange in Figure 3-13, are located in each bolometer readout crate and the HWP crate to distribute the time synchronization message to each DfMUX board.

The DfMUX boards, the cryostat housekeeping boards, and the ACS boards each increment their own time using a local on-board counter incremented by a high precision oscillator. The local board time provided by the counter is updated and synchronized with EBEX system time by a master synchronization message that is sent from each time server board to each client at 6Hz. The sync message is a Manch-
ester encoded signal which is sent to each subsystem via the CANBUS, shown in Figure 3-13 as a dotted line, or a serial RS-485 bus, shown as a solid line. The 6 Hz synchronization frequency was chosen so that the local system counter can drift by a maximum of 10 µs before re-synchronization with the timing board at 6 Hz. The time server boards each contain a high precision oven-controlled oscillator with a stability of 0.2 ppb to provide timing precision to 10 µs.

3.2.7 Power Delivery

Overview

Power delivery to all electronics was provided by non-rechargeable batteries in the engineering flight and will be provided by a solar power system during the long duration flight. Two separate parallel power systems are used in EBEX to isolate the low noise bolometer and cryostat housekeeping readout from the noisier ACS and gondola housekeeping electronics. The parallel power systems are shown in Figure 3-14. The bolometer power crates and the ACS crate provide all of the power distribution to the subsystems, as shown in Figure 3-11, where the boxes are colored based on the domain from which they draw power. The CSBF electronics are powered by a completely separate power system consisting of non-rechargeable batteries in the engineering flight and a solar power system in the long duration flight.

Power System Hardware Used in the Engineering Flight

During the engineering flight we used Saft G62 Lithium Sulphur Dioxide cells provided to us by CSBF wired with 10 cells per battery. In cold temperatures the batteries provide fewer Ahr at a slightly lower voltage than in warm temperatures, however thermal vacuum tests at the University of Minnesota indicate that the batteries self-heat, keeping them above a temperature of 10°C at float. Data from the EBEX

\footnote{For the engineering flight we specified batteries to provide for a 30 hr flight with a contingency of 1.3.}
engineering flight show that the batteries cooled to 26 °C in the tropopause, but warmed up slowly during the flight to 41 °C.

![Schematic of solar power systems](image)

**Figure 3-14**: A schematic showing the two parallel solar power systems.

**Power System Hardware to be Used in the Long Duration Flight**

During the Antarctic flight we will implement a solar panel power system, shown in Figure 3-14, since the number of rechargeable batteries required for a 14-day flight would be prohibitively heavy. The panels will charge batteries at a range of voltages, and then the instrument will draw power from the batteries at a fixed voltage; we will use Lithium-ion batteries because of their high power to weight ratio. The solar panels will be fabricated by Suncat Solar in Tucson, Arizona, the only company
currently producing solar panels for ballooning. Suncat uses SunPower\textsuperscript{15} solar cells which provide 20\% efficiency, a measurable improvement above the previous generation’s efficiencies of 13-14\%. The solar cells are encapsulated in a laminate stack with a honeycomb backing for support of the cells.

A charge controller is used between the solar panels and batteries to regulate the current and voltage drawn from the solar panels. The most basic type of charge controller charges the batteries at a fixed voltage from the panels. A more sophisticated type of charge controller called a Maximum Power Point Tracking (MPPT) charge controller draws power at different voltages depending on the temperature of the cells to maximize the power the panels can provide.

An overview of the specification of the solar power system is provided in Appendix C.

### Power Budget

Table 3.4 shows the measured consumption of each subsystem in the engineering flight configuration and the anticipated consumption in the long duration configuration. Early in the design of EBEX it became clear that we needed to limit the total power consumed by the instrument for two separate reasons: to limit the weight and solar panel area in the solar power system and to limit the amount of power that is dissipated in the bolometer readout crates, as discussed more below in Section 3.4.4.

### 3.2.8 System-Wide Grounding Scheme

The system-wide grounding scheme is shown in Figure 3-15. The power returns for the two independent EBEX power systems are referenced to each other at a single star grounding point on the gondola so the systems do not float relative to one another. The system-wide grounding scheme is complicated by the use of DC to DC converters

\textsuperscript{15}http://www.sunpowercorp.com
### Table 3.4: Measured consumption in the North American (NA) engineering flight configuration and anticipated consumption in the long duration (LD) configuration.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>NA (W)</th>
<th>LD (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolometer and HWP Readout</td>
<td>321</td>
<td>604</td>
</tr>
<tr>
<td>ACS Sensors and Readout &amp; gondola housekeeping</td>
<td>163</td>
<td>243</td>
</tr>
<tr>
<td>ACS Motors</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Flight Computer &amp; Disk Pressure Vessel</td>
<td>121</td>
<td>166</td>
</tr>
<tr>
<td>Transmitters</td>
<td>95</td>
<td>163</td>
</tr>
<tr>
<td>Cryostat Housekeeping</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>HWP Control</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td><strong>ACS &amp; Gondola Total</strong></td>
<td>427</td>
<td>596</td>
</tr>
<tr>
<td><strong>Cryostat Electronics Total</strong></td>
<td>377</td>
<td>679</td>
</tr>
<tr>
<td><strong>EBEX Total</strong></td>
<td>804</td>
<td>1275</td>
</tr>
</tbody>
</table>

in almost all subsystems which output a power return that is isolated from the input power return, creating many different power return references across the electronics. To simplify the grounding scheme and to ensure the absence of ground loops, each electronics box was designed to contain a single internal star ground point where all of the isolated DC to DC converter output power returns in that box are connected. When possible, the internal ground is isolated from the sub-system enclosure, and if it is not possible, in the case of the cryostat, the bolometer readout crates, and the gyroscope boxes, the enclosure is isolated from the gondola frame using G-10 or Kapton.

Each of the local internal grounds is connected to the same physical point on the gondola at the battery table using braided copper grounding straps wrapped around ferrites. Figure 3-15 shows the subsystems which contain internal star grounds and their connection to the gondola star ground. When operating on the ground, the star ground point is also connected to the building ground.

By strictly following a set of explicit rules about managing grounds within all electronics boxes and cable shields between all subsystems, in the full engineering flight configuration no ground loops were present in extensive tests across the gondola. Additionally, in ground tests the bolometer readout showed no evidence of pollution
by noisy signals from the ACS system, including transients from motors and the switching electronics of the DC to DC converters.

Figure 3-15: The EBEX grounding scheme. Each box contains an internal local star ground for the isolated DC to DC converter power return lines, and that ground is connected to the star ground point on the gondola. The dotted line between the cryostat and the bolometer readout crates indicates a signal reference line. When the gondola is operated in the high bay the star ground is connected to the building ground.
3.3 Warm Optics

3.3.1 Overview

The EBEX telescope is an off-axis Gregorian Mizuguchi-Dragone system. The warm optics include the primary and secondary mirrors and a hexapod for each mirror. The 1.5 m primary mirror was inherited from the Archeops experiment and the secondary mirror was fabricated for EBEX. The warm optics design built on the extensive experience provided by numerous previous and current CMB telescopes. The challenge in the design was to produce a high quality image across a large focal plane while also minimizing polarized systematic effects.

Figure 3-16: Three dimensional CAD drawing of the EBEX mirrors shown with the microwave beam incident on the telescope from the sky propagating to the cryostat window. (Figure courtesy of Huan Tran).

Figure 3-16 shows a three-dimensional computer aided drawing (CAD) of the mirrors and the propagation of the incoming microwave beam from the sky to the
cryostat window. The figure shows that the primary mirror focuses the light to the beam waist in front of the secondary mirror, a characteristic of a Gregorian telescope, and the mirrors form an image of the sky at the cryostat window. Additionally, the figure shows that system is off-axis, since the mirrors are offset from one another along their optical axes, and it is relatively compact. Less obvious in the figure is the small relative tilt in the axis of the secondary mirror relative to the primary, an optical correction referred to as the Mizuguchi-Dragone condition. This correction is implemented to reduce polarized systematic effects, as discussed below in Section 3.3.2.

Figure 3-17 shows a simulated ray diagram of all of the EBEX optics, including the warm mirrors and the cold optics in the cryostat, discussed in detail below in Section 3.4.1.

Figure 3-17: An optical simulation ray diagram showing all of the EBEX optics, including the warm mirrors and the cold optics in the cryostat. (Figure courtesy of Huan Tran).
### Optical Component Property

<table>
<thead>
<tr>
<th>Optical Component</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope Design</td>
<td>Gregorian Mizuguchi-Dragone</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>parabolic, d=1.5 m</td>
</tr>
<tr>
<td>Secondary mirror</td>
<td>ellipsoid, a=110 cm, b=98 cm</td>
</tr>
<tr>
<td>Field of View</td>
<td>6°</td>
</tr>
<tr>
<td>Primary mirror focal length</td>
<td>80 cm</td>
</tr>
<tr>
<td>Effective focal length of the telescope</td>
<td>-198 cm</td>
</tr>
<tr>
<td>Dragone tilt (angle between the primary and secondary symmetry axes)</td>
<td>12.8°</td>
</tr>
<tr>
<td>Displacement of the primary optical axis from the symmetry axis</td>
<td>100 cm</td>
</tr>
</tbody>
</table>

Table 3.5: EBEX warm optics properties.

#### 3.3.2 Polarized Systematic Effects In a Reflecting Telescope

The two polarized systematic effects present in a reflecting system are cross-polarization and instrumental-polarization. The action of cross-polarization is to rotate the incoming polarization vector into some new state. The net consequence of this rotation is to convert the Q and U Stokes vectors into one another, referred to as Q/U mixing. The Q/U mixing results in E-modes and B-modes mixing into one another. Since the E-mode signal is at least one order of magnitude larger than the B-mode signal, the effect of cross-polarization is a significant pollution of the weak B-mode signal by the E-mode signal.

Instrumental-polarization refers to a polarized signal that is generated by the instrument. Oblique reflection off of the conducting surfaces of the primary and secondary mirrors produces instrumental-polarization when one polarization state is preferentially emitted or absorbed by the mirror. The polarization produced by preferential emission only depends on the mirror temperature, which is relatively stable given the large thermal mass of the mirrors. The mirror temperature can be measured, as is done in EBEX, and the signal from polarized emission can be fit out in data analysis if necessary [34]. In Section 6.1, we discuss the characterization of scan synchronous temperatures changes in the EBEX optics. The physics of the
preferential absorption by the mirrors is not as simple and this signal is not as easily removed in data analysis. The net consequence of instrumental polarization is the conversion of the overall microwave intensity, I, into Q or U Stokes vectors. The effect is to convert some of the temperature signal, T, into E-modes and B-modes. Since the temperature signal is larger than the polarized E-mode and B-mode signals by one and at least two more orders of magnitude, respectively, even a small amount of instrumental polarization can significantly pollute the E-mode and B-mode signals.

### 3.3.3 Optics Design Principles

The primary EBEX warm optical design principles are listed below.

1. The telescope has a large enough field of view to accommodate the large EBEX focal plane. Additionally, the image across the focal plane is sufficiently high quality as defined by the high Strehl ratio\(^{16}\) across the focal plane.

2. The optical design minimizes the cross-polarization systematic effect. A number of studies of optical systems for CMB polarization telescopes find that off-axis Gregorian Mizuguchi-Dragone designs provide optimal performance in polarized systematics \(^{25}\). \(^{17}\)

### 3.3.4 Hexapods and Optical Alignment

A hexapod is constructed from two platforms that are joined by six adjustable legs. The EBEX hexapods, one of which is shown in Figure 3-18, are made out of two rings held together by six legs made out of turnbuckles; one of the rings has been machined

\(^{16}\)The Strehl ratio provides a measure of the sharpness of an image formed at the focal plane. It is defined as the ratio of the peak intensity of an image of a point source formed by the optical system of interest at the focal plane to the peak intensity of a diffraction limited image formed by a perfect optical system.

\(^{17}\)It should be noted that, although optical simulations show that the amount of cross-polarization in an on-axis reflector system is lower at the center of the focal plane, the cross-polarization at the edges of the focal plane, where the majority of the detectors lie, is comparable in on-axis and off-axis systems. \(^{63}\).
into a “u” shape to reduce weight. The full ring mounts to the mirror while the other one mounts to the gondola using custom aluminum brackets. Figure 3-1(a) shows the hexapods in place on the gondola before the mirrors have been mounted.

Building an Aligned Optical System using the Hexapods

A hexapod was chosen for mechanical support and alignment of the mirrors since it provides repeatable placement of the mirrors through measurable and easily accessible adjustments of the hexapod legs. Given the fixed position of the cryostat, the secondary hexapod is aligned relative to the cryostat, and then the primary hexapod is aligned relative to the secondary. Custom software containing an alignment algorithm allows for the alignment of the EBEX mirrors given various measured leg lengths and
distances between tooling balls. A detailed description of the hardware, the procedure for building an aligned optics system, and the performance of the alignment procedure is described in Appendix D.

Alignment pins and bushings have been installed in the cryostat and the inner frame octagon, respectively. This allows for repeatable placement of the cryostat in the inner frame in the event that the cryostat needs to be removed from the instrument after the optics have been aligned.

3.3.5 Evaluation of the Deformation of Inner Frame With Elevation Change

During the Ft. Sumner integration we made measurements to characterize the amount by which the inner frame tower deforms as the inner frame elevation angle changes over the full elevation range. We used an inside micrometer to measure the distance between a tooling ball\textsuperscript{18} on the front of the primary mirror and tooling balls on the left and right sides of the secondary mirror. Figure 3-19 shows the configuration of the gondola and the measurements completed. All shear panels on the side of the inner frame tower were in place but some panels were missing from the top, front and back of the tower, some of which impede the measurement with the inside micrometer. The missing panels provide shear support primarily in the left/right direction and against twisting. The results, shown in Figure 3-20, indicate that on the right side of the gondola no significant deflection was measured, but on the left there was a large deflection of 63.5 mils over the 47 degree elevation range. This suggests some twisting of the inner frame. Surprisingly, the elevation actuator is located on the left side where the significant deformation occurred.

The 63.5 mil deflection is an order of magnitude greater than the expected trans-

\textsuperscript{18}A tooling ball is a precision sphere mounted to a cylindrical pin that can be installed in a surface for precision distance measurements to that surface using an inside micrometer.
Inner Frame Slump Measurements

Ft. Sumner Measurements:

• Used the inside micrometer to measure the distance between a tooling ball on the front of the primary to tooling balls on the left and right side of the secondary.

• All measurements were taken with the same configuration—Britt on the scaffold by the primary and Michele perched on the quills near the secondary.

• Caveat: We didn’t have many of the upper shear panels installed but with them in, we couldn’t make the measurement.

Figure 3-19: The configuration of the gondola when inner frame deformation measurements were performed. The distances that were measured are labeled. Not that a number a shear panels on the top, front and back of the inner frame tower are not mounted.

...lication of the secondary mirror along the axis of the inner frame tower, based on simulations performed by SSL. The simulations showed that, over a theoretical 90° inner frame elevation change, the expected displacement of the secondary mirror position in the dimension along the inner frame tower is 4 mils, based on a finite element analysis of the gondola CAD model, or 1 mil, based on a hand calculation. However, it is unclear if the measurements show translation of the secondary mirror along the tower or some combination of a different translation, a tilt, or a twist.

One way to interpret the significance of the displacement of the secondary relative to its nominal in-focus position is that the displacement induces an error in the gondola pointing that depends on inner frame elevation angle. A hand calculation shows that a displacement of the secondary mirror from its nominal position by 63.5 mils in any direction is equivalent to a pointing error of about 8’ which, as discussed
Figure 3-20: Results of measurements between a tooling ball on the primary mirror and tooling balls on the left and right sides of the secondary mirror to assess the deformation of the inner frame over the full inner frame elevation range. An angle of 0° corresponds to an upright inner frame.

below in Section 3.5.7 is about 50 times larger than our required pointing. This error will enter into the data timestream as a systematic error. Early in the long duration integration we will repeat the measurements described above with all possible shear panels installed to assess if modifications are required to stiffen the inner frame, or if an elevation dependent pointing model should be implemented.
3.4 Cryostat and Receiver

3.4.1 Cryostat and Cold Optics

The EBEX receiver is housed in a liquid nitrogen and helium cryostat\(^{19}\) shown during installation in Figure 3-21(a). The drawing in Figure 3-21(b) shows a cutaway of the cryostat, including the window and the internal optics such as filters, lenses, polarimetry hardware, the focal planes, the superconducting quantum interference device (SQUID) amplifier boards, and the refrigerator.

\(^{19}\)The cryostat was machined and assembled at Precision Cryogenics, http://www.precisioncryo.com/
Overview

CMB photons enter the cryostat through a 30 cm diameter window made from ultra high molecular weight polyethylene (UHMWPE). During the engineering flight a single thick window was used, however for the long duration flight we will implement a double window mechanism. Both a thick and thin window will be in place on the ground where the pressure differential between the ambient atmosphere and the evacuated cryostat is high. At stratospheric altitudes the thick window will be displaced, leaving behind a thinner window to significantly reduce the loss of signal due to absorption. Below the window, a stack of thermal (labeled Therm1 through Therm4) and low-pass edge (labeled LPE1 to LPE2b) metal mesh filters are distributed amongst the 300, 77, and 4 K cryogenic stages, shown in Figure 3-22(a) to minimize the thermal load on the cryogens.

Figure 3-22: a: Drawing of the EBEX thermal (Therm) and low-pass edge (LPE) filters and lenses in the engineering flight configuration. (Drawing courtesy of Asad Aboobaker). b: The EBEX optics box. (Photo courtesy of Asad Aboobaker).

A cold Lyot stop at 4 K is located at the top of the optics box, shown in Figure
to minimize the presence of sidelobes in the beam. At the stop a continuously rotating half-wave plate (HWP) modulates the polarization. Next, a polarizing grid oriented at 45° to the incoming beam splits the radiation into horizontally and vertically polarized components before the radiation is incident on one of the two identical focal planes. Metal mesh band-defining filters at 150, 250 and 410 GHz are located on the top of the focal planes, shown in Figures 3-23(a) and 3-23(b); the bandwidth of each filter is about 20%, shown in Table 3.6. Below the filters the radiation couples to smooth-walled conical feedhorns, a cylindrical wave guide, and the bolometric detector array. Re-imaging lenses made out of UHMWPE are mounted above the cold stop and in the optics box to produce an image on the flat focal plane. Figure 3-17 includes a ray diagram which shows the propagation of CMB photons from the sky to the focal plane.

Temperature stages at 300 K, 240 K, 77 K, 30 K and 4 K are achieved by the nitrogen and helium cryogens and the capture of their boil-off. A helium-4 closed-cycle adsorption refrigerator 20 cools the the optics box, shown in Figure 3-22(b), to

\[\text{20Refrigerators are designed and fabricated by Simon-Chase Research,}\]

\[\text{http://www.chasecryogenics.com}\]
<table>
<thead>
<tr>
<th>Nominal Band Freq (GHz)</th>
<th>Center Freq (GHz)</th>
<th>Bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>153</td>
<td>40</td>
</tr>
<tr>
<td>250</td>
<td>253</td>
<td>71</td>
</tr>
<tr>
<td>410</td>
<td>408</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 3.6: Theoretical EBEX frequency bands.

1 K to reduce thermal loading on the focal plane. A pair of helium-3 closed-cycle refrigerators holds the focal plane at about 300 mK\(^{21}\).

**Optical Performance**

As discussed above in Section 3.3.1, the EBEX warm optical design provides for low cross-polarization and high image quality across the focal plane, as encoded in Strehl ratios at or above 0.9\(^{22}\). Diffraction-limited optical performance is achieved across the focal plane in all bands by designing for the same beam size at all frequencies. The conical feedhorns fill a smaller fraction of the primary aperture in the higher frequency bands, and additionally, the highest frequency band detectors are placed in the center of the focal plane where the optical quality is highest.

The cold optics alignment is verified using coordinate-measuring machine (CMM) measurements of the relative positions of the focal plane and lenses to reference points external to the cryostat, which allows for indexing of the cold optics to the warm optics. Before the engineering flight, CMM measurements showed that the optical alignment of all cold optics components was within 5 mils in translation and 0.1° in rotation of the nominal positions in the optics model.

\(^{21}\)The combination of two helium-3 refrigerators and one helium-4 refrigerator is referred to as a helium-10 refrigerator.

\(^{22}\)This Strehl ratio is valid for all the detectors included in the EBEX sensitivity estimates.
Thermal Loading on the Cold Stages

The large EBEX focal plane requires the use of large optical components. A significant thermal gradient is established between the center and edge of large optics made out of thermally insulating materials such as polypropylene and UHMWPE. For example, we measured a 5 K temperature gradient across the field lens and we estimate a 10 K gradient across LPE1. Consequently, these components generate a thermal load on the cryogenics, reducing the time before the cryogen volume boils off, referred to as the hold time. For the long duration flight we are implementing design modifications to meet the hold time requirement of two weeks. Before the engineering flight we added a teflon filter and we installed copper straps at the periphery of the teflon filter and the lenses to improve heat sinking to the cryogenic stage. Also, the aluminum frame that supports the filters is being replaced with copper to remove heat from this stage more efficiently, and we are investigating the potential for modifications in the filter edge frequencies and materials.

3.4.2 Polarimetry

Half-Wave Plate and Analyzing Grid

The polarimetery is achieved using a HWP modulator and a wire grid analyzer. The HWP, made of birefringent crystal, produces a phase difference of $\pi$ between the horizontally and vertically polarized components of incoming light, defined relative to the active axis of the wave plate. When a constant polarization is incident on a HWP rotating at a frequency $f$, the output electric field vector is rotated at a rate of $2f$, and the polarization rod is rotated at $4f$. Figure 3-24 shows how a constant input polarized signal would appear after being detected downstream of a wire grid analyzer. The amplitude of the detected signal is determined by the intensity and polarized fraction of the incoming radiation and the phase of the signal corresponds to the input polarization angle. Although the HWP thickness must be tuned to the
particular frequency of incident light, the EBEX HWP is made broadband using five layers of sapphire crystal with active axes rotated $^{23}$ with respect to one another and bonded using polypropylene. The resulting predicted modulation efficiency of the EBEX achromatic HWP is 98% from 120 to 450 GHz.

![Figure 3-24: Polarization modulation with a HWP rotating at f and analysis using a wire grid polarizer produces a polarized signal which is modulated at 4f. (Drawing courtesy of Johannes Hubmayr).](image)

The EBEX HWP, shown in Figure [3-25], is placed at the 4 K cold stop to minimize polarized systematics. To allow for rotation at cryogenic temperatures, where mechanical bearings show prohibitively high friction, a superconducting magnetic bearing consisting of a magnet ring and a high temperature superconductor is used. An actuator, driven by a motor outside of the cryostat, rotates the plate via a tensioned kevlar belt, and an encoder records the angular position of the plate.

In post-flight data analysis, described in Section [6.2.4], a template of the HWP motion is produced using the HWP encoder data. The polarized signal is extracted from the raw data by multiplying the HWP template by the raw data time stream, referred to as demodulation; see for example Johnson et al., 2007 [35]. The EBEX HWP rotated at 2 Hz during the engineering flight and it will rotate at 6 Hz during the long duration flight.

$^{23}$The relative rotation axes from on surface to another are 0°, 25°, 88°, 25°, and 0°.
Advantages of HWP Modulation

The purpose of HWP modulation is to mitigate systematic effects and to reduce noise. Any polarized or unpolarized signal resulting from systematic effects generated by cryostat components downstream of the HWP will be rejected by the demodulation process since these signals will not be changing at 4f. Additionally, rotating the polarization vector allows for independent measurements of the I, Q and U Stokes parameters at each detector during a single pointing at each pixel on the sky, eliminating the need to difference detectors which may have varied gains, absolute calibrations, beams, and noise characteristics. The CMB polarization signal generated by HWP modulating azimuth scans on the sky will appear in the sidebands of the 4f modulation signal, above the $\frac{1}{f}$ knee in the detector noise spectrum. Additionally, any noise sources present at frequencies other than 4f will be rejected by demodulation; signals that may arise from the HWP motor and other rotation hardware will reside at f and 2f.
3.4.3 Bolometric Detector Arrays

The EBEX Detector Wafers

The bolometric detectors are tightly packed into arrays, shown in Figure 3-26, where the drawing shows 7 detector wafers assembled on one of the two identical focal planes. The wafers, designed and fabricated at the University of California at Berkeley, are produced using thin film deposition and optical lithography on silicon.

Figure 3-26: *Left:* A drawing of the EBEX detector wafers on one of the two identical focal planes, with color coding to indicate the frequency of the band-defining filter above the detector. A Strehl ratio of 0.9 or above is achieved at detectors within the black circle. *Middle:* A decagon detector wafer. *Right:* A single detector. (Figure courtesy Clayton Hogen-Chin, photos courtesy of Xiaofan Meng).

The Transition Edge Sensor (TES) Bolometers

Figure 3-27(a) contains a conceptual schematic of a bolometer. A piece of absorbing material with heat capacity, C, is connected to a thermal bath with a temperature $T_0$ through a thermal link with conductivity G. The size of the absorber is constrained by the observation frequency. Power incident on the bolometer from the sky, $P_{in}$, is absorbed by the material and its temperature changes to T. A piece of super-
conducting material which is thermally linked to the absorbing material is used to sense the small change in temperature. If the superconductor is electrically biased in a state of transition between superconducting and normal, then a small change in the input power will result in a small change in temperature, but a large change in resistance, shown in Figure 3-27(b). Since the bias voltage is constant, the large resistance change results in a large change in current through the bolometer which is measured by the SQUID series arrays, highly sensitive low-noise current amplifiers.

An EBEX TES bolometer is shown in the right panel of Figure 3-26. The metalized silicon nitride spider web absorber is designed for low heat capacity, and thus a fast optical time constant, and reduced susceptibility to a cosmic ray hit. Silicon nitride legs provide the thermal link between the absorber and the focal plane heat sink. The aluminum/titanium TES is connected to superconducting leads that extend to the wafer periphery and to the gold ring which is visible in the middle of the detector, used to increase the sensor heat capacity to provide stability. The properties of the EBEX bolometric arrays are summarized in Table 3.7. The predicted noise per detector and
per band during a 14-day long duration flight are shown in Table 3.8.

<table>
<thead>
<tr>
<th>Component</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of detectors per array</td>
<td>139</td>
</tr>
<tr>
<td>Number of arrays per focal plane</td>
<td>7</td>
</tr>
<tr>
<td>Number of detectors per focal plane</td>
<td>973</td>
</tr>
<tr>
<td>Number of focal planes</td>
<td>2</td>
</tr>
<tr>
<td>Number of detectors available for readout(^a)</td>
<td>1946</td>
</tr>
<tr>
<td>Detector spacing on the array</td>
<td>6 mm</td>
</tr>
<tr>
<td>Design conductivity (G)</td>
<td>21 (\frac{pW}{K})</td>
</tr>
<tr>
<td>TES normal resistance</td>
<td>1 (\Omega)</td>
</tr>
<tr>
<td>TES transition temperature</td>
<td>(\sim 500 \text{ mK})</td>
</tr>
</tbody>
</table>

\(^a\) Each focal plane can accommodate up to 973 detectors with a total of 1946 detectors available for readout. However, not all of these detectors are included in the total number of light detectors elsewhere in this document since the Strehl ratio at some detectors is below 0.9 and the readout electronics may not be able to accommodate the large number of signals.

Table 3.7: Summary of the properties of the EBEX detector wafers.

| Nominal Band Freq (GHz) | # Detects (Light) in LD Flight | \(\frac{\text{NEQ|U}}{\text{band}}\) (\(\mu K\) \(\sqrt{\text{Hz}}\)) | \(\frac{\text{NET}}{\text{band}}\) (\(\mu K\) \(\sqrt{\text{Hz}}\)) | \(\frac{\text{NEQ|U}}{\text{detector}}\) (\(\mu K\) \(\sqrt{\text{Hz}}\)) | \(\frac{\text{NET}}{\text{detector}}\) (\(\mu K\) \(\sqrt{\text{Hz}}\)) |
|-------------------------|-------------------------------|--------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 150                     | 752                           | 136                                              | 96                              | 5.0                             | 3.5                             |
| 250                     | 376                           | 282                                              | 199                             | 14.5                            | 10                              |
| 410                     | 278                           | 2180                                             | 1538                            | 131                             | 92                              |

\(^a\)The noise equivalent temperature (NET) is the thermodynamic temperature at the input of the optical system that will produce a signal comparable to the detector noise in a 1 Hz band.

\(^b\)The noise equivalent Q and U (NEQ and NEU) are the comparable input polarized signal that will produce a signal comparable to the detector noise in a 1 Hz band.

Table 3.8: Total number of detectors exposed to light and read out (using a multiplexing factor of 12) during the long duration flight and detector sensitivities. The noise/band is based on a 14-day long duration flight and only includes detectors with a Strehl ratio of 0.9 or above.
3.4.4 Bolometer Readout Electronics

The bolometer readout electronics, designed at McGill University, provide a bias voltage to hold each TES at a particular location in the superconducting transition, and they sense the change in TES resistance to provide a measure of the input power. The signals from many bolometers are frequency multiplexed which reduces the total number of wires into the cryostat to limit the heat load on the cryogens, and the number of readout electronics boards to significantly decrease the instrument power consumption.

![Figure 3-28](image)

Figure 3-28: Schematic of the bolometer readout electronics including the DfMUX boards and SQUID boards. Color coding indicates the associated temperature stage.

Figure 3-28 shows a schematic of the readout electronics with color coding to indicate the corresponding temperature stage. A field programmable gate array (FPGA) on the digital frequency multiplex (DfMUX) board generates the constant amplitude AC voltage bias across the bolometers and the inductor (L)/capacitor(C) resonator; the unique value of LC at each bolometer sets the AC bias frequency. The FPGA also generates a $180^\circ$ phase-shifted bias signal used for nulling the signal read out by the SQUID array to maintain the SQUID amplifier dynamic range. Finally, the
signal measured by the SQUID array is demodulated and the DfMUX board outputs a digitized signal. During the engineering flight the bolometers were multiplexed in groups of 8 and a multiplexing factor of 12 or 16 is planned for the long duration flight; all numbers quoted above assume a multiplexing factor of 12.

The DfMUX boards, which dissipate a significant amount of power, are distributed over four electronics crates. Each board is well heat sunk to a plate at the back of the crate and heat is conducted to the gondola and radiated to the sky; convection is negligible at stratospheric altitudes where the pressure is about a thousandth of an atmosphere. Thermal simulations show that the steady state crate temperatures are near, but below, the maximum operating temperature of the boards. Temperature measurements made during the North American engineering flight, discussed below in Section 5.4.1 show that some board temperatures at stratospheric altitudes are warmer than expected.
3.5 Attitude Control System

3.5.1 System Overview

The EBEX Attitude control system (ACS) performs two primary functions. The ACS sensors provide the gondola heading and the control system electronics move the gondola so the telescope scans across the sky as specified by the scan strategy, described in Section 2.4.2.

![Diagram of the EBEX ACS electronics](image)

Figure 3-29: Overview of the EBEX ACS electronics (shaded in grey) and color coding of signal and power lines.

Figure 3-29 shows the ACS electronics (shaded in grey) and associated electronics, with color coding of the signal and power lines. A variety of sensors are required to achieve both real-time and reconstruction pointing solutions since no single sensor is highly accurate, absolute, and may be read throughout a scan. Three motors provide stepped control in elevation and fine tuned azimuth control. Table 3.9 provides a summary of the properties of each sensor, and below in Section 3.5.5 we detail the properties of each sensor.
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Absolute?</th>
<th>Accuracy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetometer</td>
<td>Absolute</td>
<td>~0.5-4°</td>
<td>Requires magnetic model for absolute heading</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>12’</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>Absolute</td>
<td>~20’ (Az, El); 40’ (Roll)</td>
<td>Heading has not been reliably demonstrated; very reliable in time and location</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>Absolute</td>
<td>~1°</td>
<td>Mixed reliability</td>
</tr>
<tr>
<td>Clinometer</td>
<td>Absolute</td>
<td>1’</td>
<td>Can only be used reliably for static measurements</td>
</tr>
<tr>
<td>Star Camera</td>
<td>Absolute</td>
<td>~5” (Az, El); ~3’ (Roll)</td>
<td>Long integration time so cannot use during a scan</td>
</tr>
<tr>
<td>Gyroscopes</td>
<td>Relative</td>
<td>~ 11°a</td>
<td>Provides rate, not position.</td>
</tr>
<tr>
<td>Rotary Encoder</td>
<td>Relative</td>
<td>20°</td>
<td>Index inner and outer frames</td>
</tr>
</tbody>
</table>

*a*Maximum RMS error on integrated gyroscopes during a scan.

Table 3.9: ACS sensor properties including whether the sensor is absolute or relative and the sensor accuracy.

### 3.5.2 Overview of Real-Time and Reconstruction Pointing

- **Real-Time Pointing:** During the flight, data from a variety of sensors, many of which are redundant to allow for the possibility of sensor malfunctions, are combined to provide a real-time pointing solution. A differential GPS system, a three-axis magnetometer, a sun sensor, and a pair of redundant star cameras along with the integrated rate data from two redundant sets of three orthogonally positioned gyroscopes provide gondola azimuth, elevation and roll, or in the case of the star camera, RA, Dec, and roll. The gyroscope rate data is used for feedback in the control loop, described below in Section 3.5.7.

- **Reconstruction Pointing:** To obtain the reconstruction pointing solution the data from the above sensors is combined in a weighted average, with the star camera and gyroscope data dominating the average when all sensors are working properly. Redundant star cameras and gyroscope boxes are mounted to the inner frame, allowing for the simplest indexing of the pointing to the microwave beam. The outer frame
is indexed to the inner frame using a rotary encoder. Table 3.10 indicates the mount location and sensitive axes of each sensor.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sensitive Axes</th>
<th>Mount Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyro 1 and 4</td>
<td>Az</td>
<td>Inner Frame</td>
</tr>
<tr>
<td>Gyro 2 and 5a</td>
<td>Telescope El</td>
<td>Inner Frame</td>
</tr>
<tr>
<td>Gyro 3 and 6a</td>
<td>Roll</td>
<td>Inner Frame</td>
</tr>
<tr>
<td>Rotary Encoder</td>
<td>Relative El</td>
<td>Intersection of Inner and Outer Frames</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>Az</td>
<td>Outer Frame</td>
</tr>
<tr>
<td>OF Clinometer</td>
<td>Platform El &amp; Roll</td>
<td>Outer Frame</td>
</tr>
<tr>
<td>IF Clinometer</td>
<td>Telescope El &amp; Roll</td>
<td>Inner Frame</td>
</tr>
<tr>
<td>Differential GPS</td>
<td>Az, Platform El &amp; Roll</td>
<td>Rotator</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>Az</td>
<td>Triangle Spreader</td>
</tr>
<tr>
<td>Star Camera 1</td>
<td>Az, Telescope El &amp; Roll</td>
<td>Inner Frame</td>
</tr>
<tr>
<td>Star Camera 2a</td>
<td>Az, Telescope El &amp; Roll</td>
<td>Inner Frame</td>
</tr>
</tbody>
</table>

*a This sensor was not present during the engineering flight.

Table 3.10: Sensitive axes and locations of the ACS sensors. Platform El is the elevation of the outer frame relative to the local gravity vector, Relative El is the relative elevation between the inner and outer frames, and Telescope El is the elevation of the telescope relative to the local gravity vector.

In Section 3.5.7 below we detail the computation of the real-time and reconstruction pointing solutions and the control of the gondola.

### 3.5.3 Required Pointing Accuracy and Indexing to the Microwave Beam

The required pointing accuracy in real-time, 0.5°, is coarse since the instrument observes extended, not point, sources. This 0.5° requirement ensures that time spent scanning calibrator sources is reasonable. In reconstruction, however, detailed calculations have shown that a pointing accuracy of 9" is required to achieve the EBEX science goal.24 Accurate attitude information for the telescope on the timescale of the detector read out is essential since position information on the sky is required for

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24 The calculations are detailed in an internal memorandum by Zaldarriaga and Leach.64
making maps and power spectra. The reconstruction pointing requirement drives the choice of sensors and the reconstruction strategy, described below in Section 3.5.7, where the star camera and gyroscope box play a crucial role.

In order to obtain a pointing timestream for the microwave beam the pointing sensors must be indexed to the microwave beam. A coarse indexing between the microwave beam and the star camera is performed on the ground in the high bay before the flight, described in Section 4.3.1, to insure that during the flight calibration sources are scanned with the appropriate coverage. In reconstruction, scans of calibrator sources provide absolute pointing for the microwave beam, and this pointing is compared with the reconstruction pointing solution relative to the star camera boresight. The other sensors are then indexed to the star camera, as described in Section 4.3.1.

3.5.4 ACS Crate and Readout Cards

ACS Readout Cards

The system-wide functions of the ACS crate are described in Section 3.2.1, including power conditioning and implementation of the discrete on/off commands provided by CSBF. The ACS crate, the flight computers, and the flight control program (fcp) provide all ACS sensor read out and control signal output to the motor control boxes. Each ACS card contains analog input channels, voltage excitation for read out of AD590\(^{25}\) temperature sensors, digital input/output channels, pulse width modulated (PWM) outputs, a field programmable gate array (FPGA), and a digital signal processor (DSP). A proprietary bus provides communication with the flight computers via the two PCI cards in the flight computer crate.

Filtering, Noise Reduction, and Grounding

Measurements performed during the integration of the ACS showed two dominant sources of noise in the analog signal channels: noise induced by the switching electronics in the DC to DC converters, and pickup of the digital gyroscope signals on the analog signal lines. Even after implementation of a variety of measures to reduce the noise\(^{26}\), the clinometers and magnetometer, both powered by the same 12 V DC-DC, showed susceptibility to these noise sources. However, the noise in the signals is low enough that the accuracy of these sensors is not limited by noise.

### 3.5.5 ACS Sensors

#### Star Camera

The EBEX star camera provides high accuracy measurements of RA and Dec (5") and less accurate measurements of roll (3") during both the day and night. Due to loading from the atmosphere, on the ground the camera can only be used at night. The camera design builds on the extensive experience of previous balloon projects, most notably the Balloon-borne Large Aperture Sub-millimeter Telescope (BLAST). The star camera electronics and optics include a lens\(^{27}\), a focus and aperture controller\(^{28}\), a charge-coupled device (CCD)\(^{29}\) detector built into the camera body, a camera controller\(^{30}\) a computer, and heaters; the camera properties are summarized in Table 3.11. The components are mounted to a frame inside a cylindrical pressure vessel. One of the vessel end flanges contains a quartz window and the other contains a valve and connectors, including an ethernet connection out to the flight computer crate and a power and signal connector for a cable out to the ACS crate. The vessel

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\(^{26}\)Noise reduction measures included adding RC filters across the outputs of the DC to DC converters, wrapping the output lines of the DC to DC converters through ferrites, and physically segregating analog signal lines from the gyroscope digital lines.

\(^{27}\)Canon EF 200 mm f/1.8, http://cannon.com

\(^{28}\)Birger EF-04571, http://www.birger.com

\(^{29}\)Kodak KAF 1603E/ME, http://www.kodak.com

\(^{30}\)Redlake MegaplusII 1603, http://www.redlake.com
is pressurized near 1 atmosphere with nitrogen gas to prevent condensation on the lens during ascent and to allow for use of standard hard disks. The star camera is mounted to the inner frame, shown in Figure 3-30, with its beam coarsely aligned with the microwave beam.

Figure 3-30: The star camera, with the baffle shown in white, and the gyroscope box mounted to the outside of the inner frame. The star camera is mounted so that its beam is coarsely aligned with the microwave beam.

To obtain a pointing solution, the star camera acquires an image of the sky on the CCD, the image is digitized by an analog to digital converter (ADC) in the camera, and the data is read into the computer. Custom software running on the computer contains a centroiding algorithm which identifies regions in the image with higher intensity than the background sky signal, considered noise, with some minimum signal to noise ratio; these are interpreted as star positions. Next a custom solving program attempts to match the relative star positions in the acquired image with known star positions in images in a star catalog. The solver algorithm uses an initial guess of the gondola heading provided by $fcp$ from coarse sensor data, and a specified search radius around the guessed heading defining the area over which to search for an image
Component | Property
--- | ---
Lens radius | 5.55 cm
Pixel size | 9 µm x 9 µm
Field of view | 4.05° x 2.70°
CCD well depth | 100 kiloelectrons
Magnitude limit | 7.3
Average # Stars centroided (sparse region/dense region) | 4/12
RMS reconstruction Error on RA and Dec | ~5”
RMS reconstruction Error on roll | ~3’

Table 3.11: Properties of the star camera optics and electronics and the expected camera performance, including the magnitude limit, the number of stars successfully centroided in a field, and the RMS reconstruction error. The magnitude limit and average number of stars centroided assumes a typical flight integration time.

match. If the image is successfully matched to a star catalogue image, the RA, Dec and roll of the center of the field are recorded and output to the the flight computer. If no match to that image is found in the catalog within a specified time the solving operation is terminated.

Star camera images are downlinked to the ground on a line of sight transmitter, as described in Section 3.2.4, when communication is available. Although the image quality is generally moderate to poor, the image can be useful for determining appropriate camera parameters. Many camera and solution parameters can be commanded from the ground, including the focus position of the lens, the aperture size, the integration time (duration of the shutter opening), the radius over which the solver searches for matches to the star catalogue, and various matching tolerances. Additionally, an autofocus algorithm allows the camera to be focused without feedback from the ground.

Threads in fcp perform all handshaking between the flight computer and the star camera and merging of the star camera pointing solution into the data stream. The camera shutter is opened when fcp commands the ACS to send a trigger signal to the camera. Since images acquired while the gondola is moving above some threshold velocity are blurred and the signal is spread over a larger number of pixels, making
the centroiding algorithm less effective, the trigger command is sent by \( fcp \) only when the gondola speed and acceleration are below specified values, as discussed in Section 4.3.2.

Preliminary tests of the camera on the night sky show an RMS error of 6". We can make predictions about the EBEX star camera performance by comparing the EBEX camera design with that of the BLAST camera, which achieved an accuracy of \(< 5"\) in flight during the day and night \([52]\). Based on comparisons of the lens size, pixel size, focal plane size, camera field of view, and CCD well depth\(^{31}\) and ADC precision, the EBEX camera signal to noise is expected to exceed that of the BLAST camera \([8]\).

**Fiber Optic Gyroscopes**

*Overview of the Sensor Functionality and Principle of Operation*

Each fiber optic gyroscope\(^{32}\) provides high precision angular rate data on a single axis; the gyroscopes are insensitive to translational motion. Three gyroscopes are mounted in the same box, shown in Figure 3-31(a). When the box is mounted to the inner frame, shown in Figure 3-30, the set of gyroscopes is sensitive to rotations of inner frame azimuth, elevation and roll. The clock, data, and synchronization signals output by each gyroscope are driven over the line to the ACS crate using Schmidt trigger inverter integrated circuits soldered to a board in the box, shown at the top of Figure 3-31(a). Each digital signal is read into a different digital input channel on an ACS card. The box also contains a power resistor heater controlled by a solid state relay commanded by the ACS card which can be set to a target temperature to ensure the box does not cool below the minimum specified operating temperature of the gyroscopes. The gyroscope cases are connected to the power return line, so a Kapton sheet and nylon shoulder washers were used for mounting the box to the

\(^{31}\)The CCD well depth is a measure of how many electrons may be collected in a well before saturation.

\(^{32}\)KVH DSP-3000, http://kvh.com
Figure 3-31:  

a The inside of a gyroscope box including three gyroscopes wrapped in magnetic shielding, a DC to DC converter, a power resistor heater controlled by a solid state relay, and a Schmidt trigger inverter board.  
b Conceptual schematic showing the principle of operation of a fiber optic gyroscope. The sensor contains a long fiber optic coil with coherent counter-propagating light beams, shown in red, and a detector to measure the interference pattern of the combined beams, shown in blue.

gondola so no ground loop was created through the gondola.

The sensor consists of a long coil of fiber optic material through which coherent beams of light travel in opposite directions, shown in red in the conceptual schematic in Figure 3-31(b). When the gyroscope casing is rotated around the axis through the coil a path difference is introduced between the two counter-propagating beams, described by the special relativistic Sagnac effect \[44\] \[54\]. When the beams are combined at the detector, shown as a blue dot in the figure, an interference pattern appears and the detected intensity is proportional to the angular speed along the axis through the coil.

Components of the Gyroscope Signals

The angular rate signal output by the gyroscope reflects the real angular motion coupled with offsets, non-linearities, noise, and effects produced by the thermal and
magnetic environment. Much effort was devoted to characterizing the gyroscopes since these sensors play such a central role in the real-time and reconstruction pointing, described in detail below in Section 3.5.7. Since high precision star camera images are acquired at each scan turnaround, the accuracy and noise of the gyroscope readings are most relevant on the timescale of a scan or less. Ultimately, the significance of the gyroscope noise and accuracy is assessed by comparing the integrated gyroscope signal on scan timescales to the reconstruction pointing requirement.

Each gyroscope signal is composed of:

1. The actual rotation of the gyroscope case about the gyroscope active axis (defined as the axis through the fiber optic coil).

2. A bias offset. Measurements of the offset stability over temperature and time are discussed below in this section.

3. Random walk noise with a nearly flat frequency response, including low frequency noise that appears as a bias offset drift. The measured noise is in agreement with the specification of 40 arcsec/sec at the 100 Hz ACS sampling rate. Additionally, measurements show that correlations in the noise are present on short timescales.

4. Revolution of the payload around the earth, which is present on the ground and at stratospheric altitudes.

5. Augmentation of the signal by ambient magnetic fields. A description of the application of Metglas magnetic shielding, and a summary of measurements of the susceptibility of a shielded gyroscope to ambient magnetic fields are discussed below in this section.

6. Small non-linearities in the scale factor over the full range of valid speeds, $\pm 375$ deg/s, and the temperature range. No corrections were made for scale factor

non-linearity since typical gondola speeds during CMB and calibrator scans are about 1 deg/s.

Characterization of the Scale Factor Temperature Dependence

The specified stability of the bias offset is 1 arcsec/s at room temperature and 6 arcsec/s over the full temperature range when the temperature gradient is less than 1 °C/s. We performed two identical overnight tests during which the gyroscopes were placed in a box with dry ice and allowed to cool. We measured a maximum slope of 0.36 arcsec/s °C over a temperature range of 45 °C. This error in speed integrates to an error of about 1” over the time between star camera readings for the largest temperature gradient we expect to encounter at stratospheric altitudes. Since the bias drift error is less than the reconstruction pointing requirement by an order of magnitude, no fine control of the box temperature was implemented.

Susceptibility to Magnetic Fields

An ambient magnetic field causes Faraday rotation of the electric field vectors in the counter-propagating beams in the gyroscope. This induces a phase shift between the beams, altering the interference pattern measured at the detector. Overlapping strips of Metglas magnetic shielding were taped to the gyroscopes to suppress the magnetic field at the gyroscope. To assess the effect of an ambient magnetic field on the gyroscopes and the effectiveness of the shielding, a gyroscope was placed in a Helmholtz coil and exposed to various magnetic field strengths with and without the magnetic shielding in place.

The plot in Figure 3-32 shows the average gyroscope signal at each magnetic field value for an unshielded gyroscope and two trials with a shielded gyroscope. The slopes of the lines in the plot show that the shielding suppresses the magnetic field at the gyroscopes significantly. The worst case error on the integrated gyroscope speed induced by movement through the earth’s field during a full scan is about

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34The gyroscope contains internal intelligence which compensates for the change in bias offset due to temperature change, however the electronics can only accommodate slow temperature changes.
4”, determined using the slope of $0.00064 \text{ deg/s}^G$. Since the integrated error using the larger of the two slopes in the shielded case is a factor of two below the reconstruction pointing requirement, we conclude that no additional shielding is required.

Figure 3-32: Data showing the susceptibility of shielded and unshielded gyroscopes to an ambient magnetic field. The magnetic field was produced by a Helmholtz coil.

**Orthogonalization and Indexing of the Gyroscope Box to the Gondola**

The active axes of the three gyroscopes in a box are aligned with the inner frame azimuth, elevation, and roll axes to an accuracy allowed by the tolerances on the individual sensor alignment within the gyroscope casing, the alignment of each sensor case with the box, and the alignment of the box with the inner frame. Consequently, the active axis of each of the three gyroscopes in a box deviates from the azimuth, elevation, or roll axis of the inner frame by some small arbitrary value. A more precise alignment between the gyroscopes and the inner frame, which can be achieved in software rather than by remounting the box, is required to meet the reconstruction pointing requirement.
Precision indexing of the gyroscopes to the inner frame is achieved in two steps:

1. Perform measurements to define a transformation matrix which will transform the gyroscope measured speeds into an orthogonal frame, referred to as an orthogonalization matrix.

The orthogonalization matrix, shown in Equation 3.1 as $\hat{O}$, converts the speeds measured along the gyroscope active axes, $\omega_1$, $\omega_2$, and $\omega_3$, to speeds in an orthogonal frame, $\omega_x$, $\omega_y$, and $\omega_z$. The external orthogonal frame is provided by a precision machined gyroscope box with the outside surfaces machined to be mutually parallel and orthogonal with a surface precision of 0.5 mils.

$$\hat{O}\vec{\omega}_{\text{measured}} = \vec{\omega}_{\text{orthogonal}}$$

$$\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & j \end{pmatrix} \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}$$

We can determine the nine values in $\hat{O}$, a through j, by rotating the precision gyroscope box around the box x, y, and z axes on a smooth and stable surface, such as a machinists table, and computing ratios between the signals of the three gyroscopes. To simplify the computation of the matrix elements we use a small angle approximation for the angle between the box x, y, and z axes and the nearest gyroscope. Additionally, we assume the factory scale factor calibration of each gyroscope, and that the box is perfectly machined.

2. Use star camera and gyroscope data collected during scans on the sky to determine the three angles by which the orthogonal frame must be rotated to line up with the inner frame azimuth, elevation and roll axes.

These angles are computed by performing an optimization on the difference
between the displacement measured by the star camera and the displacement computed by integrating the gyroscopes for the same time segment.

Preliminary data suggests the orthogonalization process described in Step 1 provides good results. However, the quality of the orthogonalization and the indexing of the orthogonal frame to the gondola can only be assessed by comparing integrated orthogonalized and indexed gyroscope data with star camera measurements; these tests are planned for Summer 2010. The error on the matrix parameters that we expect from the box machining tolerance is on the order of $10^{-5}$ in the diagonal terms and $10^{-3}$ in the off-diagonal terms.

We are currently investigating the use of a particle filter, discussed below in Section 3.5.7 to constrain the six arbitrary gyroscope mount angles relative to the gondola without first defining an orthogonalization matrix for the gyroscope box, as described in Step 1 above. Preliminary tests of the filter indicate that this method will yield sufficiently accurate values of the gyroscope mount angles\cite{26}.

**Magnetometer**

A three-axis fluxgate magnetometer\footnote{MEDA TFS-100, http://www.meda.com} is used to measure the azimuth of the outer frame. The magnetometer outputs three analog voltages corresponding to the x, y and z magnetic field flux through the coils in the sensor, and the voltages are read into an ACS card. The sensor unit is mounted to the tip of a fiberglass boom on the front of the gondola so that the x and y axes are coarsely aligned with the elevation and roll axes. A custom printed circuit board (PCB) was fabricated and an aluminum sheet box with mounting brackets and a robust connector was machined and assembled to accommodate the read out electronics which were provided by the manufacturer in a plastic case without mounting hardware or a robust electrical interface; see Figures 3-33(a) and 3-33(b)\footnote{In the case of a level gondola where the magnetometer mounting boom and sensor casing lie in the plane perpendicular to the gravity vector, the}
azimuth is calculated by fcp using the x and y field measurements:

\[ \text{mag}_{az} = \arctan\left( \frac{\text{mag}_y}{\text{mag}_x} \right) + \text{mag}_{model\_dec} \quad (3.2) \]

The z-axis data is not required to obtain a pointing solution if the gondola is balanced and the outer frame table is level.

Figure 3-33: The magnetometer, shown with the custom PCB, aluminum sheet box and connector to allow for robust mounting and electrical connection.

The first term in Equation 3.2 provides the azimuth angle relative to the local magnetic field. The second term, \( \text{mag}\_model\_dec \), is a correction to take into account the difference between the local magnetic north and geographic true north, referred to as the magnetic declination. This correction is provided by a magnetic model, published every 5 years by the National Oceanic and Atmospheric Administration (NOAA) [46], that predicts the declination given the payload latitude, longitude, and altitude. The absolute accuracy of the magnetometer azimuth solution is limited by the accuracy of the world magnetic model. At latitudes encountered in the engineering flight the accuracy is expected to be about 0.5° [24], however the accuracy at Antarctic latitudes, where the magnetic field vector is highly inclined relative to the horizontal plane, absolute accuracies of up to 5° have been demonstrated by previous balloon projects using a similar magnetometer [48].
Although the magnetometer can provide only very coarse absolute azimuth, its relative accuracy is much better. The relative accuracy is constrained by the sensor readout noise and the inherent accuracy of the magnetometer field measurements. During ground characterization of the magnetometer the peak-to-peak noise corresponds to an error of about 10’ in azimuth. The accuracy of the magnetometer field measurement is specified as an error of 0.5% of the field strength and a scale factor non-linearity of 0.01% over the full scale of ±600 mG. The 0.5% error on the field strength dominates over the noise and scale factor non-linearity, producing an error in the magnetometer azimuth of up to 12’.

**Rotary Encoder**

A 16-bit optical absolute rotary encoder\(^{36}\) is mounted at the trunnion bearing, shown in Figure 3-34(a), to provide the relative elevation angle between inner and outer frames. The optical encoder makes use of LEDs and photodiodes to locate the positions of slits of increasingly smaller size, shown in Figure 3−34(b) to determine the angular position to within 1 bit, or 20”. The signal out of the encoder is converted to a parallel signal and each bit is read into a digital input channel on an ACS card. The noise on the signal is typically a single bit.

**Clinometers**

Two-axis clinometer\(^{37}\) measure the elevation and roll of the inner and outer frames. The clinometer makes use of an upright pair of combs of excited electrodes immersed in an electrolytic fluid to sense the tilt of the sensor case with respect to gravity. The unit outputs separate analog voltages that are proportional to the tilt in the elevation and roll directions, and each signal is read into an analog channel on an ACS card. The noise on the raw signals after read out by the ACS is about 0.8’, less than the


sensor accuracy. The inner frame clinometer is mounted to the octagon near the trunnion pin, shown in Figure 3-34(a), and the outer frame clinometer is mounted on the inside of an I-beam in the table.

The clinometer is unable to accurately measure angles in systems that are accelerating in the horizontal direction since the slosh of the electrolytic fluid is interpreted as a tilt; at lower accelerations, 0.001 g of horizontal acceleration corresponds to a milliradian (0.6°) of tilt. The signal induced by fast pendulations is removed by a filter internal to the unit.

The clinometer has a resolution of 0.6’ and a repeatability of 1.2’, and the accuracy is determined by the scale factor linearity. The specified typical non-linearity is 2.5% over the full 50° clinometer tilt span, which corresponds to 1.25° error over the full range. To characterize the non-linearity, clinometer data was collected while the inner frame angle was changed in stepped increments over the full elevation range with the gondola sitting on the ground; the inner frame was stationary during data collection at each step. Figure 3-35 shows the difference between the averaged clinometer angle

---

38 Data provided by an Applied Geomechanics technical note [20]
and the encoder angle at each elevation step plotted against the encoder angle. A 5th order polynomial was fit to the data and this fit was used to create a corrected inner frame clinometer channel, shown in green in the same plot with the encoder subtracted off. The corrected inner frame clinometer channel, with an accuracy of about 3’ over the full elevation range, was used in the real-time pointing solution, described below in Section 3.5.7. The outer frame clinometer was not characterized since the signal was not expected to be used for real-time control or in the reconstruction solution.

Figure 3-35: Data taken while the inner frame was moved over the full elevation range while the gondola was on this ground. The plot shows the difference between the raw clinometer angle (clin) and the elevation encoder angle (enc) in blue, and the corrected clinometer angle (clin_fitted) and the elevation encoder angle (enc) in green. (Plot courtesy of Daniel Chapman.)

GPS

A differential GPS receiver\textsuperscript{39} with four antenna channels provides the payload position, time, and attitude and other derived channels such as the payload vertical speed, the speed over the ground, and the average direction of motion over the ground. The

\textsuperscript{39}Thales ADU5, now a subsidiary of Ashtech, http://www.ashtech.com
receiver also outputs diagnostic data including the number of satellites used in the attitude solution and flags to indicate the reliability of the position data and the attitude data. The data is read into the flight computer over an RS-232 serial cable between the GPS receiver box and the flight computer crate and a thread in \textit{fcp} merges the attitude data into the real-time pointing solution.

The four antennas are mounted in a fixed relative configuration and the array is calibrated so the receiver can provide attitude data; a single antenna channel allows the receiver to provide position and time. Carbon fiber tubes and aluminum brackets were used to build a stiff antenna mount, shown attached to the rotator in Figure 3-36(a). Carbon fiber was chosen for its high strength-to-weight ratio and because it shows minimal expansion or contraction with temperature change. The antennas are mounted to the top of thin aluminum disks to provide shielding from satellite signals that scatter off the gondola towards the antenna. Because the casings of the antennas and the receiver unit are connected to the power return line and the carbon fiber mount tubes were found to be conductive, Kapton sheet and nylon shoulder washers were used for mounting of the components so no ground loops were created through the gondola. The accuracy of the attitude, specified at 20' in azimuth and elevation and 40' in roll, is linearly related to the antenna separation.

The antenna calibration is completed on the ground before the flight using a Windows-based program provided by Thales, the GPS manufacturer. The calibration data is stored on firmware in the receiver unit which is mounted to the outer frame table. During antenna calibration or to obtain attitude solutions the antenna mount must be clear of buildings, trees or other obscurations on the horizon; operationally this the means the instrument must be placed about fifty feet from the high bay building. Time and location information can be received indoors using a GPS repeater. This reciever unit and similar ones have flown on previous balloon payloads with mixed, and often poor performance. Our experience with the receiver, described in Section 4.3.3 has been similar.
Sun Sensor

The custom sun sensor, shown in Figures 3-36(a) and 3-36(b), provides coarse azimuth. The dark squares shown in the photo are filters placed in front of the 12 surface mount photodiode detectors that are mounted around the sensor. The voltage signals from the photodiodes are digitized using an ADC and then they are read into a computer embedded in the sensor. Custom software running on the computer fits the five diode signals to a Gaussian curve in angular space along the sun sensor diodes, and then computes the azimuthal position of the sun relative to the diodes. The embedded computer transmits the azimuth solution and the diode voltage amplitudes to the flight computer over ethernet and fcp subsequently computes the azimuth of the gondola and includes it in the real-time pointing solution.

Before the engineering flight the relative gain of the diodes was calibrated with the sensor off of the gondola. Additionally, tests showed that the diodes on the side and front of the sensor (defined relative to the mount on the gondola) suffered from obscurations and reflections from the gondola so only the back-most five diode
sensors were used in the computation of the azimuth solution. In reconstruction the sun sensor accuracy was about 1° when the solution was expected to be valid, based on the azimuth region and sun elevation. Previous Antarctic flights with this design of sun sensor showed an accuracy of about 5° [52][48].

### 3.5.6 Temperature and Current Housekeeping

#### AD590 Temperature Sensors

AD590 temperature sensors are used to measure the temperatures of the mirrors and gondola and various electronics components. The mounting locations for the AD590s during the engineering flight and the maximum and minimum values reached during the flight are shown in Table 5.3. In some cases the AD590 was epoxied into a small aluminum block and the block was screwed down onto the component to be monitored while in other cases the AD590 was epoxied directly to the component. The AD590s that were not embedded in electronics boxes were soldered to shielded single pair wire, and the wire shield was connected to the sensor case in most cases; tests in the lab before the flight showed that attaching the shield reduced the noise on the signal significantly.

#### Current Monitoring

Currents to the DC-DCs in the ACS crate and the flight computer crate, and to the gyroscope boxes, sun sensor, star camera, and motors, were monitored by measuring the voltage across a low resistance power resistor\(^{40}\) in series with the power return line.

\(^{40}\)The power resistors typically had a resistance of 0.02 Ω.
3.5.7 Pointing Solution Computation and Gondola Control

Real-Time Pointing and Control

*Real-Time Pointing Solution*

The inputs to the real-time pointing solution at a given time are computed using the current absolute sensor readings, the previous headings from those sensors, and integrated gyroscope data to interpolate between the previous and current reading. The absolute sensors provide data at different rates, however the pointing solution is calculated at 100 Hz, the fastest ACS sampling rate. Below we review the steps executed by *fcp* to obtain a pointing solution at a given time, $t$.

1. The previous heading for each absolute sensor is evolved by integrating the gyroscopes over the 0.01 s interval.

2. If a new reading for an absolute sensor is available, the current heading of that sensor is computed as a weighted average of the evolved heading and the current reading; the weight of the evolved solution is lower than that of the new reading since it has been evolved by the gyroscopes. If no new absolute sensor reading is available, the current sensor heading is equated with the evolved heading.

3. The real-time pointing solution is computed by performing a weighted average of all of the current sensor headings. The weights in the average are specified by $\frac{1}{\sigma_{\text{sensor}}^2}$, where $\sigma_{\text{sensor}}^2$ is the sensor variance, determined for each sensor before the flight.

4. If a sensor is judged unreliable it can be vetoed from the pointing solution by the system user in real time by sending a command to *fcp* using *ebexcmd*.

*Azimuthal Control*

Real-time azimuthal control is achieved using motors in the rotator and the reaction wheel. The reaction wheel motor provides fine-tuned control while the rotator
motor provides bursts of torque when large angular accelerations are required, such as at scan turnarounds, to prevent saturation of the reaction wheel. The current to each motor is controlled by a motor controller \[^{41}\] which adjusts the current to the motors based on the PWM value output by the ACS card to the controller.

The reaction wheel is controlled by a proportional integral (PI) loop. P and I are constant terms which are multiplied by functions of the error term, e, described in Equation 3.3; \(v_{\text{req}}\) is the azimuth speed requested by \(fcp\) and \(v_{\text{actual}}\) is the estimated actual azimuth speed measured by the gyroscopes. The error term is written in terms of the azimuthal speed, rather than position, since the goal of the feedback loop is for the gondola to scan back in forth in azimuth at a nearly constant speed. The value of P determines the weighting of the error at the current time and the I term weights the cumulative errors over some timescale, \(\tau\). The requested system response, R, is computed by Equation 3.4; the PWM to the motor controller, PWM\(_{\text{reac}}\), and the current to the motors, Current\(_{\text{reac}}\), are linearly proportional to \(R_{\text{reac}}\).

\[
e(t) = v_{\text{req}}(t) - v_{\text{actual}}(t) \quad (3.3)
\]

\[
\text{PWM}_{\text{reac}}(t) \propto \text{Current}_{\text{reac}}(t) \propto R_{\text{reac}}(t) = P_{\text{reac}}e(t) + I_{\text{reac}} \int_{t-\tau}^{t} e(t')dt' \quad (3.4)
\]

The rotator response is controlled by a simple P feedback loop which limits the speed of the reaction wheel. The error term, shown in Equation 3.5, is the difference between the current reaction wheel speed, \(v_{\text{reac}}\), and the reaction wheel set point speed, \(v_{\text{reac set}}\), chosen to prevent reaction wheel saturation. The P feedback loop is shown in Equation 3.6; the PWM to the motor controller, PWM\(_{\text{rot}}\), and the current

\[^{41}\]The AMC dr100re20A8bdc (http://www.a-m-c.com) drive was used during the engineering flight along with a filter board that converts the PWM signal out of the ACS card to an analog signal, which is required by the controller. We are currently testing an AMC controller which uses a PWM as the input control signal for the the long duration flight.
to the motors, $\text{Current}_{\text{rot}}$, are linearly proportional to $R_{\text{reac}}$.

$$e(t) = v_{\text{reac}}(t) - v_{\text{reac set}}(t)$$  \hspace{1cm} (3.5)

$$\text{PWM}_{\text{rot}}(t) \propto \text{Current}_{\text{rot}}(t) \propto R_{\text{rot}}(t) = P_{\text{rot}} e(t)$$  \hspace{1cm} (3.6)

**Elevation Control**

The real-time elevation is controlled by a simple P feedback loop where the error term, shown in Equation 3.7, is the elevation requested by $fcp$, $e_{\text{req}}$, minus the current elevation estimated by the real-time pointing solution, $e_l$. A PWM signal, $\text{PWM}_{\text{el}}$, from the ACS card into the motor controller determines the current to the elevation motor, $\text{Current}_{\text{el}}$, shown in Equation 3.8. Using just a proportional term in the feedback loop causes jerking of the gondola when the elevation is stepped, inducing small amplitude pendulations in elevation. For the long duration flight we will implement an integral term and an acceleration limit to minimize jerking of the gondola.

$$e(t) = e_{\text{req}}(t) - e_l(t)$$  \hspace{1cm} (3.7)

$$\text{PWM}_{\text{el}}(t) \propto \text{Current}_{\text{el}}(t) \propto R_{\text{el}} = P_{\text{el}} e(t)$$  \hspace{1cm} (3.8)

**Feedback Loop Tuning**

The P and I values for the reaction wheel and rotator feedback loops, and the reaction wheel set point speed can be commanded by the system user in real time; the integral time constant, $\tau$, is hard coded at 5 s. In Appendix E we describe the azimuthal feedback loop tuning during ground tests. Feedback loop tuning is repeated during the flight since the gondola responds differently in the absence of air resistance and different friction terms in the motors due to temperature change, and the coupling to the ballon flight train is significantly different than that to the crane hook\footnote{The crane hook is immobilized during gondola scanning tests in the high bay to simulate the coupling to the flight train.} in the high bay.
Pointing Modes

Table 3.12 contains a summary of the various pointing modes that can be executed by commands to \texttt{fcp}.

<table>
<thead>
<tr>
<th>Pointing Mode</th>
<th>Inputs</th>
<th>Gondola Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{az_el_goto}</td>
<td>Requested az and el</td>
<td>Gondola points to given az and el</td>
</tr>
<tr>
<td>\texttt{ra_dec_goto}</td>
<td>Requested RA and Dec</td>
<td>Gondola points to given RA and Dec</td>
</tr>
<tr>
<td>\texttt{az_drift}</td>
<td>Az drift speed</td>
<td>Gondola drifts in az at designated speed; sign on the input parameter sets the rotation direction</td>
</tr>
<tr>
<td>\texttt{az_scan}</td>
<td>Az speed, el, duration of turnaround and entire scan</td>
<td>Gondola az scans of a fixed width at the designated speed and el for the designated duration</td>
</tr>
<tr>
<td>\texttt{cmb_dipole}</td>
<td>Az speed, el, duration of scan</td>
<td>Gondola rotation in az at designated el for designated duration</td>
</tr>
<tr>
<td>\texttt{el_slew}</td>
<td>Az, minimum and maximum el, # of slews to complete, time to pause between slews</td>
<td>Gondola slews between two specified elevations at fixed az for designated # of slews</td>
</tr>
<tr>
<td>\texttt{cmb_scan}</td>
<td>Central RA and Dec, az scan speed, width of the scan, size of Dec patch, # of el steps, # of az scans per el step</td>
<td>Gondola scans back and forth in az and then steps in el over a patch centered on the designated RA/Dec</td>
</tr>
<tr>
<td>\texttt{calibrator_scan}</td>
<td>Central RA and Dec, az scan speed, width of the scan, size of el step, total # of el steps, # of az scans per el step</td>
<td>Gondola scans back and forth in az and then steps in el over a patch centered on the designated RA/Dec</td>
</tr>
</tbody>
</table>

Table 3.12: EBEX pointing modes. An azimuth scan refers to the gondola slewing back and forth in azimuth. Width of scan refers to the peak-to-peak amplitude of the scan.
Reconstruction Pointing Solution

Although the real-time pointing solution is sufficiently accurate to allow for control of the gondola to scan the targeted sources on the sky, further analysis is required to achieve the 9” reconstruction pointing requirement. As in the real-time solution, the reconstruction pointing includes a weighted average of sensors, where star camera readings evolved by the gyroscopes dominate the average.

A state model approach is used to compute the reconstruction pointing solution, where a software filter is used to estimate the actual state of the system, the gondola heading, using noisy measurements. Previous projects, such as BLAST, have had success using a Kalman filter approach \[48\]. We are currently investigating the possibility of using a particle filter. In either case, the state of the system is computed while optimizing over a number of system parameters, including sensor mount angles and drifts in sensor offsets. Most notably, this approach allows for determination of the three mount angles of the gyroscope box to the inner frame, and for characterization of the long timescale offset drift caused by low frequency noise in the gyroscopes.

Figure 3-37 shows an idealized simulation of the RMS error on the reconstructed pointing solution from one scan turnaround to another using only the star camera and the gyroscopes. In the simulation star camera solutions are acquired at 2 and 32 seconds and the gyroscopes are used to interpolate between the star camera readings. Even in this idealized case the RMS error on the reconstructed pointing is larger than the 9” requirement. However, since the noise on the gyroscopes is random and not correlated with the scan phase, the gyroscope noise will be reduced by numerous repeated visits to the same pixel on the sky. A rough calculation indicates that the reconstruction RMS pointing error will be averaged down to 0.4” over a 14-day long duration flight, well below the 9” requirement \[64\].

\[43\] The simulation assumes the star camera RMS error is 5”, the gyroscope noise is white and uncorrelated, and the mounting angles of the gyroscopes are known.
Figure 3-37: Simulation of the RMS error on the reconstructed pointing using only the star camera and gyroscopes.
Chapter 4

System Characterization and Engineering Flight Integration

At the end of 2008 the EBEX cryostat and related electronics were shipped from the University of Minnesota to Nevis Labs at Columbia University for two months of instrument integration and testing. All of the components of the instrument were installed on the gondola to check for proper mechanical fit and to perform electrical and optical tests. Proper implementation of the grounding scheme, described in Section 3.2.8 was verified, and noise in the bolometer, cryogenic housekeeping, and ACS systems was measured under a variety of conditions, including with and without an aluminum plate over the cryostat window and with the gondola stationary and scanning. The warm optics were aligned and preliminary beam maps were produced.

In this chapter we detail a wide range of tests performed at NASA facilities in Palestine, TX, and Ft. Sumner, NM, to characterize and integrate the instrument.
4.1 Thermal Vacuum Tests of the ACS and Flight Computer Crate

4.1.1 Overview of Tests Completed

A series of tests were performed in the thermal vacuum chamber at the CSBF facility in Palestine, TX, to characterize the EBEX electronics over the full range of pressures and temperatures expected on the launch pad, during ascent, and at stratospheric altitudes. The goal of the tests was to assess if all electronics components operate within the specified operating range, and if mechanical failures result from contraction or expansion of materials or the changing behavior of lubricants under all test conditions. During the tests we monitored temperatures and currents through the existing ACS channels and we read out additional temperature sensors through a Labview interface. The temperature and pressure in the chamber were set to follow a typical launch profile followed by typical stratospheric nighttime and daytime environments; a representative plot of one of the tests is shown in Figure 4-1.

Two extreme thermal environments were created in the chamber:

- **Tropopause**: Moderate pressure and low temperature. In the tropopause convection is not negligible and temperatures are low so the tropopause test assesses the extreme low temperature regime of the system thermal design.

- **Stratospheric Night and Day**: Low pressure environment at both high and low temperatures. At low stratospheric pressures convection is extremely inefficient so the warm low pressure test assesses the extreme high temperature regime of the thermal design.

Tables 4.1 and 4.2 include a summary of the results of thermal vacuum tests of the ACS crate, sensors and motors and the flight computer crate, and any subsequent modifications to the thermal design. If modifications were required, the component was tested afterwards to confirm the appropriateness of thermal design.

---

1 The tropopause is the atmospheric layer between the troposphere and the stratosphere.
Figure 4-1: Temperature measurements acquired during a thermal vacuum test where a typical launch profile was followed by typical stratospheric nighttime and daytime environments. The following temperatures were measured: Flight computer CPU, flight computer network switch, DC to DC converter in the flight computer crate, power resistors used to sense motor currents, flight computer crate walls, motor controller, gyroscope box A, and the ambient temperature.
<table>
<thead>
<tr>
<th>Component Tested</th>
<th>Result from Original Design Configuration</th>
<th>Modifications to the Thermal Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS crate</td>
<td>One linear regulator overheated in extreme heat</td>
<td>The regulator was heat sunk directly to the mounting panel and a second regulator was added in parallel</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>No issues</td>
<td>None</td>
</tr>
<tr>
<td>Clinometer</td>
<td>No issues</td>
<td>None</td>
</tr>
<tr>
<td>Gyroscope box</td>
<td>Gyroscope box temperature fell below specified minimum in extreme cold</td>
<td>Add power resistor heater to gyroscopebox</td>
</tr>
<tr>
<td>Encoder</td>
<td>No issues</td>
<td>None</td>
</tr>
<tr>
<td>Sun sensor</td>
<td>Offset in diode output voltage with temperature change</td>
<td>None</td>
</tr>
<tr>
<td>Star camera</td>
<td>1. Overheating of computer CPU in extreme heat 2. Computer did not respond in the most extreme cold 3. Focus mechanism unable to move lens in extreme cold</td>
<td>1. Replaced the CPU passive heatsink with an active heatsink 2. None&lt;sup&gt;a&lt;/sup&gt; 3. Heater tape installed around the lens body</td>
</tr>
<tr>
<td>GPS receiver</td>
<td>Not tested due to successful flight heritage</td>
<td></td>
</tr>
<tr>
<td>Flight Comp Crate&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1. Flight computer unresponsive in extreme cold 2. Computer temperature above specified maximum in extreme heat</td>
<td>1. Power resistor heaters added to computer board 2. Add thermally conductive foam between base of the computer and the crate wall.</td>
</tr>
</tbody>
</table>

<sup>a</sup>Space constraints precluded adding a heater on the computer and temperatures as low as those at which the computer failed were not anticipated in flight.

<sup>b</sup>The flight computer crate was not complete when the tests were run. A power resistor was used to simulate the heat dissipation by the second computer and the timing board was not installed.

<sup>c</sup>This behavior was observed in a thermal vacuum test of the computer alone at the University of Minnesota.

Table 4.1: Summary of the results from thermal vacuum tests of the ACS crate and sensors and the flight computer crate.
## 4.1.2 Discussion of Rotator Thermal Design

The rotator, discussed in Section 3.1.5, is the only ACS component that required substantial modifications in the thermal design based on the thermal vacuum test results. During the tests we discovered that the current required to drive the rotator, shown in red in Figure 4-3, and the rotator motor alone increased significantly as the rotator temperature dropped below 0 °C. After completing a series of tests in which we altered the percent fill of lubrication and the pre-loading of the bearings in the rotator, we concluded on two primary causes of the low temperature failure and implemented solutions, described below.

- When the rotator was assembled the bearings in the motor and on the rotator shaft were filled with an excessive amount of Braycote lubrication\(^2\). We cleaned the rotator shaft bearings with an ultrasonic cleaner and re-greased the bearings with a very thin

\(^2\)The motor and shaft bearings were filled with Braycote lubrication to 35% and 50%, respectively.
119 layer of Molykote\textsuperscript{3} lubricant, and the rotator and reaction wheel motors were sent to the manufacturer where the motor bearings were cleaned and re-greased with a thin layer of Molykote.

- Differential contraction between the aluminum rotator housing and the steel bearings resulted in excessive loading of the bearings. To reduce the pre-loading of the bearings at low temperature we added wavy\textsuperscript{4} springs between the plates at the end of the rotator cylindrical housing and the outside of the bearing race, shown in Figure 4-2. Additionally, we increased the inner diameter of the cylinder where the bearing race sits by 4.5 mils. Figure 4-3 shows the current required to turn the rotator at full speed before and after modifications in the thermal design. The figure shows that in the modified configuration the current required to turn the rotator was reduced significantly at warm, and more significantly, cold temperatures.

\begin{figure}[ht]
\centering
\includegraphics[width=0.5\textwidth]{image}
\caption{Implementation of spring washers between the outside of the bearing race and the rotator cap plate to reduce the bearing pre-loading at cold temperatures.}
\end{figure}

\textsuperscript{3}Molykote 33 Light, http://www.dowcorning.com. Molykote and Braycote both have relatively low viscosity at low temperatures but Molykote is significantly cheaper than Braycote.

\textsuperscript{4}Smalessy SSR-0612, http://www.smalley.com
4.2 Certification Test of Suspension Ropes

In order to reduce payload weight the steel suspension cables used in the original payload assembly were replaced with \(\frac{5}{8}\)" diameter Plasma \(^5\) ropes made with Honeywell Spectra \(^6\) fiber spliced by Helinets \(^7\). Although some data for the Spectra fiber ropes is available from the manufacturer, we certified the ropes on a test flight in September, 2008, from Ft. Sumner, NM. There were two concerns with using Spectra fiber ropes in place of steel cables:

1. Although the ropes are covered with an ultraviolet (UV) inhibitor, their strength degrades with exposure to UV light. At the top of the stratosphere the ropes will be exposed to a high intensity of UV flux.

\(^6\)Spectra Fiber, http://www51.honeywell.com
\(^7\)http://www.helinets.com/
2. Ground tests of Spectra fiber performed by Honeywell show that the ropes undergo permanent lengthening, or creep, which is greater with time, increased temperature, and increased load \[^{30}\]. Rope creep is a concern for EBEX since significant creeping can cause titling of the gondola outer frame table and loading of the triangle support, for which it was not designed.

During the 28 hour certification flight we aimed to assess the level of UV degradation of the rope’s strength and the rope creep. Additional tests to assess the creep were also performed on the ground before and after the flight. Two of four of the ropes were covered with a layer of single-sided vapor deposited aluminized (VDA1) mylar to shield against UV degradation and infrared radiation. A clinometer was mounted to the payload to sense differential creep between the covered and the bare ropes. The four ropes that were flown, and a reference rope that was not flown but acquired along with the other four ropes, were break tested\[^{8}\] after the flight; the results are shown in Table 4.3. We detail the tests performed and discuss the data in Appendix F.4. Below we summarize the test results.

<table>
<thead>
<tr>
<th>Rope Tested</th>
<th>Breaking Strength (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 (Bare)</td>
<td>49,400</td>
</tr>
<tr>
<td>B2 (Bare)</td>
<td>51,200</td>
</tr>
<tr>
<td>M1 (Mylar Covered)</td>
<td>55,200</td>
</tr>
<tr>
<td>M2 (Mylar Covered)</td>
<td>53,900</td>
</tr>
<tr>
<td>Not Flown</td>
<td>55,600</td>
</tr>
</tbody>
</table>

Table 4.3: Results from rope break tests after the rope certification flight. The specified minimum tensile strength of the \(\frac{5}{8}\)” diameter rope is 51,400 lb.

- The break tests showed minimal degradation in the breaking strength of the covered ropes and more significant degradation of the bare ropes.

\[^{8}\]Break testing was provided for free by Puget Sound Rope Corp, http://www.psrope.com.
The ropes were deemed safe for use in the roughly 1-day EBEX engineering flight from Ft. Sumner.

The aluminized mylar was effective at keeping the ropes cool enough to expect negligible creep at float, based on manufacturer creep data from the ground \[30\]. Additionally, the data suggests that a double layer of mylar is more effective than a single layer at keeping the ropes cooler at higher ambient temperatures at float. For the long duration flight we will implement a double layer of mylar.

There was no evidence of significant differential creep between the bare and covered ropes during the flight.

The ropes did not show measurable creep during a pre-flight outdoor ground test over four hours. The post-flight ground test indicates that, if the gondola is hung in the high bay for as little as a couple weeks before the long duration flight, subsequent creep is not expected during the long duration flight.

4.3 Pre-Engineering Flight ACS Integration

At the CSBF facility in Ft. Sumner, NM, outdoor tests can be performed far from the high bay building, either hanging from the launch vehicle or on the ground, and a wide swath of sky is visible from within the high bay. Since neither of these testing conditions is available at Nevis Labs at Columbia University, the final steps in the integration of the ACS with the gondola were completed in Ft. Sumner.

4.3.1 Sensor Indexing to the Gondola and Microwave Beam

Before the engineering flight the sensor headings were indexed to the gondola to allow for sufficiently accurate real-time pointing data and gondola control. The magnetometer, differential GPS, rotary encoder and clinometer headings were indexed to the star camera during a nighttime outdoor test. The sun sensor was then indexed to the GPS and magnetometer during a daytime test. No indexing was performed for
the gyroscope box since system tests indicated that agreement between the gyroscope active axes and the inner frame azimuth, elevation and roll axes was sufficiently good to allow for the required precision of gondola control.

The pointing sensors were indexed to the microwave beam using the star camera. In the high bay an LED was placed next to an extended microwave source. With the gondola positioned so that a known bolometer was aligned with the microwave source, the location of the LED image in the star camera focal plane was noted. After calibration of the star camera linear and angular plate scales in the near field, the angular offset between the LED and the center of the microwave source was determined. We considered the possibility of performing the indexing of the star camera and microwave beams on the night sky using a planet, however we concluded that the atmospheric loading on the detectors on the ground would be too high to allow for observation of the planet.

4.3.2 Star Camera Triggering During a Scan

Night time scanning tests were performed to characterize the reliability of star camera solutions at various gondola speeds for a typical integration time. With the gondola sitting on the ground, the inner frame moved in elevation at various speeds while the star camera acquired and attempted to solve images. The test showed that although some accurate solutions were obtained at speeds of up to 0.2 deg/s, when the gondola moved at about 0.1 deg/s or faster a significant fraction of the star camera solutions was either unreliable or unavailable. Based on the test results, the thread in fcp that controls when the ACS commands the star camera shutter to open was modified to stipulate that the gondola speed and acceleration are below specified values before the shutter open command is sent by the ACS at the scan turnaround.
4.3.3 Differential GPS

Although the GPS system performed consistently and reliably in tests at Nevis Labs when it was not mounted to the gondola, outdoor tests of the integrated instrument in Ft. Sumner allowed us to assess three aspects of the GPS system, described below.

- *Accuracy of heading solutions:* The heading solutions, as compared to the other pointing sensors, proved repeatable and reliable during many outdoor tests spread out over weeks.

- *Stiffness of Antenna Mount:* The antenna mount proved to be sufficiently stiff such that the antenna calibration was maintained while the gondola was moved inside and outside many times over weeks of testing. We found that the first set of calibration results was valid even after disassembly and reassembly of the mount.

- *Electronic Configuration:* The grounding configuration of the system on the gondola, described in Section 3.5.5, differed from that at Nevis Labs where no care was taken to isolate the receiver or antennas from the ground. The receiver unit demonstrated four independent electrical failures during the integration, two of which occurred in the EBEX GPS receiver and the other occurred in a loaned CSBF GPS receiver of the same model with an independent power supply.

  During all of the failures a receiver channel did not acknowledge receipt of one of the antenna signals. After the first failure a burnt component was discovered on the failed channel board in the receiver box; the receiver was sent to the manufacturer for replacement of the board. After the other failures the unit simply worked as expected the next time it was tested. The fourth failure occurred on the morning of the flight, discussed in Section 5.3.3. Tests to understand the cause of the failures and the possible role of the grounding configuration are currently being performed at Columbia University.
4.4 Characterization of the Flight Bolometers and the Receiver

In this section we provide the results from some of the calculations and tests performed on the ground in Ft. Sumner and during the North American engineering flight, where noted, to characterize the detectors, the receiver, and the telescope. Here we report the results of the tests while detailed descriptions of how each test was performed and discussions of the results are provided in the associated references below. Additional results of characterization of the detectors and receiver that are unrelated to the analysis in this thesis, including thermal transport across the bolometer, thermal loading on the detectors by the receiver components, the HWP polarization modulation efficiency, and the instrumental polarization, can be found in Hubmayr, 2009 [33], and Polsgrove, 2009 [50].

During the ground tests and in the flight most of the bolometers were exposed to radiation through the cryostat window, referred to “light” bolometers, although some were obscured by a plug of ECCOSORB\(^9\) microwave absorber, referred to as “eccosorb” bolometers, and others were made “dark” by placing aluminum tape on the wave guide above the bolometer. Additionally, double and single layer neutral density filters\(^10\) (NDFs) were placed in front of the 250 and 410 GHz bolometer arrays, respectively, to prevent saturation of the detectors.

**Time Constant Measurements**

Bolometer time constants, \(\tau\), were measured at 12.2 ms, 12.9 ms, and 8.2 ms for a small subset of the bolometers at 150, 250, and 410 GHz, respectively, in tests at the University of Minnesota (150 GHz) and in Ft. Sumner (250 and 410 GHz) [33]. The values of \(\tau\) are a factor of 3 to 4 larger than the design goal.

\(^9\)MF-110 ECCOSORB, http://www.eccosorb.com
\(^10\)The filters are made of 1.08 mm thick pieces of MF-100 ECCOSORB.
Responsivity Measurements

The responsivity of a bolometer, given in units of \( \frac{\text{Current}}{\text{Power}} \), is a measure of the change in current through the sensor induced by a change in thermal power dissipated in the bolometer. The curves in Figure 4-4 show that the responsivity is higher and more linear for bolometers biased deeper into the superconducting transition. The measured responsivities are about a factor of two higher than expected, based on bolometer theory \[33\].

Figure 4-4: Responsivity measurements of a single bolometer as a function of position in the transition from ground tests \[33\]. R refers to the bolometer normal resistance. (Plot courtesy of Johannes Hubmayr).

Receiver Efficiency Measurements

The end-to-end receiver efficiency is defined as \( \epsilon_r \equiv \frac{P_{\text{det}}}{P_{\text{in}}} \), where \( P_{\text{det}} \) is the power detected by the bolometer and \( P_{\text{in}} \) is the power into the cryostat window in a detector beam. The efficiencies are relatively low at all frequencies due to the absence of anti-reflection coatings on the lenses and the HWP, and at 250 and 410 GHz due to the presence of the NDF. Note that given the presence of the polarizing grid, the maximum possible \( \epsilon_r \) is 50%.

Optical and Bolometer Efficiency Calculations

Calculated values for the optical efficiency, \( \epsilon_o \), and bolometer absorption efficiency,
Table 4.4: Measurements of $\epsilon_r$ for a subset of the light, eccosorb plugged, and dark bolometers at each wafer frequency, $\nu$, from ground tests [33]. The table includes the standard deviation of the measured values in each class; only one light bolometer was measured at 250 GHz.

<table>
<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>Bolo Type</th>
<th>Receiver Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>light</td>
<td>15.5±2.4</td>
</tr>
<tr>
<td></td>
<td>eccosorb</td>
<td>2.9±0.7</td>
</tr>
<tr>
<td></td>
<td>dark</td>
<td>0.94±0.71</td>
</tr>
<tr>
<td>250</td>
<td>light</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>eccosorb</td>
<td>0.02±0.03</td>
</tr>
<tr>
<td></td>
<td>dark</td>
<td>0.03±0.1</td>
</tr>
<tr>
<td>410</td>
<td>light</td>
<td>0.58±0.18</td>
</tr>
<tr>
<td></td>
<td>eccosorb</td>
<td>0.13±0.01</td>
</tr>
<tr>
<td></td>
<td>dark</td>
<td>0.12±0.22</td>
</tr>
</tbody>
</table>

The bolometer absorption efficiency is calculated using the relation $\epsilon_b = \frac{\epsilon_r}{\epsilon_o}$. The non-physical value of 118% for $\epsilon_b$ in the 150 GHz band could result from inaccuracy in the calculation of $\epsilon_o$ or inaccuracy in the responsivity, which is used to determine $\epsilon_r$.
Unpolarized Sidelobe Measurements

Two tests were performed on the ground to characterize the sidelobes of the microwave beams once the instrument was fully integrated for flight. The power detected by the instrument at various azimuth and elevation angles away from a directed microwave source was plotted. The measurements are summarized in Table 4.6.

<table>
<thead>
<tr>
<th></th>
<th>Low Resolution Test</th>
<th>High Resolution Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Azimuth Cut</strong></td>
<td>-85 dB at 15°</td>
<td>-80 dB at 5°</td>
</tr>
<tr>
<td><strong>Elevation Cut</strong></td>
<td>-90 dB at 12°</td>
<td>-80 dB at 5°</td>
</tr>
</tbody>
</table>

Table 4.6: Unpolarized far sidelobe measurements from low resolution and high resolution tests [50]. For each test we report the level of signal suppression and distance from the main lobe of the beam.

4.5 Ground Beam Mapping

A calibrator scan was performed on a stable modulated microwave source mounted in the high bay to characterize the detector beams once the entire EBEX instrument was integrated for the engineering flight. To reconstruct the pointing during the scan the gyroscopes were integrated since data from an absolute sensor was not available[11]. The earth’s rotation and a third order polynomial offset were removed from the gyroscope data before integration. The bolometer data was filtered to remove the modulation in the signal due to a chopper in front of the microwave source, and the HWP modulation signal was subtracted, as described in detail in Section 6.2.4.

All of the resulting beam maps of the individual detectors indicate asymmetric beams that are larger than the 8’ symmetric beam design goal; an example beam map at each frequency is shown in Figure 4-5. An average of the full width of the power distribution in the maps at half maximum (FWHM) in azimuth and elevation

[11] The magnetometer proved unreliable in the irregular magnetic environment in the high bay, the inner frame elevation angle required to view the microwave source precluded star camera observations of the sky, and the GPS cannot provide heading data inside the high bay.
is provided in Table 4.7. Analysis is ongoing to understand the discrepancy between the design and measured beam shapes and sizes.

Figure 4-5: Example beam maps for bolometers at 150 GHz, 250 GHz, and 410 GHz from the top left, clockwise. The triangle symbol in the center of each beam map indicates the centroid of the map calculated using pixels with a brightness of 20% or greater of the peak flux in the map. (Plots courtesy of Chaoyun Bao).
Table 4.7: Average FWHM of the detector beams in azimuth and elevation at each frequency, $\nu$, using a subset of the bolometers. Data from Polsgrove thesis [50].

<table>
<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>Az Beam Size (arcmin)</th>
<th>El Beam Size (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>54</td>
<td>50</td>
</tr>
<tr>
<td>250</td>
<td>33</td>
<td>20</td>
</tr>
<tr>
<td>410</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>
Chapter 5

North American Engineering Flight

The primary purpose of the EBEX North American engineering flight was to test the instrument in an environment similar to the one the payload will encounter at flight altitudes over Antarctica during the long duration science flight. During the flight we aimed to achieve the goals listed below.

1. Test the operation of all of the electronics during ascent and in a low pressure stratospheric environment during the day time to assess the thermal model of the instrument

2. Determine the bolometer sensitivity by measuring the in-flight noise properties and optical loading at stratospheric altitudes.

3. Assess the ability of the attitude control system to point the instrument

4. Test the remote operation of the bolometer readout electronics and the attitude control system (ACS).

5. Test data downlink and on-board data writing

6. Test alignment of the warm and cold optics and make a beam map.
The configuration of the instrument during the engineering flight is shown in Table 5.1. In the following sections we provide an overview of the flight and we assess the successes and failures of the EBEX thermal model and the general performance of all EBEX subsystems. In cases where a subsystem has failed, plans for improving it for the long duration flight are noted.

<table>
<thead>
<tr>
<th>Component</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td># of focal planes</td>
<td>1</td>
</tr>
<tr>
<td># of 150/250/410 GHz wafers</td>
<td>1/1/1</td>
</tr>
<tr>
<td># of light bolometers at 150/250/410 GHz</td>
<td>64/32/71</td>
</tr>
<tr>
<td># of SQUID series arrays</td>
<td>46</td>
</tr>
<tr>
<td>DfMUX boards multiplexing factor</td>
<td>8</td>
</tr>
<tr>
<td>HWP rotation frequency</td>
<td>2 Hz</td>
</tr>
<tr>
<td># of gyroscope boxes</td>
<td>1</td>
</tr>
<tr>
<td># of star cameras</td>
<td>1</td>
</tr>
<tr>
<td>Power system</td>
<td>Non-rechargeable batteries</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of the instrument configuration during the engineering flight.

5.1 Flight Overview

The payload was launched from the CSBF facility at Ft. Sumner, NM, at 14:02 UTC (8:02 local time) on 6/11/09. It reached the altitude at which the atmospheric loading on the bolometers was low enough for bolometric observations, referred to here as float altitude, at about 16:50 UTC. At about 3:40 UTC 6/12/09 the flight was terminated by CSBF and the payload came down on a parachute. The last communication with the CSBF GPS occurred at 3:55 UTC at 41,714 ft, and the payload landed just outside Yucca, AZ.

Due to the increased high altitude winds characteristic of the late spring flight date the payload traveled from Ft. Sumner, NM, to the far western border of Arizona near Lake Havasu City in about 14 hours; the flight trajectory is shown in Figure 5.1. Since the flight occurred mostly during the day, the altitude and air temperature,
shown in Figure 5-2 were generally stable at float altitudes. The maximum flight altitude, achieved early in the flight, was 36,065 m, and the average altitude during the 10.5 hours at float was 34,500 m.

Figure 5-2: The altitude and temperature for the EBEX engineering flight. (Raw Data provided by CSBF.)
5.1.1 The Launch

The pre-launch configuration for the EBEX payload, the balloon, and the cabling between the payload and balloon, called the flight train, is shown in Figure 5-3. The payload hangs from the launch vehicle, held in place by a pin that passes through a plate at the base of the flight train. The flight train, including the parachute, is laid out horizontally on the ground, and then the inflated balloon is held by a CSBF vehicle at the far end of the flight train.

![Figure 5-3: The EBEX Launch.](image)

Figure 5-3: The EBEX Launch.  

To initiate the launch CSBF releases the balloon and it slowly rises and is pulled laterally by tension provided by the flight train until the balloon floats above the payload and launch vehicle. When the balloon is above the payload, the flight train is under tension since the balloon is pulling up on it and the payload weight is pulling
down. The launch is complete when the launch vehicle releases the payload by pulling the pin out of the plate at the base of the flight train.

During the EBEX launch the balloon was not directly above the payload when it was released, creating a small non-vertical angle in the flight train stretching between the launch vehicle and the balloon; see Figure [5-3b]. When the pin was pulled to release the payload, tension was released from the flight train and the gondola outer frame table accelerated down and forward, shown by the green arrow in Figure [5-3b]. However, due to inertia, the inner frame did not accelerate down as rapidly and the angle between the inner and outer frame increased, pulling the elevation actuator in tension. Eventually the inner frame began to accelerate downwards and the force of the unbalanced inner frame on the actuator was greater than its breaking strength in compression. Post-flight analysis confirms that the actuator broke in compression, not in tension. After the actuator broke the inner frame continued to accelerate downwards but was eventually stopped by pieces of L-channel that were screwed to the trunnion legs, put in place in the event of an actuator failure. This left the elevation of the inner frame fixed at a relatively low angle of $15^\circ$. A post-flight analysis shows that the accelerations present during the launch were not atypical compared with some other payload launches.

5.1.2 Summary of Observations Made During the Flight

Before the flight we generated a flight plan that included CMB patch scans, a CMB dipole scan, calibration scans on Saturn, and scans on the galactic plane. The flight plan was written into schedule files that, as part of the flight control program ($fcp$), provide automatic control of the gondola in the event that communication between the payload and the ground is unavailable. The flight plan was foiled by the breakage of the elevation actuator during launch, forcing us to rethink our flight plan in real time and to perform all control of the gondola by commanding from the ground. Additionally, the flight plan was hampered by the lack of accurate absolute azimuth
sensor readings as discussed below in Section 5.3. As a result, we performed CMB patch and dipole scans at constant elevation and we made some passes across the galactic plane; we did not perform a calibrator scan since our poor real-time pointing accuracy did not allow us to properly scan across Saturn.

5.1.3 Payload Landing and Recovery

The payload landed in a sandy flat area only a few hundred feet from a serviceable dirt road. Upon impact the payload was moving at a non-negligible horizontal speed which resulted in it landing squarely on the back of the gondola. Although the landing stressed the gondola frame immensely, resulting in significant damage to the gondola inner frame and battery table, the mirrors and all but one of the electronics boxes, including all of the readout crates and the ACS sensors, sustained no damage. The sun sensor was destroyed, buried in the sand because of its exposed position at the back of the gondola. The cryostat itself was not damaged, however there was minimal damage to a few of the components inside including a crack in one of the vespel legs that supports the focal plane and some breaks in the internal wiring. The vespel leg could have cracked during the launch or landing, however the wiring damage occurred at landing since the electronic signals that travel on those wires were functional during the flight. Although the landing was not ideal since some damage was sustained, it was fortuitous since most of the gondola frame components that were damaged are stock metal pieces that require minimal coarse machining before installation. In contrast, had the landing resulted in the damage of more of the custom built electronics and optics, the cost in manpower, time and money to rebuild the instrument would have been much more significant.

5.1.4 Summary of EBEX Flight Temperatures

One goal of the engineering flight was to test the EBEX electronics in the thermal conditions encountered during ascent and in a daytime environment at float altitudes
to assess the EBEX thermal design for an long duration flight. Ideally we hoped to see all systems reach a steady state temperature during the daytime. However, many subsystems, including the gondola itself, never stabilized thermally, as discussed below.

Figure 5-2 shows that the air temperature followed a typical profile for a daytime balloon flight. The temperature decreased during ascent to -66 °C, reflecting the colder temperatures in the tropopause, the atmospheric layer between the troposphere and the stratosphere. Once at float altitudes the air temperature was generally level around a mean temperature of -29 °C with spikes varying between -34 and -8°C. At the end of the flight the temperature began to drop at 2:00 UT 6/12/09 (19:00 6/11/2009 local time) due to the decrease in the sun’s elevation.

Figure 5-4 shows that the boresight of the millimeter wave beam passed through the azimuth of the sun many times during the flight; the sun’s elevation was high enough that the telescope boresight did not point directly into the sun. During these periods, parts of the gondola that were normally shaded from the sun by the baffles were exposed to it. The temperatures of some EBEX electronics systems, the gondola, and the air as reported by CSBF show spikes in temperature that are, in some cases, correlated with the passes in azimuth across the sun, as shown in Figure 5-2 and the temperature plots for each subsystem below.

Many of the electronics boxes were mounted in specific locations or covered with materials for the purpose of temperature regulation. The bolometer readout crates were mounted on the sides of the gondola outside of the inner baffling so that the crates would radiate efficiently to the sky. Some electronics boxes were covered with insulating foam to prevent them from cooling too much in the tropopause where the temperatures are relatively cold and the pressure is not yet low enough to make convection negligible. Other electronics boxes were covered in custom blankets made

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1The CSBF air temperature sensor hung from the bottom of the gondola so it was shielded by the baffles when the gondola pointed away from the sun but highly exposed when the gondola pointed towards the sun.
Figure 5-4: Telescope boresight azimuth minus the sun azimuth during the engineering flight. The azimuth of the telescope boresight passed across the sun a number of times: at 17:48, 17:49, 19:11, many times between 19:19 and 19:21, many times between 20:03 and 20:08, 21:39, 21:43, 22:12, and many times between 23:01 and 22:03 UT, during ascent, and during the dipole scan late in the flight.

with aluminized mylar, with the mylar side facing outwards, for two different purposes. First, the blankets were placed on electronics that were in danger of becoming too cold at float altitudes since the inner aluminum layer reflects heat back into the enclosure. Second, the blankets were also placed on bare aluminum components that were directly exposed to the sun to protect against overheating since the aluminum layer provides shielding from the sun and the mylar can radiate internal heat outwards.

The gondola and ACS temperature channels are shown in Table 5.3 and the temperatures of the gondola, batteries, and the baffles are shown in Figure 5-5. All of the gondola and baffle thermometers show a decrease in temperature in the tropopause and many show spikes correlated with passes in azimuth across the sun. Due to the anticipated self-heating of the batteries discussed in Section 3.2.7, the battery
temperature did not decrease significantly in the tropopause, and once at float the
temperature increased gradually.

Table 5.2 summarizes the thermal behavior of the non-cryogenic electronic sub-
systems, including the specified operating ranges of the components. The thermal
behavior of each electronics subsystem will be detailed and evaluated in the subsec-
tions below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Op. $T_{\text{min}}$ (°C)</th>
<th>Op. $T_{\text{max}}$ (°C)</th>
<th>Component Within Specified T Range?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Computer</td>
<td>0</td>
<td>60</td>
<td>Too hot$^a$</td>
</tr>
<tr>
<td>DC to DC Converter</td>
<td>-40</td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>Ethernet Switch</td>
<td>-40</td>
<td>85</td>
<td>Not measured</td>
</tr>
<tr>
<td>Data Hard Disks</td>
<td>5$^b$</td>
<td>50</td>
<td>Yes</td>
</tr>
<tr>
<td>ACS Cards</td>
<td>-40</td>
<td>85</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun Sensor Hard Drive</td>
<td>-40</td>
<td>85</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun Sensor Computer</td>
<td>-40</td>
<td>85</td>
<td>Yes</td>
</tr>
<tr>
<td>Star Camera Computer</td>
<td>-40</td>
<td>70</td>
<td>Yes</td>
</tr>
<tr>
<td>Clinometers</td>
<td>-10</td>
<td>70</td>
<td>Too cold$^c$</td>
</tr>
<tr>
<td>Fiberoptic Gyroscopes</td>
<td>-40</td>
<td>75</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>-55</td>
<td>120</td>
<td>Not measured$^c$</td>
</tr>
<tr>
<td>Encoder</td>
<td>-40</td>
<td>85</td>
<td>Not measured$^c$</td>
</tr>
<tr>
<td>Rotator &amp; Reaction</td>
<td>-40$^d$</td>
<td>155</td>
<td>Yes</td>
</tr>
<tr>
<td>Wheel Motors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Controllers</td>
<td>0</td>
<td>65</td>
<td>Too cold$^c$</td>
</tr>
<tr>
<td>DfMUX Board</td>
<td>-10</td>
<td>65</td>
<td>Marginally hot$^a$</td>
</tr>
</tbody>
</table>

$^a$ The thermal design for this component requires redesign for the long duration flight.

$^b$ These disks were tested during repeated thermal vacuum tests down to a disk pressure vessel enclosure temperature of -30 °C.

$^c$ This particular model has been flown successfully on many balloon flights in a similar thermal environment.

$^d$ Although the motor was tested down to -40 °C and is rated to -55 °C, a higher current draw was measured below about 0 °C.

Table 5.2: Specified maximum and minimum operating temperatures, $T_{\text{max}}$ and $T_{\text{min}}$, for some of the non-cryogenic EBEX electronics and an assessment of whether or not the electronics component operated within the specified range.
<table>
<thead>
<tr>
<th>Label Name</th>
<th>Location</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>$T_{\text{max}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_ACS_P+S_L</td>
<td>ACS crate left power &amp; signal panel</td>
<td>15.57</td>
<td>42.41</td>
</tr>
<tr>
<td>T_ACS_P+S_R</td>
<td>ACS crate right power &amp; signal panel</td>
<td>21.57</td>
<td>47.22</td>
</tr>
<tr>
<td>T_ACS_PWR</td>
<td>ACS crate left power panel</td>
<td>6.88</td>
<td>36.02</td>
</tr>
<tr>
<td>T_BAF_BAK_OUT</td>
<td>Back outer baffle (mounted on inside surface)</td>
<td>-44.59</td>
<td>27.60</td>
</tr>
<tr>
<td>T_BAF_IN_L_F</td>
<td>Front L inner baffle</td>
<td>-35.05</td>
<td>20.07</td>
</tr>
<tr>
<td>T_BAF_IN_R_F</td>
<td>Front R inner baffle</td>
<td>-34.97</td>
<td>17.67</td>
</tr>
<tr>
<td>T_BAF_OUT_L</td>
<td>Front L outer baffle (mounted on front facing side)</td>
<td>-46.01</td>
<td>25.43</td>
</tr>
<tr>
<td>T_BAF_OUT_R</td>
<td>Front R outer baffle (mounted on front facing side)</td>
<td>-41.86</td>
<td>24.07</td>
</tr>
<tr>
<td>T_BOLOPWR_L</td>
<td>Outside of bolometer power crate 1</td>
<td>-6.91</td>
<td>32.76</td>
</tr>
<tr>
<td>T_BRO1</td>
<td>Outside of bolometer readout crate 1</td>
<td>-5.76</td>
<td>28.02</td>
</tr>
<tr>
<td>T_BRO2</td>
<td>Outside of bolometer readout crate 2</td>
<td>-6.34</td>
<td>27.13</td>
</tr>
<tr>
<td>T_CLIN_IF</td>
<td>Inner frame clinometer (internal sensor, not AD590)</td>
<td>-24.08</td>
<td>14.41</td>
</tr>
<tr>
<td>T_CLIN_OF</td>
<td>Outer frame clinometer (internal sensor, not AD590)</td>
<td>-26.13</td>
<td>14.27</td>
</tr>
<tr>
<td>T_DAS_BATT</td>
<td>LiO battery pack (for bolometer power system)</td>
<td>26.14</td>
<td>41.37</td>
</tr>
<tr>
<td>T_ELEVMOT</td>
<td>Elevation motor outer casing</td>
<td>-7.94</td>
<td>52.36</td>
</tr>
<tr>
<td>T_ELMC</td>
<td>Inside elevation motor controller box</td>
<td>-33.31</td>
<td>10.20</td>
</tr>
<tr>
<td>T_FCI</td>
<td>Flight computer 1 CPU heatsink</td>
<td>19.31</td>
<td>64.59</td>
</tr>
<tr>
<td>T_FIC3</td>
<td>Flight computer 2 CPU heatsink</td>
<td>23.69</td>
<td>68.29</td>
</tr>
<tr>
<td>T_FCDCDC</td>
<td>Flight compuer crate DCDC mounting panel</td>
<td>36.19</td>
<td>69.69</td>
</tr>
<tr>
<td>T_FC,TOSC</td>
<td>Oven controlled oscillator on FC timing board</td>
<td>136.19</td>
<td>64.37</td>
</tr>
<tr>
<td>T_FERROFL</td>
<td>Half wave plate motor ferrofluidic</td>
<td>-15.17</td>
<td>15.39</td>
</tr>
<tr>
<td>T_GYROA</td>
<td>Outside of gyroscope box A</td>
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</tr>
<tr>
<td>T_GYROB</td>
<td>Outside of gyroscope box B</td>
<td>0.02</td>
<td>24.98</td>
</tr>
<tr>
<td>T_HWPCR</td>
<td>Half wave plate crate</td>
<td>-2.28</td>
<td>24.93</td>
</tr>
<tr>
<td>T_IF_PRI</td>
<td>Inner frame near primary mirror</td>
<td>-21.47</td>
<td>17.00</td>
</tr>
<tr>
<td>T_IF_SEC</td>
<td>Inner frame near secondary mirror</td>
<td>-28.43</td>
<td>16.36</td>
</tr>
<tr>
<td>T_ISC_COMP</td>
<td>Star camera computer</td>
<td>18.98</td>
<td>51.25</td>
</tr>
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<td>T_ISC_FLANGE</td>
<td>Star camera front flange</td>
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<td>30.02</td>
</tr>
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<td>T_ISC_HEAT</td>
<td>Star camera 5V DC-DC</td>
<td>7.94</td>
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</tr>
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<td>T_ISC_LENS</td>
<td>Star camera lens</td>
<td>1.15</td>
<td>38.51</td>
</tr>
<tr>
<td>T_OF1_IN</td>
<td>Front outer frame table, inside baffles</td>
<td>-32.83</td>
<td>17.65</td>
</tr>
<tr>
<td>T_OF2_OUT</td>
<td>Front outer frame table, outside baffles</td>
<td>-26.76</td>
<td>17.74</td>
</tr>
<tr>
<td>T_PIVMC</td>
<td>Inside rotator motor controller box</td>
<td>-22.45</td>
<td>41.70</td>
</tr>
<tr>
<td>T_PIVMOT</td>
<td>Top bearing pre-load plate of rotator casing</td>
<td>-1.43</td>
<td>36.42</td>
</tr>
<tr>
<td>T_PRI_L</td>
<td>Primary mirror left, back side</td>
<td>-21.09</td>
<td>18.48</td>
</tr>
<tr>
<td>T_PRI_R</td>
<td>Primary mirror right, back side</td>
<td>-20.6</td>
<td>19.27</td>
</tr>
<tr>
<td>T_PV1</td>
<td>Disk pressure vessel, inside frame</td>
<td>-8.71</td>
<td>31.26</td>
</tr>
<tr>
<td>T_PV_BARE</td>
<td>Disk pressure vessel, outer casing</td>
<td>-13.74</td>
<td>20.89</td>
</tr>
<tr>
<td>T_RFSCAN1</td>
<td>Cryostat RF can (under cryostat bottom plate)</td>
<td>-17.36</td>
<td>17.53</td>
</tr>
<tr>
<td>T_RFSCAN2</td>
<td>Cryostat RF can (under cryostat bottom plate)</td>
<td>-17.12</td>
<td>18.20</td>
</tr>
<tr>
<td>T_RXNMC</td>
<td>Inside reaction wheel motor controller box</td>
<td>-23.22</td>
<td>18.86</td>
</tr>
<tr>
<td>T_RXNMOT</td>
<td>Reaction wheel mount plate</td>
<td>-8.70</td>
<td>16.82</td>
</tr>
<tr>
<td>T_SEC_L</td>
<td>Secondary mirror left, back side</td>
<td>-15.35</td>
<td>18.76</td>
</tr>
<tr>
<td>T_SEC_R</td>
<td>Secondary mirror right, back side</td>
<td>-16.70</td>
<td>17.35</td>
</tr>
<tr>
<td>SS_T_CASE</td>
<td>Sun sensor case, inside</td>
<td>-14.05</td>
<td>46.85</td>
</tr>
<tr>
<td>SS_T_CPU</td>
<td>Sun sensor computer CPU</td>
<td>11.25</td>
<td>50.25</td>
</tr>
<tr>
<td>SS_T_HDD</td>
<td>Sun sensor hard drive</td>
<td>-22.85</td>
<td>43.65</td>
</tr>
<tr>
<td>SS_T_PORT</td>
<td>Port side of sun sensor module ring</td>
<td>-41.45</td>
<td>34.85</td>
</tr>
<tr>
<td>SS_T_STAR</td>
<td>Starboard side of sun sensor module ring</td>
<td>-40.95</td>
<td>37.35</td>
</tr>
</tbody>
</table>

Table 5.3: Gondola and ACS temperature sensors read out during the engineering flight.
Figure 5-5: Temperatures of the gondola and baffles during the engineering flight; for a description of the channel names see Table 5.3

Evaluation of AD590 Performance

The AD590s were extremely reliable as a temperature sensor. Not a single sensor failed at any point during the building and integration of EBEX or during the flight; some sensors had been installed in flight hardware and operated for up to three years. We conclude that the room temperature absolute error on the sensors was within specification of ± 5°C, based on comparing temperatures around the gondola.
before the flight. The flight data does not reveal anything about the absolute error of the thermometers over the full environmental temperature range. For the long duration flight we plan to calibrate the thermometers in the lab over the anticipated temperature range to allow for much higher absolute accuracy.

When using the AD590s differentially, such as measurement of temperature drifts on some characteristic timescale, the sensor noise is most relevant. Below in Section 6.1 we provide a detailed analysis of the scan synchronous temperature signals, including a discussion of whether the signals are generated by electrical noise or by real temperature change, and whether or not the noise on the AD590 signals is sufficiently low.

5.2 Evaluation of the System-wide Control, Data Management, and Communication Hardware and Software

5.2.1 Flight Computers and the Flight Control Program

The flight computer crate electronics performed all of the required functions throughout the flight. Upon startup in the high bay the morning of the flight, the flight control program, fcp, started up on both flight computers, and Flight Computer 2 (FC2) was the computer in control of the payload, as designated by the watchdog card. fcp ran continuously throughout the entire flight on FC2, and, as a result, it underwent no reboots and remained in control for the duration of the flight. Flight Computer 1 (FC1) underwent three reboots which occurred during a ten minute period beginning at 17:27 UT. No cause for the reboots has been determined; at the time of the reboot the computer temperature was within the specified operating range.

Figure 5-6 shows the temperatures of the CPU of the two flight computers, t_{fc1}²

²It is not understood why the signal for FC1 is significantly noisier than the other temperature
and $t_{fc2}$, during the flight. Although the computers did not cool excessively in the tropopause, they both heated above the maximum operating temperature, shown as a horizontal black dashed line in the figure, early in the flight. Additionally, the computer temperatures increased somewhat linearly once out of the tropopause, not showing any sign of leveling off before the late day decrease in the elevation of the sun, shown as a black line in the plot. The flight computer crate was not covered with foam to provide insulation in the tropopause because the temperatures of the computers in the high bay in Ft. Sumner were marginally high without the foam in place.

Figure 5-6: Temperatures of the flight computer crate and disk pressure vessel during the engineering flight; for a description of the channel names see Table 5.3. The black dashed horizontal line shows the maximum specified operating temperature of the flight computers.

The thermal behavior of the flight computer crate in flight is not consistent with that from the thermal vacuum tests, discussed in section 4.1. In these tests, at an ambient temperature of about -9 °C, the computer CPU temperature leveled off to about 8 °C in just under 2 hours. Nevertheless, we conclude from the flight data that signals in the flight computer crate.
the thermal design of the flight computer crate will be modified for the long duration flight.

5.2.2 Ethernet Network

The network connections between the flight computer crate, disk pressure vessel, sun sensor, star camera, HWP crate and bolometer readout crates functioned throughout the flight without dropouts. We did not monitor the status of the ring switches during the flight so we can only conclude that at least one of the two redundant paths over which signals travel between subsystems and the flight computers functioned at all times. Although we have not experienced any problems with the ethernet network, we will implement monitoring of the ring switches before the integration and testing for the long duration flight to provide additional confidence in the system.

5.2.3 Data Writing

No problems were experienced with the disk pressure vessel. Both flight computers wrote data to the disks throughout the flight, except during the reboots of FC1. Figure 5-6 shows the temperatures measured by AD590s epoxied to the outside of the disk vessel and to the frame inside the vessel which holds the disks, labeled t_{pv\_bare} and t_{pv1}, respectively. Both temperatures remained well above the minimum temperature of -30°C reached during thermal vacuum tests of the disks. During the flight the pressure vessel was insulated using an aluminized mylar blanket.

5.2.4 Data Uplink and Downlink

Data uplink and downlink were maintained continuously during the entire flight via the line of sight transmitter, although a small number of downlinked data packets were corrupted. Commands were successfully sent to the flight computer and executed. The simulated links to the TDRSS and IRIDIUM satellites functioned intermittently
during the flight. The error messages generated during the periods of failure point to bugs in the thread of \texttt{fcp} that controls communication between the payload and the satellites. We will modify and test this part of \texttt{fcp} before the long duration flight.

5.3 Evaluation of the Attitude Control System

5.3.1 ACS Readout Cards

The ACS cards functioned continuously during the flight. Figure 5-7 shows temperatures measured by AD590s mounted and heat sunk to three different aluminum panels in the crate to which DC-DCs and relays are mounted, $t_{\text{acs.p+s.l}}$, $t_{\text{acs.p+s.r}}$, and $t_{\text{acs.pwr}}$ in. The panel temperatures remained well within the allowed operating temperature of the cards, -40 °C to 85 °C, throughout the flight. Although the panel temperatures did not stabilize before the late day decrease in the elevation of the sun, the shape of all three of the temperature curves, starting around 16:30 UT, is closer to an exponential than a linear increase, indicating that the temperature of the crate was slowly stabilizing and not simply increasing linearly. The crate was covered on five sides with foam to provide insulation in the tropopause.

5.3.2 The Clinometers and Magnetometer

Clinometer Thermal Behavior

The temperatures of the inner and outer frame clinometers during the flight are shown in Figure 5-8 as $t_{\text{if.clin}}$ and $t_{\text{of.clin}}$, respectively. The inner frame clinometer temperature channel on the ACS card had a known DC offset corresponding to about -29°C that was not resolved before the flight. Using this offset for the inner frame clinometer, both clinometers operated between -24 and +26 °C throughout the flight\footnote{The significantly higher noise on the inner frame clinometer signal is not well understood. One possible cause of the noise is pickup of electromagnetic interference from other electronics since the cable connecting the inner frame clinometer to the ACS crate was much longer than the one}. 

The significantly higher noise on the inner frame clinometer signal is not well understood. One possible cause of the noise is pickup of electromagnetic interference from other electronics since the cable connecting the inner frame clinometer to the ACS crate was much longer than the one
The clinometers were covered on five sides with foam to provide insulation in the tropopause.

During and just after traveling through the tropopause the clinometer temperatures were significantly lower than the specified minimum temperature, shown as a horizontal black dashed line in the figure. At the lower temperatures the clinometer scale factor non-linearity may exceed the specification. Later in the flight the temperature of the inner frame clinometer did begin to stabilize about 1 hour before the air temperature decrease, however the outer frame clinometer continued to warm up even during the last hour of the flight. Nevertheless, since this model of clinometer has worked reliably in comparable thermal environments on repeated balloon flights, including Antarctic flights, and it worked continuously during the EBEX engineering flight, we are not concerned about the thermal behavior.

connecting the outer frame clinometer to the crate.
The clinometer and magnetometer signals contained common mode noise in ground tests, as discussed in Section 3.5.4. In order to characterize the noise in these sensors in flight we identified a 120 second long time segment, the length of about two scan periods, when the azimuth and elevation speeds were quite constant and close to zero.
and the magnetic field and elevation and roll angles were changing minimally. Under these conditions the variation in the sensor signals should be dominated by noise in the ACS readout electronics or by other electronics, allowing us to set and upper bound on the noise in the sensors during flight.

Figure 5-9 shows the magnetometer and clinometer signals during the 120 second segment. Common mode noise spikes similar to those seen on the ground are present in many channels in both sensors and in the magnetometer azimuth solution throughout the segment. Although there is a smooth drift in some of the signals throughout the time segment, at the end of the segment a shift in DC level is apparent.

A similar shift is also present in the rotator motor requested PWM value and current, shown in Figure 5-10 suggesting possible interference of the motor with the magnetometer and clinometer signals. For the purpose of estimating the noise in the sensors due to the ACS readout and steady state electronics, we focus on the first half of the time segment, where the motor PWM and current signals are relatively constant. During the first 60 seconds of the segment the peak-to-peak value of each sensor signal provides an upper bound on the noise caused by the ACS readout and other steady state electronics, as shown in Table 5.4.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak-to-Peak Signal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mag_x</td>
<td>0.7 mG</td>
</tr>
<tr>
<td>mag_y</td>
<td>0.5 mG</td>
</tr>
<tr>
<td>mag_z</td>
<td>0.6 mG</td>
</tr>
<tr>
<td>mag_az</td>
<td>0.212°</td>
</tr>
<tr>
<td>clin_if_el</td>
<td>0.23'</td>
</tr>
<tr>
<td>clin_if_roll</td>
<td>0.24'</td>
</tr>
<tr>
<td>clin_of_el</td>
<td>0.054'</td>
</tr>
<tr>
<td>clin_of_roll</td>
<td>0.012'</td>
</tr>
</tbody>
</table>

Table 5.4: Noise on the clinometers and magnetometers during a roughly stationary 60 second period during the engineering flight.

Since the peak-to-peak value of the signals during the first half of the segment is lower than or similar to the sensor accuracy, there is not a driver to improve the
Figure 5-9: Magnetometer and clinometer signals during a 120 second segment of the engineering flight when the gondola was close to stationary.
Figure 5-10: Reaction wheel and rotator PWM and current signals during a 120 second segment of the engineering flight when the gondola was close to stationary.

noise in the readout electronics for future flights. However, the data from the end of the 120 second time segment suggests that motor currents through the gondola or PWM signals in the ACS crate can produce noise in the magnetometer and clinometer signals that may be more significant. A more detailed analysis of the noise in the magentometer and clinometer signals due to the motors should be completed in outdoor tests during integration for the long duration flight in the Palestine, TX, to ensure that interference in these signals does not limit the sensor accuracy for real-time pointing.
Magnetometer Azimuth Solution

The magnetometer provided azimuth solutions during the entire flight. The solutions were calculated by $fcp$ as described in Section 3.5.5 using

$$mag_{az} = \arctan\left(\frac{mag_y}{mag_x}\right) + mag_{model_{dec}}$$

(5.1)

This solution was found to be inaccurate in post-flight analysis because of the tilt of the outer frame table, and the magnetometer boom along with it, caused by the imbalance of the inner frame. The tilt in the magnetometer boom resulted in mixing of the magnetometer x and y components with the z component. Also, an apparent non-linearity in the magnetometer was detected by integrating the gyroscope azimuth solution over 360°.

In post-flight analysis we implemented an azimuth solution that takes into account the titling of the outer frame table and fits out the apparent non-linearity of the magnetometer with azimuth. This new magnetometer azimuth solution shows a marked improvement over the mag_{az} shown in Equation 5.1. However the new solution shows some correlations with azimuth speed that are not well understood.

The in-flight azimuth as calculated by Equation 5.1 would have been accurate to about 5°. However, the offset in the magnetometer angle that was determined on the ground during indexing of the sensor, described in Section 4.3.1 was inaccurate by about 11°. Due to the lack of other reliable azimuth sensors during the flight the inaccurate offset was not apparent and could not be corrected.

5.3.3 Global Positioning System (GPS)

As discussed in Section 3.5.5 the GPS receiver failed three times before the flight during integration in Ft. Sumner. In all cases, one of the four antenna input channels in the receiver did not receive antenna signals, resulting in no attitude solutions from the receiver. The single antenna channel failure mode was displayed by the receiver
the morning of the engineering flight in the high bay. When the gondola was on the launch pad and during the flight the diagnostic channel which indicates if the attitude solution meets a minimum accuracy criterion displayed a “bad solution” flag. However, the GPS did output attitude solutions. Since \textit{fcp} only writes the GPS attitude solution to the data file if a “good solution” flag is present, these attitude solutions were not written to disk in the usual channels. However, the GPS azimuth solution was recorded as an integer to a debugging channel which was created for testing on the ground, providing solutions to 1° precision. The heading data agrees well with the flight pointing solution, described below in Section 5.3.8, to about 1° in most samples. The data in the channel also includes occasional flags which indicate no solution was obtained by the receiver.

We are currently attempting to reproduce the GPS receiver failure mode which may allow us to understand and resolve the cause or causes of the failure. If we are unable to understand the receiver failure sufficiently well before integration and testing for the long duration flight we will consider using a different model of receiver.

The temperatures of the GPS receiver and antennas were not monitored during the flight since this model of receiver unit has flown on multiple balloon flights in North America and Antarctica.

5.3.4 Sun Sensor

Thermal Behavior

The sun sensor temperatures during the flight are shown in Figure 5.11. The computer and hard drive, show as \texttt{ss\_t\_cpu} and \texttt{ss\_t\_hdd} in the figure, respectively, remained within the specified operating temperature range.
Figure 5-11: Temperatures of the sun sensor during the engineering flight; for a description of the channel names see Table 5.3

Accuracy of Azimuth Solutions

The sun sensor did not provide reliable azimuth solutions during the flight. Since only five diodes along the part of the sensor facing the back of the gondola were used to calculate the azimuth solution, the sensor only functioned over an azimuth of about 130°. In addition, a number of problems were encountered even within this allowed azimuth regime. First, we saw spurious readings in diodes located furthest from the back of the gondola, most likely due to reflections and obscurations of the sun by the gondola before it reached the sensor. Second, the sun’s rays were distorted by the balloon when the sun was at higher elevations, producing erroneous solutions. Consequently, the sun sensor was unreliable between 16:35 to 19:00 UT. Finally, there may have been larger than expected errors of up to 0.5° in the positioning of the surface mount diode sensors on the electronics boards that support them, although the analysis of the mount angles is currently inconclusive. As a result, the sun sensor was not used in the real-time pointing solution. A plot showing the post-flight analysis of the sun sensor, and the new magnetometer solution for reference, is
shown in Figure 5-12. The portion shaded in blue shows the period of time when the sun’s rays were distorted by the presence of the balloon.

**Figure 5-12:** The post-flight analysis of the sun sensor and the new magnetometer solution for reference. The portion shaded in blue shows the period of time when the sun was at it’s maximal elevation and the sun’s rays were distorted by the presence of the balloon. (Figure courtesy of Seth Hillbrand).

Before the long duration flight we will complete a careful calibration of the sensor diodes with sun azimuth and elevation to properly characterize the two diode mount angles relative to the sensor and the individual diode gains; this can be completed off of the gondola. This calibration will also provide the exact function to which we should fit the five diodes for obtaining a solution; currently we use a Gaussian which, as some preliminary analysis shows, does not reflect the actual change in sun’s brightness with angle and may be limiting the accuracy of the sensor. We will also complete outdoor tests with the sun sensor mounted on the gondola to identify and try to eliminate spurious reflections from the baffling and other parts of the gondola. Finally, we note that during the EBEX long duration flight we will not encounter high sun elevations.
5.3.5 Star Camera

Thermal Behavior

The temperatures of the star camera components during the flight are shown in Figure 5-13. Based on the results of the thermal vacuum tests discussed in Section 4.1, we focus on the computer and lens temperatures, $t_{isc\_comp}$ and $t_{isc\_lens}$. In the tropopause the computer stayed well above the minimum allowed temperature and the lens heater, that was set to turn on at -20 °C by an automatic bang-bang switch, was never activated. During the day the computer temperature did not exceed the minimum or maximum operating temperatures, and it stabilized well before the late day decrease in the elevation of the sun.

![Figure 5-13: Temperatures of the star camera during the engineering flight; for a description of the channel names see Table 5.3](image)

Pointing Solutions

The star camera recorded sky images reliably throughout the flight and it provided pointing solutions before the launch when the sky was still dark. However, the star camera computer did not solve any images during the flight to provide real-time
pointing. Two primary factors contributed to the failure of the star camera in real-time:

1. **Gain**: The star camera gain factor defines how the number of electrons that are freed by photons incident on a given CCD pixel are converted to a number of bits by the analog to digital converter (ADC) in the camera. The gain units are electrons/ADC count. If the gain is set very low, a small number of electronics will saturate the ADC, while a higher gain allows for more electrons to be counted before the ADC is saturated. Post-flight measurements in the lab at Brown University and at the camera factory and analysis of flight data all show that the gain was set too low during the flight, either in a factory error or as a result of corruption of the camera firmware after the camera was shipped from the factory. As a result, the daytime images taken by the star camera were nearly saturated, showing very little contrast between the stars and the background sky.

2. **Focus**: The star camera was focused on the ground before the launch. However, as anticipated, the position of the lens corresponding to in-focus images was different at float altitudes due to the difference in temperature at float altitudes and on the ground. Post-flight tests of the camera over a range of temperatures show that the blur in the images taken during the flight is consistent with the blur in images taken on the ground over a similar temperature differential. Although the change in focus position at float altitudes was anticipated, because the daytime star camera images were nearly saturated the camera could not be focused during the flight.

Despite these two problems in flight, to date we have obtained pointing solutions for about 100 images in post-flight analysis. A new centroiding algorithm was written to locate the positions of the stars in the low contrast and out of focus images. The original star camera solver and a new solver routine were run
on the images for which a sufficient number of stars could be resolved by the centroiding algorithm. All but two of the solved images were recorded at the end of the flight when the sun was low in the sky and the gondola was nearly stationary.

5.3.6 Fiberoptic Gyroscopes

The fiberoptic gyroscopes did not display any failure modes during the flight. The temperatures of the boxes remained well within the gyroscope operating temperature range, -40 °C to 75 °C, as shown in Figure 5-14. The boxes did not cool significantly in the tropopause since the set point for the box heaters was set to 0 °C. The boxes were covered on five sides with foam to provide insulation in the tropopause.

![Figure 5-14: Temperatures of the gyroscope boxes during the engineering flight; for a description of the channel names see Table 5.3](image)

The noise in the gyroscopes during flight appears to be similar to that on the ground, as discussed in section 3.5.5. We can only obtain a precise measure of the gyroscope noise level in flight by integrating the rate signals over a time segment and comparing the gyroscope displacement to that reported by a precise and accurate
sensor, such as the star camera. This analysis requires a large number of star camera solutions during gondola scans in order to constrain properties such as the three angles that define the mounting of the gyroscope box to the inner frame, as discussed in Section 3.5.7. This analysis has not been completed for the engineering flight due to a lack of star camera solutions during the flight.

5.3.7 Absolute Rotary Encoder

The Gurley A25S encoder value fluctuated over only 1 bit during the entire flight since the inner frame elevation was not changed. There was no temperature sensor on the encoder since this model has flown successfully on a number of other balloon flights.

5.3.8 Complete Pointing Solution

Real-Time Solution

A limited number of sensors were included in the real-time pointing solution due to the lack of reliable sensors during the flight, as detailed above. The magnetometer, inner frame elevation clinometer, and elevation encoder were included in the pointing solution during the entire flight. The star camera was included during the beginning part of the flight since star camera pointing solutions were obtained before launch when the sky was still dark and these solutions were evolved forward in time using the gyroscopes.

Reconstruction Solution

The reconstruction pointing solution for the entire flight was calculated using a particle filter approach, as described in Section 3.5.7. A particle filter was chosen since previous experience suggests that a Kalman filter approach would likely fail on this data set because of the lack of the high accuracy star camera readings in conjunction
with the noise level and lower accuracy of the other sensors. The filter was tested on a simulated time stream of noisy data and the constrained parameters converged to reasonable values \cite{26}. Next the filter was run on the flight data set and the parameters constrained by the filter did converge. The inputs to the filter were data from the three gyroscopes in gyroscope box A, the magnetometer, and the inner and outer frame clinometers throughout the flight, and the star camera solutions from late in the flight. The parameters that were constrained by the filter include the scale factor, offset, and mount angle relative to the gondola for each gyroscope and the magnetometer and the mount angles of the clinometers relative to the gondola. The particle filter solution agrees well with the new magnetometer solution, described in Equation 5.1 throughout the flight, and with the star camera solutions late in the flight. Additional tests will be completed to verify the robustness of the software.

5.3.9 Control of the Gondola

Motor Electronics Thermal Behavior

The motor control box temperatures are shown in figure 5-15 as $t_{\text{rxnmc}}$, $t_{\text{pivmc}}$ and $t_{\text{elmc}}$ for the reaction wheel, rotator, and elevation motors, respectively. The temperature of the reaction wheel motor controller box was below the minimum operating temperature of 0 °C for about half the flight\footnote{The elevation motor control box temperature was below 0 °C during almost the entire flight, however the motor controller was not powered}. However, the boxes were tested and performed well at temperatures down to $\sim$ -40 °C during the thermal vacuum tests, discussed in Section 4.1 and this model of motor control box has flown on numerous balloon flights without any issues. The motor control boxes were covered on five sides with foam to provide insulation in the tropopause.

The temperature of the rotator housing, shown as $t_{\text{pivmot}}$ in Figure 5-15, barely fell below 0 °C, the temperature at which an increased current draw was observed in the thermal vacuum tests, discussed in Section 4.1. Since the conditions in the
tropopause and at float altitudes over Antarctica will not be significantly cooler than those encountered in the engineering flight, we can conclude that the cold regime of the thermal behavior of the rotator is acceptable for the long duration flight. However, the rotator did not begin to cool down until later in the day with the decrease in the elevation of the sun, suggesting that the warmer regime of the thermal design should be reevaluated before the long duration flight. The rotator was covered in a multi-piece blanket made of aluminized mylar to prevent the bare Aluminum casing from overheating in the sun. The reaction wheel motor temperature, shown as $t_{\text{rxnmot}}$ in Figure 5-15, cooled to -9 °C, just above the temperature at which the required current for the reaction wheel motor increased significantly in the thermal vacuum tests. It is impossible to assess the thermal behavior of the elevation motor during the flight since it was not powered for most of the flight.

Figure 5-15: Temperatures of the motors and motor control boxes during the engineering flight; for a description of the channel names see Table 5.3. The black dashed horizontal line shows the minimum specified operating temperature of the motor controllers.
Azimuth Control

Scans were performed in azimuth, including narrow and wide azimuth scans back and forth and a dipole scan with continuous motion in one direction. However, a number of times during the flight the gondola did not move in azimuth as expected based on the level of the PWM signal commanded to the system and the current drawn by the rotator motor. Post-flight analysis suggests that a combination of an intermittently seized universal joint and the imbalance of the gondola resulted in the inability of the gondola to scan in azimuth at times [27].

The universal joint, shown in Figure 3-4, is made primarily of stainless steel, including the pins that join the cross pieces. However bronze bushings built into the steel pieces allow for motion of the joint components around the pins. Given that the bronze bushings have a higher coefficient of thermal expansion than the steel pins and cross pieces, and the clearance between the moving pieces is very tight, it is possible that the joint can seize when heated. After the flight a test was completed in the lab in which the universal joint was heated while the temperature of the joint was monitored and the joint was moved by hand. The tests showed that at 23 °C, 40 °C, 55 °C and 65 °C the universal joint moved freely, showed some noticeable increased stiction, showed greatly increased stiction, and seized, respectively. The universal joint was subsequently cooled and heated between 55 °C and 60 °C, and the seizure temperature was identified as about 57 °C. During the flight the universal joint temperature was not monitored, however, bare aluminum is known to heat excessively in the bare sun [6].

If the universal joint is seized and the gondola is unbalanced, at some azimuth angles the rotator motor needs to lift the gondola weight in order to move in azimuth in a particular direction. The clinometer and magnetometer data from the periods in flight when the gondola did not rotate in azimuth as expected supports the theory of a seized universal joint stalling gondola motion in one direction. Before the long duration flight we will rebuild the inner frame so that it will be balanced, we will
redesign the universal joint, and we will increase the voltage provided to the motors to allow for more torque.

**Elevation Control**

The elevation control was not tested at float altitudes because the elevation actuator broke during the launch.

### 5.4 Evaluation of the Cryostat and Related Electronics

#### 5.4.1 Cryostat

Most of the temperatures within the cryostat, including those of the focal plane, were slightly lower than the nominal ground operating temperatures due to the lower optical loading through the window at float altitudes. The one exception is the temperature of the optics box which was about 0.8 K above the expected temperature. This was caused by an unexplained refrigerator expiration just before the launch, well before the expected expiration time. The motors that open the valves to the Nitrogen and Helium tanks in the cryostat, allowing for venting of the cryogens to prevent pressure build-up on landing and during recovery, moved when commanded just before system shutdown at termination.

#### 5.4.2 Bolometer and Half-Wave Plate Readout Crates

The temperatures of the DfMUX boards remained below the maximum operating temperature of 65 °C, however the crate temperatures did not stabilize during the flight and they only decreased late in the day with the decrease in the sun elevation. The temperatures of the warmest DfMUX board are shown in Figure 5-16. We are
Figure 5-16: Temperatures of DfMUX board 59 during the flight. This board reached the highest operating temperatures of all of the DfMUX boards during the flight. The temperature signals correspond to temperatures of the board at the front panel (DfMUX frontpanel), the backplane (DfMUX backplane), and on the field programmable gate array on the board (DfMUX FPGA) in addition to two temperatures on the mezzanine board (mezz #1 and mezz #2). The colored lines show the following events: red (gondola moved outside), green (launch), black (beginning and end of in-flight tuning), blue (19:00 local time when the sun was low in the sky), and yellow (termination). (Figure Courtesy of François Aubin).

currently designing a liquid cooling system to ensure that the bolometer readout crates do not overheat during continuous daytime operation in the long duration flight.

The half-wave plate (HWP) rotated continuously on the magnetic bearing during the entire flight. The large accelerations experienced at launch and when the linear actuator broke did not dislodge the HWP from the magnetic bearing, providing a stringent test of mechanical robustness of the rotor and stator assembly. One of the two HWP DfMUX boards functioned continuously for most of the flight, with the exception of some parser crashes in the tropopause and one additional crash while at
float; the board recovered after all crashes upon reboot. The second DfMUX board, which was not well monitored during the flight, crashed at some point early in the flight and was not rebooted.

5.4.3 CANBUS and Timing System

The cryostat electronics housekeeping boards read out cryostat temperatures and other housekeeping sensors continuously, and the digital outputs that control the half-wave plate gripping before termination functioned properly. The board temperatures did not exceed the allowed operating temperature range. Some of the housekeeping boards will be redesigned for the long-duration flight to reduce the noise on some signals.

All subsystems read from the primary timing board continuously during the flight. There were no known general problems with the timing system and the data allowed us to properly synchronize the three asynchronous timestreams. Over the 19 hour duration of the flight day, the two DfMUX crates remained synchronized within about 300 \( \mu s \), two orders of magnitude less than the bolometer time constant. Each bolometer crate did show a small number of missing time samples and the ACS data included some glitches that were easily removed. We will modify the firmware on the ACS readout card that reads in the signal to eliminate the glitches.

5.4.4 Bolometers and SQUIDs

The bolometers and SQUIDS were tuned using automated algorithms during the flight, although two SQUIDS were unable to be tuned successfully. 61% of the bolometers that were wired to signal channels responded as expected to network analysis during the flight, and 94% of the detectors that responded to the network analysis were successfully biased into transition. A preliminary analysis of the bolometer noise indicates that the noise levels in flight were higher than predicted, especially at 150 and 410 GHz.
Chapter 6

In Depth Analysis of Engineering Flight Data

6.1 Assessment of Scan Synchronous Temperature Signals

6.1.1 Overview and Goal of the Analysis

As discussed in Section 3.3.2, instrumental polarization describes the generation of a polarized signal by the instrument measured at the detectors. Since EBEX measures differentials in the polarization of the CMB across the sky, an instrumental signal that is constant in time will only affect the absolute calibration of EBEX, which we need not characterize to high precision. However, a time varying polarized signal that propagates to the detectors will affect the sensitivity of EBEX to measurements of the Q and U Stokes vectors across the EBEX CMB patch. Polarized emission from parts of the instrument that change temperature on scan timescales can produce a systematic polarized signal.

We examined temperature signals around the gondola during three azimuth scans to characterize the temperature changes in components such as the baffles and mirrors.
In our analysis we aimed to assess two things:

- The amplitude of scan synchronous temperature signals present in the mirrors and baffles, and whether or not we believe the signals reflect true temperature changes.
- If the noise on the AD590 signals is low enough to allow for characterization of a scan synchronous temperature change to sufficient precision.

We examined the signals from various AD590 sensors placed on the gondola and in electronics boxes, as detailed in Table 6.1. The analysis showed that many of the temperature signals contain noise pickup from other electronics on the gondola, as will be discussed below. As a result we examined the temperature signals from a variety of AD590s so we can compare the AD590 signals that were mounted deep in electronics boxes and inside the baffling, where we do not expect a scan synchronous signal induced by a real temperature change, with those mounted to the gondola frame and baffles where a real temperature change is more likely to occur. In the cases where the sensors were embedded in electronics boxes no shield was connected to the AD590 casing, but for sensors mounted directly to the gondola and baffles the shield of the cables was attached to the AD590 casing, as noted in Table 6.1. The AD590 datasheet indicates the sensor noise is $9 \times 10^{-5} \degree C$ at the 5 Hz slow ACS sampling rate, and the 16-bit and 32-bit temperature channels have a resolution of $0.006 \degree C$ and $9 \times 10^{-8} \degree C$, respectively. All temperature channels in Table 6.1 were 32 bits except for $T_{ACS,P+S_L}$, $T_{ACS,P+S_R}$, $T_{GYROA}$ and $T_{GYROB}$, which were 16-bit channels.

We analyzed the temperature signals recorded during three different azimuth scans: the “Saturn Scan”, when we attempted to map Saturn early in the flight, a short scan later in the flight referred to as the “Late Scan”, and the CMB “Dipole Scan” that was performed at the end of the flight. Figure 6–1 shows the average central azimuth throughout each scan as reported by the magnetometer, the average location of the sun during each scan, and the time of day for each of these scans.

Knowledge of the sun position during the scans can be used to check the observed
<table>
<thead>
<tr>
<th>Label Name</th>
<th>Location</th>
<th>Shield Connected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_ACS_P+S_L</td>
<td>ACS crate left power</td>
<td>No</td>
</tr>
<tr>
<td>T_ACS_P+S_R</td>
<td>ACS crate right power</td>
<td>No</td>
</tr>
<tr>
<td>T_BAF_BAK_OUT</td>
<td>Back outer baffle (mounted to inside surface)</td>
<td>Yes</td>
</tr>
<tr>
<td>T_BAF_IN_L_F</td>
<td>Front L inner baffle</td>
<td>Yes</td>
</tr>
<tr>
<td>T_BAF_IN_R_F</td>
<td>Front R inner baffle</td>
<td>Yes</td>
</tr>
<tr>
<td>T_BAF_OUT_L</td>
<td>Front L outer baffle</td>
<td>Yes</td>
</tr>
<tr>
<td>T_BAF_OUT_R</td>
<td>Front R outer baffle</td>
<td>Yes</td>
</tr>
<tr>
<td>T_GYROA</td>
<td>Outside of gyroscope box A</td>
<td>Yes</td>
</tr>
<tr>
<td>T_GYROB</td>
<td>Outside of gyroscope box B</td>
<td>Yes</td>
</tr>
<tr>
<td>T_IF_PRI</td>
<td>Inner frame near primary mirror</td>
<td>Yes</td>
</tr>
<tr>
<td>T_IF_SEC</td>
<td>Inner frame near secondary mirror</td>
<td>Yes</td>
</tr>
<tr>
<td>T_OF1_IN</td>
<td>Outer frame table, inside baffles</td>
<td>Yes</td>
</tr>
<tr>
<td>T_OF2_OUT</td>
<td>Outer frame table, outside baffles</td>
<td>Yes</td>
</tr>
<tr>
<td>T_PRI_L</td>
<td>Primary mirror left, back side</td>
<td>Yes</td>
</tr>
<tr>
<td>T_PRI_R</td>
<td>Primary mirror right, back side</td>
<td>Yes</td>
</tr>
<tr>
<td>T_SEC_L</td>
<td>Secondary mirror left, back side</td>
<td>Yes</td>
</tr>
<tr>
<td>T_SEC_R</td>
<td>Secondary mirror right, back side</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 6.1: AD590 temperature sensors that were examined in the scan synchronous temperature analysis.

temperature signals against expectations to determine if the general trend in the temperature signal reflects a true scan synchronous temperature change rather than some electronics noise pickup; some unexpected signals may arise from unaccounted for reflections of the sun off the gondola. During the Saturn and Late Scans, as the gondola moves to lower azimuth the sun’s rays become more orthogonal to the back of the gondola. Consequently, during these scans we expect the gondola temperatures to change monotonically, with temperature increasing with decreasing azimuth. During the Dipole Scan the sun is located at an average azimuth of 302°, and the gondola moves in decreasing azimuth. During this scan we expect temperatures to peak near a gondola azimuth of 122°, and the right baffle temperature to peak earlier in time and at a higher azimuth than the left baffle.
Figure 6-1: Azimuth scan profile and sun location for the three scans examined. The bottom row shows the EBEX gondola as viewed from above, looking down along the gravity vector; the angles shown are azimuth referenced to North. The microwave beam shows the incoming beam for the center of the scan and the Sun is shown at its average azimuth during the scan. Universal Time (UT) is 6 hours ahead of New Mexico’s Mountain Time (MT).

6.1.2 Analysis of Gondola Temperature Measurements

For each of the temperature signals in each of the scans we did the following:

1. **Remove the Drift:** Plot the temperature vs. index to locate segments of data where the temperature drift can be fit to a second order polynomial. Data segments which did not vary smoothly on timescales longer than a scan period were excluded. A polynomial fit of second order was performed and the result was subtracted from the data. This removes drifts that may be induced by the changing elevation or azimuth of the sun or electronics effects that occur on timescales much greater than the scan. An example plot is shown in Figure 6-2.
Figure 6-2: Removing the drift of the temperature data. This plot from the Saturn San, characteristic of most of the data sets, shows smoothly varying data. The index is at 5 Hz.

2. **Despike:** We chose to despike the temperature data since, in some temperature signals, we observed rapid changes that we suspect resulted from electrical noise pickup since a large thermal mass such as a mirror is unlikely to change temperature so quickly. Figure 6-3 shows the gondola azimuth and secondary mirror temperatures during part of the Saturn Scan. The temperature spikes contain gradients two orders of magnitude larger than the general temperature drift during the scans. In order to remove the spikes the standard deviation of the temperature signals in each scan was computed and temperatures that lie outside of $2\sigma$ were removed. The plots in Figure 6-4 show examples of raw data with and without clear noise spikes, in green, and the despiked component in pink. The duration of the spikes is about 0.2 s.

3. **Bin in Azimuth:** The temperature data was binned in azimuth and temperature vs. azimuth plots were made. Since in some cases the plots showed scan synchronous signals that we suspect are not thermal in origin we binned the temperature signals in rotator current, one potential cause of the non-thermal
Figure 6-3: The gondola azimuth and the secondary mirror temperatures during part of the Saturn Scan.

scan-synchronous signals, discussed in more detail below. The resulting plots show temperature vs. azimuth with a colorbar showing rotator current. Characteristic plots of the temperature signals for the duration of each scan are shown in Figures 6−5, 6−6, and 6−7 for the Saturn, Late, and Dipole scans, respectively. The magenta points show the raw data after drift and spike removal and the circular points show the magenta points binned in azimuth and rotator current. Note that the diagonal stripes in the t_acs_p+s_l plots are artifacts of removing the polyfit offset on temperature data with bit noise.

6.1.3 Discussion of the Results

We see three types of signals in the plots of the temperature sensors:
Figure 6-4: Despiking the temperature data. Both plots show data from the Saturn Scan.  

(a) This plot, characteristic of about half of the data sets, shows a signal with no large spikes, and the spikes that are present are not asymmetric.

(b) The signal in this plot contains large asymmetric spikes which are scan synchronous. The index is at 5 Hz.
Figure 6-5: Plots showing Saturn Scan temperature data in azimuth bins with color coding for rotator current.
Figure 6-6: Plots showing Late Scan temperature data in azimuth bins with color coding for rotator current.
Dipole Scan

Figure 6-7: Plots showing Dipole Scan temperature data in azimuth bins with color coding for rotator current.
1. **No clear scan synchronous temperature dependence:** An example is the gyroscope box A and ACS crate signals, \( t_{\text{gyroa}} \) and \( t_{\text{acs p+s l}} \), in the Saturn Scan shown in Figure 6-5 and all signals in the Late Scan, shown in Figure 6-6.

2. **A scan synchronous signal is present but it cannot be physically motivated:** Examples of this type of signal appear in the AD590s on the left and right side of the primary mirror, \( t_{\text{pri l}} \) and \( t_{\text{pri r}} \), during the Saturn Scan, shown in Figure 6-5. In these plots the temperature signals do not change monotonically and they do not decrease with azimuth as expected based on the sun’s position. Additionally the signals on the opposite sides of the mirror do not follow the same trend, where during the scan one signal trend is low to high to low while the other signal trend is the opposite. Finally, one would not expect a large thermal mass such as the primary mirror, or a highly baffled object such as the inner frame, to respond to temperature changes on the short timescales of the Saturn Scan. Although we strongly suspect these temperature signals do not show real temperature change across the mirrors, further analysis needs to be completed to understand the signals, as described below in Section 6.1.5.

3. **A scan synchronous signal that likely shows real temperature change:** An example is the outer baffle temperature signals in the Dipole Scan which do change with azimuth in a way that may result from real temperature change, shown in Figure 6-7 as \( t_{\text{baf bk out}} \) and \( t_{\text{baf out r}} \) and \( t_{\text{baf out l}} \). The mylar on the outer baffles contains a very low thermal mass and the baffles are well exposed to the sun. By contrast, the inner baffles, which are shielded from the sun, do not show a change in signal with azimuth during the dipole scan, shown in the flat shape of \( t_{\text{baf in r f}} \) in Figure 6-7.
The right, center, and left baffle temperatures peak at azimuth values significantly higher than the naively expected 122° for the center baffle, based on the position of the sun. Additionally, the left baffle peaks at a higher azimuth and before the right baffle in the time domain, against our expectations based on the gondola rotation in the negative azimuth direction. It is possible that, since the sensors were mounted to the front side of the back baffle, the sun shined on the sensors either directly or through reflections, causing the temperatures to peak at an unexpected azimuth.

6.1.4 Assessment of Baffle Temperature Changes and AD590 Noise

In Appendix G we conclude that scan synchronous temperature changes in the baffles and the end-to-end noise in the AD590 signals must be below 1 K to insure that no significant polarized signal is induced by the temperature changes in the detectors. Table 6.2 shows the standard deviations of the AD590 signals during the three scans examined in the engineering flight. The values for $\sigma_T$ are typically between 0.001 °C and 0.01 °C. Although the values of $\sigma_T$ for the left and right outer baffles are higher in the dipole scan, where we suspect real temperature change, the standard deviation of the AD590 signals is well below the required 1 K in all sensors in all scans. Similarly, during all scans the peak to peak change in the AD590 signal, whether resulting from noise pickup or real temperature change, is below the required 1 K. We conclude that both the scan synchronous temperature changes in the baffles and the AD590 noise are sufficiently low in all sensors in all scans.

6.1.5 Noise Pickup in the AD590 Signals

If the scan synchronous temperature signals described above are not produced by real temperature change then the cause is some source of noise in the EBEX electronics.
The colorbars on the plots in Figures 6−5 through 6−7 show a scan synchronous rotator current signal. Although the correlation between the azimuth and the rotator current is expected since the rotator current peaks at scan turnarounds, the correlation between rotator current and temperature signal may or may not be causal. However, it is possible that the surge in current to the rotator motor at the scan endpoints produced electromagnetic interference that was picked up by the AD590 cables or induced an offset in the ACS card temperature channels.

In order to understand how well the rotator current is correlated with the temperature signals we computed the covariance of each pre-despiked temperature signal with the rotator current. Here we are not merely probing the expected correlation between azimuth, rotator current, and temperature, but rather a point by point correlation in time between the temperature and the rotator current. This latter correlation should

<table>
<thead>
<tr>
<th>Label Name</th>
<th>Saturn $\sigma_T$ (°C)</th>
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<th>Dipole $\sigma_T$ (°C)</th>
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<tbody>
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<td>0.000</td>
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<td>0.002</td>
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</tr>
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<td>0.001</td>
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<tr>
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<td>0.007</td>
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<td>0.005</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 6.2: The standard deviation of the temperature signals binned in azimuth over the Saturn, Late and Dipole Scans.
be present only if the rotator current contributes significantly to the noise in the temperature signals. The normalized standard deviation of the covariance, \( \frac{\sqrt{\det(\text{cov}(T,I))}}{\sigma_T \sigma_I} \), is shown in Table 6.3. Note that a perfect correlation between two data streams will result in \( \frac{\sqrt{\det(\text{cov}(T,I))}}{\sigma_T \sigma_I} = 0 \), while no correlation at all results in \( \frac{\sqrt{\det(\text{cov}(T,I))}}{\sigma_T \sigma_I} = 1 \). We show \( 1 - \frac{\sqrt{\det(\text{cov}(T,I))}}{\sigma_T \sigma_I} \) since most of the values are so close to 1. We also computed \( \frac{\sqrt{\det(\text{cov}(T(t+\Delta t),I(t)))}}{\sigma_T \sigma_I} \), where \( \Delta t = 0.2 \, \text{s}, 0.4 \, \text{s}, 0.6 \, \text{s}, 0.8 \, \text{s}, \) and \( 1 \, \text{s} \) to test for a lagged response in the temperature signal to changes in the current; these time intervals were dictated by the 5 Hz slow ACS sampling rate. The results did not differ significantly from the case of \( \Delta t = 0 \).

<table>
<thead>
<tr>
<th>Label Name</th>
<th>Saturn</th>
<th>Late</th>
<th>Dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_ACS_P+S_L</td>
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<tr>
<td>T_ACS_P+S_R</td>
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<tr>
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<tr>
<td>T_OF1_IN</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>T_OF2_OUT</td>
<td>0.015</td>
<td>0.015</td>
<td>0.001</td>
</tr>
<tr>
<td>T_PRI_L</td>
<td>0.030</td>
<td>0.006</td>
<td>0.000</td>
</tr>
<tr>
<td>T_PRI_R</td>
<td>0.016</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>T_SEC_L</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>T_SEC_R</td>
<td>0.006</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 6.3: The normalized square root of the determinant of the covariance matrix between the unbinned temperature signal in column 1 with the unbinned rotator current.

The values of the correlations are low, with most under 1%. One significant exception is the correlation calculated for the sensor on the inner frame near the
primary mirror, T_{IF,PRI}, in the Saturn and Late Scans; it is noteworthy that the top of the inner frame is geographically close to the rotator motor. The correlation calculations show no clear correlation between temperature and motor current in most channels. Further study of the sources of non-physically motivated scan synchronous temperature signals is required to gain a full understanding of the data. We can look for correlations between the temperature and the sensor wire length, physical proximity to noisy electronics like motors, how well the component was heat sunk to the gondola, and whether or not the AD590 case was connected to the cable shield.

6.1.6 Conclusions

We can conclude that no physically motivated scan synchronous temperature changes were observed in the mirrors or baffles in most scans, however the outer baffles showed potential for real scan synchronous temperature changes, particularly during the Dipole Scan. Many temperature signals do show non-negligible electrical noise pickup. Nevertheless, we conclude that the scan synchronous temperature changes in the baffles and the AD590 noise are sufficiently low to meet the 1 K requirement set in Appendix G.

6.2 Search for the Galactic Signal

6.2.1 Overview and Goal of the Analysis

One of the goals of the North American engineering flight was to determine the bolometer responsivity at float altitudes. During the flight the gondola did not perform the planned calibrator scans across Saturn due to a combination of the error in the real-time azimuth pointing solution and the constant gondola elevation resulting from the broken linear actuator. However, the gondola did scan across the galactic plane a number of times during the middle of the flight, and late in the flight a CMB
A dipole scan was performed\(^1\). Since the optical efficiency of the receiver was relatively low during the flight due to the absence of anti-reflection coatings on the half-wave plate (HWP) and lenses and the presence of neutral density filters\(^2\) over the 250 and 410 GHz bolometers, the anticipated level of both the galactic and dipole signals is quite low. The galactic and dipole signals have not yet been detected in the data, although analysis is ongoing. Below we report on the results of the search for the galactic signal to date.

### 6.2.2 The Galactic Scans

During the middle of the flight the gondola scanned across the galactic plane 12 times; the pointing is shown in white tracks on the sky in Figure [6-8]. The figure shows maps of the sky flux at 250 and 410 GHz with the CMB monopole\(^3\) and dipole signals removed. The maps were produced using Model 8 of Finkbeiner et al. \[^{17}\] discussed in Section 1.7, and the Hierarchical Equal Area isoLatitude Pixelization (HEALPIX) software package\(^4\). HEALPIX partitions the spherical sky into pixels for two-dimensional mapping so that each pixel contains nearly the same amount of surface area \[^{23}\]. The figure emphasizes that the galactic crossings during the flight occurred in two distinct longitude regions: near 145°, where the galactic flux is relatively low, and near 350°, where the galactic flux is significantly higher.

---

\(^1\)The CMB dipole signal is produced by the motion of the solar system relative to the nearly isotropic CMB radiation field \[^{18}\]. The orientation of the dipole signal during the flight allowed for scanning of only a small component of the signal.

\(^2\)Neutral density filters were placed over the 250 and 410 GHz bolometers for the engineering flight to allow for pre-flight ground tests without saturation of the bolometers, described in Section 4.4.

\(^3\)The CMB monopole is the mean background temperature of 2.725 K.

\(^4\)http://healpix.jpl.nasa.gov/
Figure 6-8: EBEX engineering flight crossings over the galactic plane, in white, with the CMB monopole and dipole removed. The flux scale maximum is equal to the maximum flux in all of the EBEX crossings divided by 5.
6.2.3 The Data Set

The analysis described below included all light\textsuperscript{5} 250 and 410 GHz bolometers which met two requirements: they were successfully tuned by the read out system at the beginning of the flight and their noise during the flight was less than twice the predicted value\textsuperscript{6}. The 25 bolometers were spread over five readout boards. We also examined 17 dark\textsuperscript{7} and eccosorb\textsuperscript{8} bolometers that met the same requirements, for comparison. It should be noted that there is evidence from lab tests of non-negligible cross-talk between both the eccosorb and dark bolometers and the light bolometers.

6.2.4 The Analysis

1. HWP Template Subtraction: Since the polarization fraction of the galactic dust emission is expected to be roughly 5\%, we chose to look first at the temperature, rather than the polarization, signal. The raw data timestream is modulated at four times the HWP frequency, as described in Section 3.4.2. To allow for subtraction of the HWP signal modulation from the raw bolometer signal, the HWP template signal was estimated by fitting the HWP encoder signal to a sum of 8 harmonics. The HWP template signal was then subtracted from the raw bolometer data after the removal of a linear drift. This subtraction algorithm was performed on three separate 30 minute segments of data which contained all 12 galactic crossings.

2. DfMUX Gain Application: Since the gain of the DfMUX readout boards was increased in the middle of the flight, the bolometer signals read out before the gain change were multiplied by the effective DfMUX gain change. The value of the gain change was estimated by determining the peak-to-peak amplitude

\textsuperscript{5}So-called light bolometers were exposed to radiation from the sky through the cryostat window.

\textsuperscript{6}The galactic signal at 150 GHz is relatively weak so these bolometers were not included in the analysis.

\textsuperscript{7}Aluminum tape was placed over the wave guide of the so-called dark bolometers

\textsuperscript{8}So-called eccosorb bolometers were obscured by a plug of ECCOSORB microwave absorber
of the HWP signal in the raw bolometer data just before and just after the gain change and taking the ratio; this allowed for the best signal to noise in the estimate of the gain.

3. **Alignment of Data Timestreams** The bolometer data was aligned with the ACS data using common time stamps from the system-wide timing system, described in Section 3.2.6. The ACS data had previously been interpolated to increase the sample rate to match that of the bolometers.

4. **Calculation of Individual Bolometer Pointing**: Since the pointing of each bolometer is offset from the pointing of the center of the focal plane in azimuth and elevation by up to a couple of degrees, the galactic latitude and longitude for each bolometer was computed using the clinometer elevation and the new magnetometer azimuth solution, described in Section 5.3.2. Figure 6-9 includes plots of galactic latitude and longitude for a single bolometer for each of the galactic crossings appended together.

5. **Crossings of Interest**: After looking at the HWP template removed time streams, one typical example of which is shown in Figure 6-10, we concluded that we should focus on crossings 1 through 6 and 9. The bolometer signals in other crossings show unusual and not well understood behavior such as extreme drifts and changes in the noise. Crossings 1 and 9 were made close to the galactic center where the signal should be highest. However, during these crossings the sun azimuth was within 90° of the microwave beam for part or all of each crossing, coming as close as 60° in azimuth. The sun azimuth was more than 90° away from the gondola azimuth during crossings 2 through 6, however the signal is expected to be weak at the corresponding galactic longitudes. The gondola speed was about 1 deg/s or less during crossings 1 and 9 while it was up to almost 8 deg/s in some other crossings.

The unusual behavior that almost all of the bolometers exhibited in crossings 7,
Figure 6-9: Galactic latitude and longitude pointing for a single bolometer. The plots include data from the 12 separate crossings appended, labeled at the top of the plot. The red vertical lines delineate the different galactic crossings. The index runs at 191 Hz; 10,000 indices = 52 seconds.
Figure 6-10: Plots of bolometer power in ADU, with color coding for galactic latitude, for a typical light bolometer. The plots include data from the 12 separate crossings appended, labeled at the top of the plot. The red vertical lines delineate the different galactic crossings. The index runs at 191 Hz; 10,000 indices = 52 seconds.
8, 11 and 12 is not well understood, although we note that the sun azimuth was within 90° of the microwave beam azimuth during these crossings. The unusual signals may also be caused by interference from the motors or large gondola accelerations. None of these unusual features was prominently present in the eccosorb or dark bolometers.

6. **Corrected for Relative Responsivity**: The relative responsivity of the bolometers was normalized by computing and applying a normalized gain factor for each bolometer. The responsivity was estimated as $\frac{1}{V_{\text{bias}}}$, where $V_{\text{bias}}$ is the value of the bolometer voltage bias. This estimate of the responsivity should be valid when the bolometer is biased deep in the superconducting transition [33]. The estimate of the responsivity is likely to be accurate to roughly a factor of two, based on our knowledge of the bolometer bias position during the flight and the discrepancy between the measured and estimated responsivity from ground tests, discussed in Section 4.4.

7. **Binning of the Signals in Galactic Latitude**: Each bolometer was binned in equal sized galactic latitude bins during each crossing. The error on the binned bolometer power data points is equal to the RMS of the bolometer signals in that bin. After examining plots of each bolometer binned in each crossing, only two bolometers in crossing 9 were rejected for an anomalous signal shape that was not understood. In Appendix I also show plots of the individual binned bolometer signals in crossing 1.

8. **Co-Adding Signals from Binned Bolometers**: After removal of an offset for each binned bolometer in each crossing, a weighted sum\(^9\) of the bolometers was performed for each crossing, and for multiple crossings at once.

---

\(^9\)The weight of each bolometer signal in each bin was equal to the inverse of the error on that data point squared.
Figure 6-11 shows the binned and co-added signal for crossing 1 with 0.5° wide latitude bins. A lower signal in ADU corresponds to a higher flux on the bolometer. The data show a possible detection of the galactic plane, however the error bars are large compared to the dip in the amplitude of the signal of roughly 1 ADU. Additionally, there is a drift in the signal with latitude. One possible cause of the drift is the position of the sun during the crossing; the sun azimuth drifted from 65° to 75° away from the microwave beam azimuth during the crossing.

![Figure 6-11: Plot of all 25 bolometers binned and co-added during crossing 1.](image)

No candidate signal was present in the plots of binned and co-added bolometers from crossing 9, or from crossings 2 through 6 alone or summed together. For reference, in Appendix I we show plots of binned and co-added bolometers for crossing 9 (excluding the two bolometers that showed an unusual drift during this crossing) and for all bolometers in crossings 2 through 6 summed together.
6.2.5 Discussion of Preliminary Results

We have not yet resolved a clear galactic signal, however the plot in Figure 6-11 shows that a signal may be present. None of the other crossings alone or summed together showed a similarly promising signal. In Appendix H we calculate an estimate of the expected signal in each bolometer at 250 and 410 GHz in crossings 1 and 2, which are representative of the expected signals in the high flux and low flux longitude crossings. The expected signal level is about 2 ADU and 0.2 ADU in crossings 1 and 2, respectively, at both frequencies, with a width of about 3°. The possible signal in crossing 1 is of the expected order of magnitude, although the shape is less peaked and wider by a few degrees than the example estimated signal shown in Figure H-1. Given the size of the error bars in the individual binned bolometer plots and the co-added binned bolometer plots we are not surprised to detect no signal in crossings 2 through 6, which were made in a low flux longitude region. We expect to see a signal in crossing 9 similar to that seen in crossing 1, based on the flux profiles made for each bolometer in each crossing and it is not clear why we do not.

6.2.6 Future Work

We will reduce the noise in the bolometer signals by low-pass filtering the data. We will also demodulate the data to search for the polarized galactic signal which is weaker, but may also be significantly lower in noise, than the temperature signal. After reducing the noise as much as possible, we will either resolve a convincing signal, providing an estimate of the average responsivity at float altitudes, or we will place an upper limit on the responsivity. We will also search for the cause of the unexpected drifts in the bolometer HWP template removed time stream in crossings 7, 8, 11 and 12, where we can cross-correlate the bolometer signal with potential noise sources such as the sun position, motor currents, and azimuth acceleration.

\[10\text{For a discussion of demodulation of HWP modulated data see Johnson et al., 2007[35].}\]
6.2.7 Conclusions

Many of the goals of the engineering test flight were met. However, the known low optical efficiency of the receiver and the absence of a calibrator scan on Saturn have made the characterization of the responsivity challenging. During the long duration flight the optical efficiency will improve significantly due to three factors: the presence of anti-reflection coatings on the HWP and lenses, the absence of the neutral density filter on the 250 and 410 GHz bolometers, and the thinner window on the cryostat. Additionally, tests in the lab show responsivities similar to or greater than expected based on bolometer theory, and noise levels comparable to the nominal design expectation. The projections for the performance of the receiver in the long duration flight are in line with the expectations detailed in Chapter 3.4.4. Despite the low anticipated signal amplitude and the higher bolometer noise in flight, we continue to search for a detection of the galaxy and the dipole to allow for instrument characterization, including constraining the responsivity and performing an absolute calibration.
Bibliography


Appendix A

Transforming Q and U to E and B

In this appendix we show how the spin-2 nature of \((Q + iU)\) and \((Q - iU)\) can be exploited to define two convenient spin-0 quantities, E and B, to describe the CMB polarization field on the celestial sphere.

A.1 Transformation of \(Q \pm iU\) as a Spin-2 Object

To develop convenient mathematical formalism to describe the CMB polarization field on the sky we can consider how \(Q\) and \(U\) transform under a rotation \(\alpha\) about the z-axis, defined perpendicular to the x-y plane in which \(Q\) and \(U\) are defined. The quantity affected by the rotation is \(\chi\), and we can substitute \(\chi - \alpha\) for \(\chi\) in Equation \[A.1\] reproduced here for convenience\(^1\):

\[
I \equiv \mathcal{E}_x^2 + \mathcal{E}_y^2 = \mathcal{E}_0^2 \nonumber \\
Q \equiv \mathcal{E}_x^2 - \mathcal{E}_y^2 = \mathcal{E}_0^2 \cos 2\beta \cos 2\chi \tag{A.1} \\
U \equiv 2\mathcal{E}_x\mathcal{E}_y \cos(\phi_y - \phi_x) = \mathcal{E}_0^2 \cos 2\beta \sin 2\chi \\
V \equiv 2\mathcal{E}_x\mathcal{E}_y \sin(\phi_y - \phi_x) = \mathcal{E}_0^2 \sin 2\beta.
\]

\(^1\)Note that because the two other Stokes vectors, I and V, do not depend on \(\chi\), they are invariant by a rotation under \(\alpha\).
We can write transformed $Q'$ and $U'$ as
\[ Q' = Q \cos 2\alpha + U \sin 2\alpha \]
\[ U' = -Q \sin 2\alpha + U \cos 2\alpha. \quad (A.2) \]

Based on how $Q$ and $U$ transform under a rotation by $\alpha$ we can conclude that two independent quantities can be written in terms of $Q$ and $U$ with a definite value of spin. We choose two combinations of $Q$ and $U$, $Q \pm iU$, which will prove to be convenient for defining the desired parameters below. We can write Equation (A.2) in terms of these combinations of $Q$ and $U$ in a compact form:
\[(Q \pm iU)' = e^{\pm 2i\alpha(Q \pm iU)}. \quad (A.3)\]

We identify $Q \pm iU$ as spin $\pm 2$ quantities. See the appendix of Zaldarriaga, 1997 [65], for a summary of spin-weighted spherical harmonics, and Goldberg et. al., 1967 [22], for a more complete discussion.

By identifying this combination of $Q$ and $U$ as a spin-2 object, we can expand it in spin-weighted spherical harmonics, just as $T$ is expanded in spherical harmonics above in Section 1.2.2. Just as with spin-0 spherical harmonics, the spin-s spherical harmonics form a complete orthogonal basis on the sphere:
\[ \int d\Omega_s Y_{\ell,m}^s(\Theta,\phi) Y_{\ell',m'}^s(\Theta,\phi) = \delta_{\ell\ell'}\delta_{m'm} \quad (A.4) \]
and
\[ \sum_{\ell,m} Y_{\ell,m}^s(\Theta,\phi) Y_{\ell,m}^s(\Theta',\phi') = \delta(\phi - \phi')\delta(cos \Theta - cos \Theta') \quad (A.5). \]

Working with spin-weighted spherical harmonics eliminates the need to define a specific coordinate frame, as with $Q$ and $U$, and therefore simplifies computation of the polarized field on the sky.\footnote{Note that spherical harmonics are spin-weight 0 spherical harmonics.} \footnote{This approach to describing the field of the polarized CMB on the celestial sphere was taken by}
We can define raising and lower operators with the following properties:

\[
\begin{align*}
\sharp s Y_{\ell,m} &= \sqrt{(l-s)(l+s+1)}_{s+1}Y_{\ell,m}, \\
\flat s Y_{\ell,m} &= -\sqrt{(l+s)(l-s+1)}_{s-1}Y_{\ell,m}.
\end{align*}
\] (A.6)

These raising and lowering operators allow us to raise and lower the spin state of the spin-weighted spherical harmonics, and thus produce spin-0 spherical harmonics from higher and lower order ones.

### A.2 From Q and U to E and B

Following the approach above in Equation 1.1 to describe the temperature anisotropies on the celestial sphere, we expand \(Q \pm iU\) in spin-2 spherical harmonics:

\[
\begin{align*}
(Q + iU)(\hat{n}) &= \sum_{\ell,m} a_{2,\ell m} Y_{\ell m}(\hat{n}), \\
(Q - iU)(\hat{n}) &= \sum_{\ell,m} a_{-2,\ell m} Y_{\ell m}(\hat{n}).
\end{align*}
\] (A.7)

We apply the raising operator twice to \((Q - iU)\) and the lowering operator twice to \((Q + iU)\) to obtain expressions in terms of spin-0 spherical harmonics:

\[
\begin{align*}
\sharp^2 (Q - iU)(\hat{n}) &= \sum_{\ell,m} \sqrt{\frac{(\ell+2)!}{(\ell-2)!}} a_{-2,\ell m} Y_{\ell m}(\hat{n}), \\
\flat^2 (Q + iU)(\hat{n}) &= \sum_{\ell,m} \sqrt{\frac{(\ell+2)!}{(\ell-2)!}} a_{2,\ell m} Y_{\ell m}(\hat{n}).
\end{align*}
\] (A.8)

two groups in 1997: Zaldarriaga and Seljak [65] and Kaminokowski, Kosowsky, and Stebbins [36]; Liu and Wandelt follow the approach of Zaldarriaga and Seljak.
This allows us to define two new quantities that are linear combinations of the raised and lowered $Q \pm iU$, called $E$ and $B$:

\[
\tilde{E} \equiv -\frac{1}{2} (\phi^2(Q + iU)(\hat{n}) + \bar{\phi}^2(Q - iU)(\hat{n})) \tag{A.9}
\]

\[
= \sum_{\ell,m} \sqrt{\frac{(l + 2)!}{(l - 2)!}} a_{E,\ell m} Y_{\ell m}(\hat{n}) \tag{A.10}
\]

\[
= \sum_{\ell,m} a_{E,\ell m} Y_{\ell m}(\hat{n}) \tag{A.11}
\]

and

\[
\tilde{B} \equiv -\frac{1}{2i} (\phi^2(Q + iU)(\hat{n}) - \bar{\phi}^2(Q - iU)(\hat{n})) \tag{A.12}
\]

\[
= \sum_{\ell,m} \sqrt{\frac{(l + 2)!}{(l - 2)!}} a_{B,\ell m} Y_{\ell m}(\hat{n}) \tag{A.13}
\]

\[
= \sum_{\ell,m} a_{B,\ell m} Y_{\ell m}(\hat{n}) \tag{A.14}
\]

where

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

\[
a_{B,\ell m} \equiv -(a_{2,\ell m} + a_{-2,\ell m})/2i. \tag{A.15}
\]

In the body of the text in Section 1.5.2 we discuss the rationale for these specific definitions of $E$ and $B$. In particular, the chosen combination of $Q$ and $U$, $Q \pm iU$, allowed us to expand the polarization field in parameters with distinct parities that describe patterns in the polarization field which result from different physical mechanisms.
Appendix B

Alignment of the Trunnion Bearing
With the Outer Frame Table

Section 3.1.2 describes how the inner frame and outer frame structures are connected at the trunnion bearings, which are mounted to the top of the trunnion legs. It is critical that the trunnion leg tops are aligned with each other and the gondola to minimize stress on the bearing. Alignment pins installed in the bottom of the trunnion blocks fit squarely into bushings that are installed in the top surfaces of the trunnion legs to insure proper alignment.

Figure B-1 shows that the EBEX elevation axis runs between the trunnion legs, and it is defined by the line that connects the center of the two trunnion pins. The roll axis is defined as the line perpendicular to the elevation axis lying in the plane of the outer frame table that bisects the gondola in the left/right direction. The azimuth axis is perpendicular to the plane of the outer frame table, and it runs through the center of the table. The figure shows that the top surfaces of the legs must be flat in the roll direction, square with the gondola table edges so that there is no offset in the azimuth direction, and at the same height above the outer frame table. However they needn’t be coplanar in the elevation direction.
Figure B-1: The trunnion leg top surfaces must be flat in the roll direction, square with the gondola table angles so that there is no offset in the azimuth direction, and at the same height above the outer frame table. However they needn’t be coplanar in the elevation direction.
Appendix C

Specifying the Solar Power System

Below we list the primary factors that are important in the specification of the solar power system, including mounting location on the gondola, mounting angle, the type of charge controller, the total panel area, and the total battery capacity.

• **Mount location on the gondola** As the temperature of a solar cell increases, the voltage, and therefore power, that it can provide decreases. The panels will be mounted to the back of the gondola away on the far right and left sides so that the back inactive surface of the panels can radiate to the sky to keep the panels as cool as possible.

• **Mount angle of the panels** The panels will be mounted at an angle of 24° to the vertical, shown in Figure C-1 so that the sun will strike the panels as close to normal as possible when the gondola azimuth is in the anti-sun direction.

• **Charge Controller Selection:** Solar panels are able to provide their maximum power only when current is drawn from the panel at a particular voltage, $V(P_{max})$. The value of $V(P_{max})$ varies inversely with temperature, and thus will change over time in the diurnal cycle. The most recent generation of charge controllers, the maximum power point tracking (MPPT) type, determines $V(P_{max})$ for the panels at small time intervals and draws power at that voltage. This type of charge controller
Figure C-1: The angle of the sun on the EBEX solar panels during the long duration flight when the gondola is pointing anti-sun in azimuth. The angle $\Theta$ is $24^\circ$.

typically has an efficiency of 95%.

- **Specification of total panel area:** The total panel area required by each subsystem is determined by the average gondola azimuth during calibration and CMB patch scans since the solar flux will be suppressed at azimuth angles away from anti-sun. The panel area should be large enough such that during the CMB patch scan, where the gondola points during a large fraction of the flight, the power provided by the panels is greater than the estimated power draw, allowing the batteries to charge. Additionally, a contingency factor of 1.2 is applied to the estimated power draw of both the ACS and cryostat electronics systems to allow for panel damage or other problems that may arise during launch and ascent.

- **Specification of total battery capacity:** In specifying the total battery capacity for the two power systems we allow for realistic conditions on the launch pad and during ascent before the gondola arrives at float altitudes and begins the scheduled scans. We assume that that panels will receive no solar flux on the launch pad since the payload orientation will be dictated by the direction of surface and low level winds. During ascent the gondola will spin at a relatively constant speed to ensure
the rotator motor remains warm while traveling through the tropopause, providing the solar panels with some flux. Given the assumptions above, in specifying the battery capacity we allow for 1.5 hours on the launch pad, 3 hours for ascent, and 1.5 hours of contingency time.
Appendix D

Optical Alignment Procedure

The mounting hardware at each end of the hexapod turnbuckles contains rod ends to provide a reference point for measurements of the length of each hexapod leg. To measure the leg lengths an inside micrometer is placed between the rod ends; the distance measured is labeled as ”Leg Length” in Figure 3-18. Three tooling balls\(^1\) shown in the figure with protective covers in place, are mounted to each hexapod ring and to the cryostat top to allow for measurement of distances between the two rings within a hexapod, and between the secondary hexapod and both the primary hexapod and the cryostat.

The procedure for configuring an aligned optical system, summarized in Section 3.3.1, is detailed below. The inputs and outputs to the alignment algorithm software are:

**Inputs:**
- The relative locations of the tooling balls on both rings of a single hexapod
- The length of each of the hexapod legs

**Outputs:**
- The new target hexapod leg lengths that will bring the optics system into alignment.

\(^1\)A tooling ball is a precision sphere mounted to a cylindrical pin that can be installed in a surface for precision distance measurements to that surface using an inside micrometer.
The distances between the tooling balls on the secondary hexapod and those on the primary hexapod and the cryostat that correspond to an aligned optics system.

**Steps in the Alignment Procedure:**

1. Align the cold optics in the cryostat using a CMM as described in Section 3.4.1.

2. Characterize the internal geometry of each hexapod separately using a coordinate measuring machine (CMM) by measuring the relative locations of the tooling balls on the hexapod rings. Enter this data into the alignment algorithm software.

3. Mount the primary and secondary hexapods to the gondola.

4. Using an inside micrometer, set the leg length of each of the 12 hexapod legs to the nominal value specified in the alignment software.

5. Measure the distance between each of the secondary hexapod tooling balls on the outer hexapod ring and the tooling balls on both the primary hexapod outer ring and the cryostat using an inside micrometer.

6. Input the 18 tooling ball distances into the alignment algorithm software and run the code. Record the new target turnbuckle leg lengths and the expected distances between the secondary hexapod tooling balls and those on the primary hexapod and the cryostat output by the software.

7. Adjust the turnbuckle legs to the new target lengths using an inside micrometer.

8. Repeat the measurements in step 5 to verify alignment by comparing the new distances to those output by the alignment software.

9. If agreement in the above step is poor, repeat steps 4 through 8. In step 4 the leg lengths from step 7 can be put into the alignment software rather than resetting the legs to the nominal value.
Table D.1: Summary of the hexapod alignment results during the Nevis and Ft. Sumner integrations. We show the number of iterations required to achieve acceptable alignment, the maximum absolute distance error and the average absolute distance error. Here the distance refers to the distance measurements between the secondary hexapod tooling balls and those on the primary hexapod and cryostat.

Assessment of the Hexapod Alignment Procedure

We completed the hexapod alignment procedure during the Nevis and the Ft. Sumner integrations. In Table D.1, we summarize the results of the procedure.

- **Required accuracy** of measurements between the secondary hexapod tooling balls and those on the primary hexapod and cryostat: 20 mils, referred to below as “distance errors”.
- **Repeatability** of measurements with the inside micrometer: 1 mil

Table D.1 shows that during integrations at Nevis Labs and in Ft. Sumner an optical alignment that met the 20 mil criterion in distance error was achieved. However, during the Ft. Sumner integration four alignment iterations were required to achieve acceptable results. After the North American engineering flight CMM measurements of one of the hexapods showed that some assumptions about the hexapod geometry that were inputs to the alignment algorithm software were not well founded. Consequently, two upgrades to the hexapods will be performed. First, the rod ends will be replaced with proper tooling balls which are more precisely machined. Second, the screws that housed the rod ends and also attach the turnbuckles to the rings will be precision machined and measured.
Appendix E

Azimuth PI Loop Tuning

To tune the EBEX reaction wheel PI loop, discussed above in Section 3.5.7 on the ground we used the Ziegler-Nichols method. The value of $I_{\text{reac}}$ was set to zero and $P_{\text{reac}}$ was increased slowly until it reached the critical value, $P_c$, at which the system became unstable, exhibiting oscillations around the requested azimuth value. Once $P_c$ and the oscillation period, $T_c$, were determined, $P_{\text{reac}}$ was set to $0.45 P_c$ and $I_{\text{reac}}$ was set to $\frac{1.2P}{T_c}$. We found this method provided acceptable performance of the control system.

Table E.1 shows the typical system response to $P$ and $I$ values that are higher or lower than optimal. Figures E-1(a) and E-1(b) show examples of azimuth scans in which the $P$ value was too low and close to optimal.

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too High</td>
<td>System responds quickly but may become unstable</td>
<td>Overshoot occurs</td>
</tr>
<tr>
<td>Too Low</td>
<td>System takes too long to reach the requested value and overshoot can occur</td>
<td>System takes too long to reach the requested value</td>
</tr>
</tbody>
</table>

Table E.1: System response to $P$ and $I$ values that are greater or less than optimal.
Figure E-1: Examples of tuning of the proportional term, P, in a PI loop; the index is at 5 Hz. The requested azimuth velocity is shown in pink and the actual azimuth velocity is shown in red; the indices on the x-axis are at 5 Hz. 

(a) P=400, I=4000. 

(b) P=800, I=4000.
Appendix F

Rope Certification Test: Hardware Details and Data

F.1 Hardware Overview

The goals of the test and conclusions from the data are laid out in Section 4.2. We purchased 5/8” diameter rope with a minimum tensile strength of 51,400 lb to exceed the minimum allowed tensile strength of 35,000 lb, based on the CSBF gondola design requirements listed in Section 3.1.1. We covered two of the four ropes with a layer of single-sided vapor deposited aluminized mylar (VDA1) with the aluminum side facing inward\(^1\) and a foot-long section with a second layer of mylar was added to one of the ropes. The other two ropes were left bare. The ropes were connected to the 7,000 lb payload and to the balloon via an interface plate shown in Figure F-1(a). Steel cables of a slightly longer length than the ropes were connected in parallel with the ropes in the event of a rope failure.

In order to monitor the temperatures of the ropes we attached a thermistor directly to each rope and an additional thermistor under the double layer of mylar. We

\(^1\)The aluminum layer was oriented inwards so that the mylar could radiate heat to the sky while the aluminum reflected the infrared radiation incident on the rope
monitored the tilt of the payload using the EBEX two-axis clinometer screwed to a platform on the gondola, shown in Figure F-1(b). We used a stand alone data logger\textsuperscript{2} to monitor the signals.

\section*{F.2 Short Pre-Flight Creep Test}

A 7,000 lb dummy payload was hung from the interface plate outside the high bay. Each rope length was measured four times during the duration of the 4 hour test; the gondola was suspended for 2 hours outside before the data collection began. The data, shown in Figure F-2 suggests no clear lengthening of the ropes over time.

\textsuperscript{2}Datataker DT80, http://www.datataker.com
F.3 Flight Test

F.3.1 Temperatures

Figure F-2: Data from the pre-flight outdoor test on the ground.

Figure F-3(a) provides an overview of the flight temperatures and altitude, including the rope and clinometer temperatures and the air and radiation temperatures and the altitude, provided by CSBF. Figure F-3(b) shows the differential between the average temperatures of the bare and covered ropes. In warm ambient temperatures the ropes covered with aluminized mylar were cooler than the bare ropes, as predicted. However, at colder ambient temperatures the covered ropes were slightly warmer than the bare ones, likely because the inner aluminum layer on the mylar prevented the covered ropes from radiating efficiently to the colder ambient environment. The maximum temperature reached by any rope during the whole test was 22 °C, occurring on the launch pad, and the maximum temperature reached at float was -5 °C.
Figure F-3: Data from CSBF rope certification test flight. 

(a): The following temperatures were measured by the data logger: the outer mylar covered rope, the outer mylar covered rope in the section that contained two layers of mylar, the inner mylar covered rope, the bare inner rope, the bare outer rope, the data logger itself, and the clinometer. The plot also includes the air and radiation temperatures and the altitude, provided by CSBF.

(b): The differential between the average temperatures of the bare and covered ropes
F.3.2 Differential Creep

We used the clinometer to measure the difference in creep between the bare and covered ropes. In the scenario in which the warmer bare ropes, shown in purple on the right in Figure F-4, creep more than the colder covered ones, shown in grey, two of the ropes will become slack and two will be taught. The distance between the ropes that would be taut in this scenario, \( d \), was measured to be 13” ± 1/16”. The tilt angle can be converted to a length differential between the longer and shorter ropes, \( \Delta L \) by

\[
\Delta(L) = d \tan(\theta)
\]  

(F.1)

Figure F-4 shows clinometer tilt data plotted against temperature; the clinometer x angle was sensitive to differential creep. There is no clear trend in clinometer angle as a function of temperature. The clinometer data provides an upper limit on the amount of differential creep, \( \Delta(L) \), between the bare and covered ropes of 7.5 mils, based on the accuracy of the clinometer.

F.3.3 Post-Flight Break Tests

Only the central 8’ of the ropes was used for break testing in order to eliminate the effects of splicing the loop on the end of the rope. The test results, shown in Table
4.3 indicate that the aluminized mylar did provide significant shielding against UV degradation of the rope strength. If the degradation is linear, the mylar should provide enough shielding for a 20 day long duration flight, using an average of the two values of tensile strength loss for the covered ropes (1,050 lb). However, since the degradation profile isn’t known, a test which simulates longer timescales in a UV chamber on the ground should be completed before the long duration flight.

F.4 Post-Flight Creep Test

After the certification flight we purchased a small diameter rope and loaded it at 3.6% of the specified tensile strength, similar to the ∼3.4% loading of the flight ropes. We hung the rope in the high bay at Columbia University’s Nevis Labs and monitored the change in length, using a dial indicator, and the temperature. A typical daytime temperature in the unheated high bay was 11°C, higher than the temperatures of the
covered and uncovered ropes during the certification flight. The test results, shown in Figure [F-6] indicate that the rope crept for about 9 days, after which the rope length stabilized. The data suggests that if the EBEX flight ropes are pre-stretched simply by the hanging of the gondola during months of high bay tests then minimal creep during the flight should be expected.

Figure F-6: Data from indoor creep test at Nevis Labs at Columbia University.
Appendix G

Setting a Requirement on the Baffle Temperature Change and the AD590 Noise

In Figure G-1 we show that, as the gondola performs a 20° peak-to-peak azimuth scan across the EBEX CMB patch, the angle of the sun on the gondola will always be more orthogonal at lower azimuth angles and less orthogonal at higher azimuth angles. This will induce slightly hotter baffle temperatures at the extreme low azimuth of the scan and slightly cooler temperatures at the extreme high azimuth of the scan, particularly in the right and back baffles. Although the azimuthal position of the sun relative to the EBEX CMB patch will drift during the two-week flight, and the scan patch will be approached at varying angles, as discussed in Section 2.4.2, the pattern of hotter and colder temperatures with scan phase will be maintained. The result will be a scan synchronous temperature change in the baffles that will not average down during the flight. With a 20° azimuth scan size the temperature change will be roughly linear, where the amplitude will vary due to the diurnal cycle and the changing azimuthal position of the sun through the 14-day flight.

Changes in the temperatures of the baffles during a scan will result in a change
in the power emitted by the baffles, which can induce a differential signal in the bolometers on scan timescales. For a given temperature differential in the baffles, the signal induced in the bolometers will be orders of magnitude lower than the temperature change since the baffle signal appears in the sidelobes of the telescope beam. We can specify the maximum temperature change allowed in the baffles by requiring that the signal induced in the bolometers is lower than the sensitivity of the instrument.

The baffle temperature change across the EBEX CMB patch should induce a scan synchronous polarized signal with a magnitude less than the value of the NEQ/U per pixel for the entire 14-day flight, 0.6 $\mu$K. Since the power emitted by the baffles is suppressed by a factor of $4 \times 10^{-4}$ (about 35 dB) at the detectors, the polarized signal emitted by the baffles can be as large as 1.5 mK. However, the polarized fraction for radiation emitted from an Aluminum surface at 150 GHz is about 0.1%, allowing for a baffle temperature change of 1.5 K to produce a polarized signal of 0.6 $\mu$K in the detectors. Therefore, we conclude on the requirement that the baffle temperature cannot change by more than about 1 K during a scan.

Similarly, the maximum noise allowed in the AD590 signals is set by the precision required to reconstruct the scan synchronous temperature signal in the baffles

---

1 The relative antenna gain in the sidelobes of the beam is estimated using simulations of the EBEX optics.

2 The magnitude of the fractional polarization was calculated as $\frac{\delta}{\lambda_0}$ as specified in [10], where $\delta$ is the skin depth at the given frequency, $f$, for aluminum, and $\lambda_0$ is $\frac{2\pi}{2\pi f}$. 

---

Figure G-1: Overhead view of the average gondola and sun positions as the gondola scans in azimuth across the EBEX CMB patch.
over the width of the CMB patch. The noise in the AD590 signals should allow for measurement of scan synchronous temperature changes of 1 K.

Finally, we note that, in theory, a scan synchronous change in the temperatures of the baffles could induce a scan synchronous change in the mirror temperatures since the baffles radiate power to the mirrors. However, a conservative calculation shows that the changes in mirror temperatures induced by the expected baffle temperature changes, based on the data in Section 6.1, is orders of magnitude below the value required to induce a non-negligible signal in the detectors.
Appendix H

The Anticipated Galactic Signal

Below we estimate the expected change in signal (in analog to digital converter units, ADU) in a single bolometer while crossing the galaxy. We provide estimates for detectors at 250 and 410 GHz in crossings 1 and 2 since these crossings were made in the high flux and low flux longitude regions, respectively, and are therefore representative of all of the crossings. In order to estimate the signal we used HEALPIX\(^1\) to obtain values for the flux\(^2\) for each bolometer pointing across the sky. Since our measured beam size is larger than our design beam size, discussed in Section 4.5, we provide values for an approximate map pixel size\(^3\) of 6’, similar to the design beam size of 8’, and for 30’ which is closer to the measured beam size\(^4\). In Figure [H-1] we show an example profile of the binned flux for crossings 1 and 2 at 410 GHz for the two pixel sizes.

HEALPIX outputs flux in units of \(\frac{Jy}{sr}\), which is equivalent to \(\frac{W}{m^2 H z sr} \times 10^{-26}\). In Equation [H.1] we show the conversion from flux to Watts input on a detector in a beam width by multiplying the flux by the throughput and bandwidth, values for

\(^1\)http://healpix.jpl.nasa.gov/\(^2\)The maps were produced using Model 8 from Finkbeiner et al., 1999 \(^3\)The HEALPIX nside parameter of 512 and 128 corresponds to a 6’ and 30’ square pixel size, respectively.\(^4\)It should be noted that increasing the pixel size of the map is not equivalent to smoothing the map over a larger beam. However, converting the map to a larger pixel size indicates how small scale flux features get averaged over larger pixels in the HEALPIX pixelization scheme
Figure H-1: Binned flux from FDS Model 8 in a typical bolometer for EBEX engineering flight crossings over the galactic plane at 410 GHz. Top: Crossing 1 with rough pixel size of 6’, left and 30’, right. Bottom: Crossing 2 crossing with rough pixel size of 6’, left, and 30’, right.

which are provided in Table H.1

Power (W) = Flux in Jy/sr \( \frac{W}{m^2 H z \ sr} \) \( \times \) throughput (m^2sr) \( \times \) bandwidth (Hz) \( \times \) \( \frac{1}{10^{26}} \) (H.1)

Finally, we divide the power in W by the average conversion factor from W to ADU for each band, given in Table H.1

In Table H.2 we provide results for the estimated signal, binned in 0.5’ latitude bins, for a bolometer in each band, crossing, and map pixel size. We report an average of the values for all bolometers since the maximum flux of each bolometer varies with
<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>Throughput $A\Omega \ (m^2sr)$</th>
<th>Bandwidth (GHz)</th>
<th>aW/ADU</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>$1.44 \times 10^{-6}$</td>
<td>288 - 218 = 70</td>
<td>10,000</td>
</tr>
<tr>
<td>410</td>
<td>$5.36 \times 10^{-7}$</td>
<td>450 - 366 = 84</td>
<td>30,000</td>
</tr>
</tbody>
</table>

Table H.1: Values used in predicted galactic signal calculation.

its unique pointing. The only effect of increasing the pixel size is to smooth out the small bright features that are only present at 410 GHz in crossing 1. We conclude that, given the assumptions in Table [H.1], we should expect a change in signal of about 2 ADU in crossing 1 and 0.2 ADU in crossing 2 at both frequencies.

<table>
<thead>
<tr>
<th>Typical Maximum Binned Flux / Expected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>250</td>
</tr>
<tr>
<td>410</td>
</tr>
</tbody>
</table>

Table H.2: Typical value of the estimated maximum galactic flux in the binned galaxy crossings at the given frequency and pixel size and the expected signal in ADU.
Appendix I

Additional Results from Galactic Crossing Analysis
Figure I-1: *Top:* Plot of all 25 bolometers binned and co-added during crossings 2 through 6. *Bottom:* Plot of 23 of the 25 bolometers binned and co-added during crossing 9; two bolometers were rejected from the sum due to unexplained drifts.
Figure I-2: Plots of bolometers 1 through 13 binned during crossing 1. In all plots the y scale runs from -8 to 10, in ADU, and the x scale runs from -20° to 20° in galactic latitude.
Figure I-3: Plots of bolometers 14 through 25 binned during crossing 1. In all plots the y scale runs from -8 to 10, in ADU, and the x scale runs from -20° to 20° in galactic latitude.