EBEX, THE E AND B EXPERIMENT

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The E and B experiment (EBEX) is a balloon-borne telescope designed to measure the polarization of the cosmic microwave background radiation as well as that from Galactic dust. The instrument is equipped with a 1.5 meter aperture Gregorian-Dragone telescope, providing an 8' beam at three frequency bands centered on 150, 250 and 410 GHz. Polarimetry is achieved by rotating an achromatic half-wave plate on a superconducting magnetic bearing. In January 2013, EBEX completed 11 days of observations in a flight over Antarctica covering 6000 square degrees of the sky. This marks the first time that arrays with about 1000 transition-edge sensor bolometers have made science observations on a balloon-borne platform. These proceedings describe the EBEX instrument, the science flight and the status of the data analysis.

1 Introduction

Measurements of the temperature anisotropy in the Cosmic Microwave Background (CMB) have provided us with a tremendous amount of information about the origin, composition and dynamics of the universe, and played a major role in establishing the standard ΛCDM cosmological model. The inflationary paradigm is the leading model that accounts for the flatness of the universe, the uniformity of the CMB, the absence of magnetic monopoles, and the nearly scale-invariant spectrum of primordial fluctuations [1]. In this paradigm, quantum fluctuations stretched by the expanding universe to astronomical scales imprint a unique primordial B-mode polarization signal in the CMB at degree angular scales. Experiments that measure the polarization of the CMB can thus provide the strongest evidence yet supporting or ruling out the theories of inflation. B-modes can also be created on arcminute scales through the gravitational lensing of CMB photons by intervening large-scale structure along the line of sight. In recent years, experimentalists have made increasingly sensitive measurements of CMB polarization. In the past year, a measurement of inflationary B-modes was announced by the BICEP2 collaboration [2] and the SPTPol and POLARBEAR experiments have reported preliminary evidence of lensing B-modes [3,4].

2 The Instrument

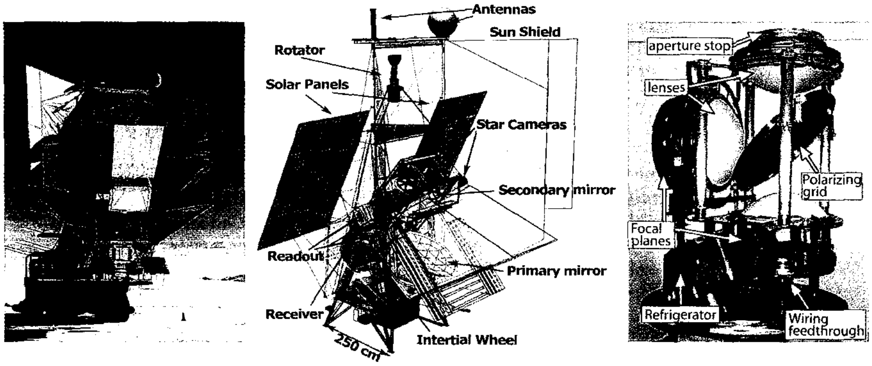

Figure 1 – **Left Panel**: EBEX on the launch pad in Antarctica prior to its long duration flight. **Middle Panel**: A 3D rendering with major gondola elements and overview of optical system. Telescope attitude can be adjusted in both azimuth and elevation. **Right Panel**: The EBEX optics box. As the light enters through the top, the polarization of the light gets rotated by the HWP (not shown), which is placed at the aperture stop. The light is then either reflected by the wire-grid polarizer into the vertical focal plane or transmitted to the horizontal focal plane.

EBEX is a balloon-borne telescope designed to measure the polarization of the CMB. The 2,700 kg (6,000 lb) instrument collects data while suspended from a 10^6 cubic meter stratospheric balloon at an altitude of $\sim$35 km that circumnavigates Antarctica. The telescope is a compact, off-axis Gregorian Mizuguchi-Dragone system chosen to minimize polarization systematics. The 1.5 meter primary mirror combined with conical feedhorns produces an 8 arcminute beam. The telescope has a 6 degree field of view and observes the sky at three frequency bands centered on 150, 250 and 410 GHz. Observing the CMB from the stratosphere enables EBEX to collect data at relatively high frequencies, and be sensitive to only one significant foreground – galactic dust. The payload consists of a gondola with a telescope, detectors, pointing sensors and telemetry. Fig. 1 shows a picture of the telescope before it was launched and a view of the polarizing optics and the focal plane hardware. EBEX has two focal planes. They each consist of 7 silicon wafers with more than 100 transition edge sensor bolometers that are micro-fabricated on each wafer. The wafers are maintained at a temperature of 260 mK. The bolometers are read out using a digital frequency multiplexed system (DfMUX), in which 16 detectors are read out using only two wires. The current through each set of bolometers is measured by a superconducting quantum interference device (SQUID). The polarization of the incoming radiation is modulated by a continuously rotating achromatic half-wave plate (AHWP) located at the 4 K Lyot stop. To minimize power dissipation, the AHWP rotates on a superconducting magnetic bearing. The polarization is then analyzed by a fixed wire grid polarizer. The AHWP rotates at $f_o = 1.23$ Hz and the scanning of the telescope across the sky puts sky polarization signals at side bands of $4f_o = 4.92$ Hz.

3 Overview of The Antarctic Science Flight

On December 28th 2012 EBEX launched from the NASA long duration balloon facility near McMurdo station, Antarctica.

Shortly after reaching the float altitude, EBEX had 945 detectors in transition and collecting data. During flight we observed the CMB and calibrated the instrument through observations of RCW38 and the galaxy. This marks the first time that cosmological observations were conducted in a space-like environment with a kilo-pixel array of transition edge sensor bolometers, and the first time that a 16x DfMUX system was used.

Liquid Helium hold time was 12 days, matching pre-flight predictions, and matching the expected data collection time of 11 days. The sub-K cryogenic system was based on a ^{4}He-based adsorption refrigerator that cooled the cold optics cavity to 1 K, and a ^{3}He-based adsorption refrigerator that maintained the focal plane near 0.26 K. Both refrigerators worked well and, according to specification, required cycling once every 2.5 days. The AHWP levitated continuously on the superconducting magnetic bearing [5] during the entire flight, achieving about 645,000 rotations at 1.23 Hz with an estimated power dissipation of 15 mW at the 4K stage.

The attitude control system (ACS) of the telescope provided sensor information to reconstruct the pointing and actuated the motors to orient the gondola. To mitigate a malfunction with the azimuth motor controller we changed our planned observation pattern, covering a large strip in declination for a total of 6000 square degrees observed. The coverage map is shown in Fig. 2. All other critical ACS subsystems worked well. In particular we acquired continuous attitude information from both star cameras and the gyroscopes, enabling us to reconstruct the pointing with an accuracy that matches pre-flight prediction (see Fig. 2).

On January 23rd, 2013 the payload was terminated. The data and the payload were successfully recovered and shipped to home institutions.

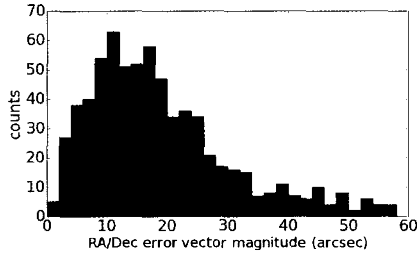

Figure 2 – **Left Panel**: Histogram of the reconstructed pointing error for the entire flight. The mean is 19 arcseconds, a factor of 3 better than required to extract information on the inflationary B-mode signal with negligible pointing systematic error. We expect the final error to be less than 11 arcseconds. **Right Panel**: EBEX coverage map, in galactic coordinates.

4 Current Status

Data from the science flight is currently being analyzed, and preliminary data products are presented in these proceedings. The attitude of the telescope is reconstructed with an Unscented

Kalman filter, using star camera solutions and gyroscope rates. The histogram of the reconstructed attitude is plotted in Fig. 2. As with other experiments using a continuously rotating HWP [6], the raw time streams are dominated by a rotation synchronous signal (HWPSS). The HWPSS is modeled and removed using the measured angle of the HWP. Fig. 3 shows a power spectrum of a section of in-flight data from one of the detectors before and after subtraction of the HWPSS, showing no residuals from the HWPSS in the signal bandwidth. The HWPSS-subtracted time streams are used to calibrate the instrument against Planck, using RCW38 and galaxy crossings. The time streams are then demodulated using the measured HWP angle to produce Q and U Stokes parameters. A preliminary map of galaxy temperature and polarized intensity is shown in Fig. 3 (right panel). The EBEX data analysis is well underway and we anticipate release of cosmological results within $\sim$ 1 year.

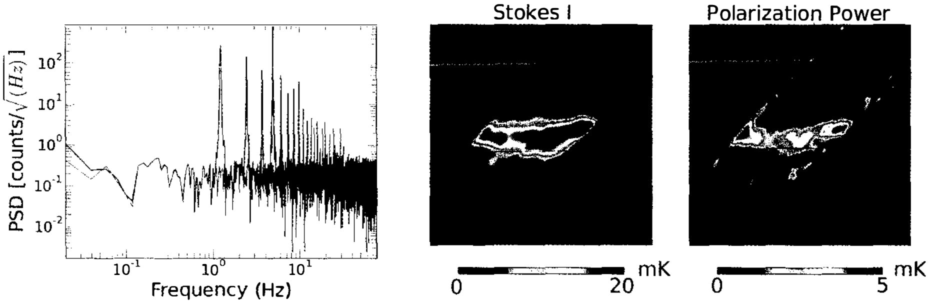

Figure 3 – **Left Panel:** Power Spectrum of a 250 GHz detector before (blue) and after (red) HWPSS subtraction. The HWPSS was removed only up to the 10th harmonic because sky signals are expected at frequencies below 7 Hz. The black peaks correspond to the higher harmonics not removed. **Right Panel:** Preliminary Stokes I and polarization power maps of the galactic plane using 91 250 GHz detectors over a 17 minute section of the flight.

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