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Polarization Calibration of the QUaD Experiment

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Abstract. We describe the polarization calibration of the QUaD experiment, including determination of the polarization efficiency of the detectors and their orientation angles. QUaD is a millimeter-wavelength polarimeter that observed the Cosmic Microwave Background (CMB) from a site at the South Pole. The experiment comprises a 2.64 m Cassegrain telescope equipped with a cryogenically cooled receiver containing an array of 62 polarization-sensitive bolometers. The focal plane contains pixels at two different frequency bands, 100 GHz and 150 GHz, with angular resolutions of 5' and 3.5', respectively. The high angular

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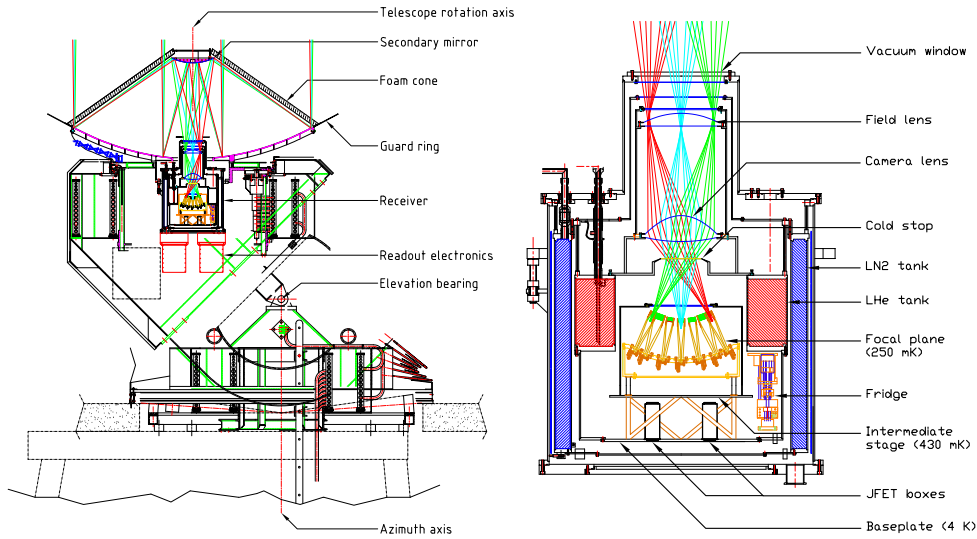


Figure 1. Schematic of the QUaD telescope (left) and receiver (right).

resolution allows observation of CMB temperature and polarization anisotropies over a wide range of scales. The instrument commenced operation in early 2005 and collected science data during three successive Austral winter seasons of observation.

1. Introduction

This paper discusses QUaD,¹ a polarimeter designed to observe the Cosmic Microwave Background (CMB). QUaD operated from an observing site near the geographic South Pole from February, 2005 until October, 2007. Section 2 reviews the instrument design and Section 3 describes the calibration procedure for the detector polarization angles and efficiencies.

2. Instrument Description

QUaD comprises a bolometric receiver located on a 2.64 m telescope near the geographic South Pole. The QUaD receiver contains a focal plane array of 31 pixels, each composed of a corrugated feed horn and a pair of orthogonal polarization-sensitive bolometers (PSBs). Each pixel simultaneously measures both temperature and one linear polarization Stokes parameter. The pixels are divided between two observing frequencies with 12 at 100 GHz and 19 at

¹QUaD stands for QUEST (QU Extragalactic Survey Telescope) at DASIS (Degree Angular Scale Interferometer).

150 GHz. The angular resolution is $5'.0$ at 100 GHz and $3'.5$ at 150 GHz, and the instantaneous field of view is $1^\circ.5$.

The QUaD telescope is an axisymmetric Cassegrain design. The warm foreoptics comprise a parabolic primary mirror and hyperbolic secondary. The upward-looking cryogenic receiver contains two cooled re-imaging lenses, a cold stop at the image of the primary, and a curved focal plane. The design requirements were for high image quality (Strehl ratios > 0.98) over a large ($1^\circ.5$) field of view, and a cold stop for sidelobe control. Minimizing the secondary blockage required curving the focal plane and moving the field lens above the primary. On the focal plane, corrugated feeds couple the optical signal from the lenses onto the polarization-sensitive bolometric detectors. The focal plane operates at a temperature of 250 mK and is cooled by a 3 stage Helium sorption refrigerator.

Bolometers detect incident optical power by measuring the temperature increase of an absorber that is weakly thermally connected to a fixed bath temperature. QUaD uses polarization-sensitive bolometers (PSB) where the absorber is patterned as an array of parallel line conductors, so that it only couples to one linear polarization. These detectors were fabricated at the JPL Micro Devices Laboratory, where similar detectors were developed for the Planck satellite (Jones et al. 2003).

Pairs of orthogonally-oriented PSBs are mounted in protective brass modules. Each module forms a cylindrical integrating cavity, $\lambda/2$ in length, so that a standing wave is created and the electric field is maximized in the center where the PSBs are located. The two absorbers are coaxial and are separated by only 100 μm to ensure that they sample the same electric field. The PSB modules are referenced in position and heatsunk to the back flange of the feedhorns. The angular alignment of each module is set by a stainless steel dowel pin on the module and a machined radial slot in the back of the focal plane.

3. Polarization Calibration

The voltage response of a single PSB to arbitrarily-polarized incident radiation is given by

$$v = s \left[\mathcal{I} + \frac{1 - \epsilon}{1 + \epsilon} (\mathcal{Q} \cos 2\theta + \mathcal{U} \sin 2\theta) \right] \quad (1)$$

where θ gives the orientation angle of the PSB, ϵ gives the cross-polar leakage and s is a calibration constant that depends on detector responsivity, optical throughput ($A\Omega$), optical efficiency, bandwidth, and readout electronics gain (Jones et al. 2003). From equation 1, leakage can be seen to result in a loss of optical efficiency to polarized radiation. This has the effect of reducing sensitivity but not of mixing Stokes parameters.

Because there are no bright, well calibrated polarized astronomical sources visible at these wavelengths, we characterized the polarized response of the instrument by observing a near-field, polarized source mounted on a tower located outside the ground shield. The source consisted of a rotating chopper wheel viewed through a circular aperture and a linear polarizing grid (measured to have polarization efficiency $> 99\%$). The chopper wheel alternated between ambient temperature Eccosorb and reflective aluminum aimed at cold sky with a modulation rate of 5 Hz. A phase-synchronous reference signal was digitized on

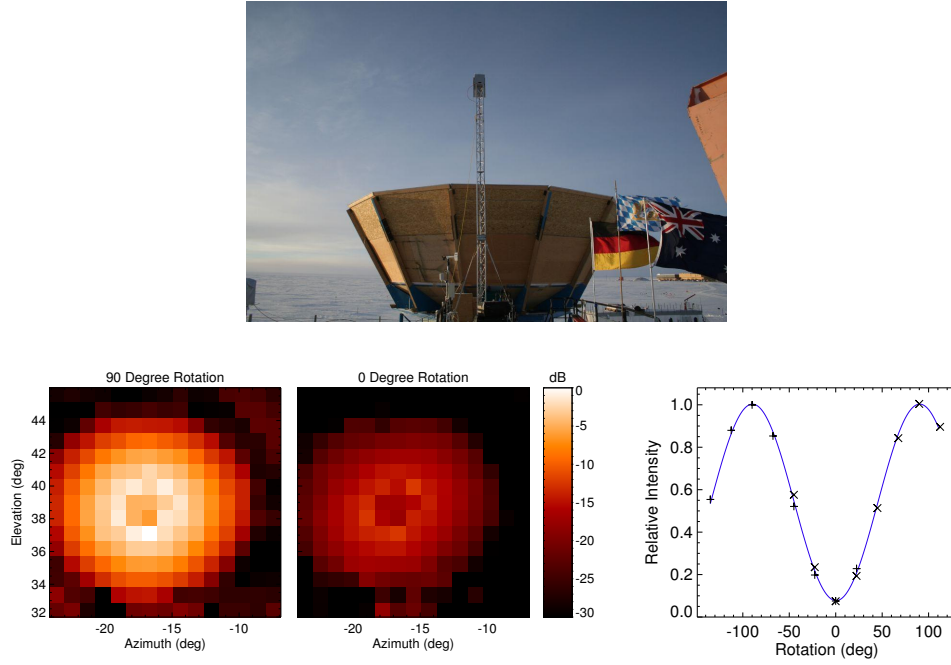


Figure 2. Top: The polarization calibration source, mounted on a tower outside the telescope ground shield. Left: Maps of the near field response of a single QUaD pixel made by rastering the telescope over the source. The left and middle panels show the response with the relative angle of the telescope and the source aligned for maximum and minimum response, respectively. Right: The signal from each raster map is integrated to provide a single data point on this plot. The best-fit sine wave gives the cross-polar leakage and PSB orientation angle. The ‘+’ data points were taken with the source grid vertical, and the ‘x’ data points with the grid horizontal. The rotation of the telescope was limited to $\pm 80^\circ$ to prevent cryogenics from spilling.

one of the spare analog input channels and used to demodulate the bolometer voltages in post processing.

A series of $15^\circ \times 15^\circ$ raster maps of the calibration source were recorded, rotating the telescope about the optical axis in steps of 22.5° between each map. After eight maps, the source grid was rotated by 90° and the entire process was repeated. Each raster map required approximately 45 minutes of observation. Two complete polarization calibration runs were performed two months apart, during the second season of observation. For the first run, a source aperture made from aluminum was used. For the second run, an Eccosorb aperture was used. Results from the two runs are similar, with slightly lower values of ϵ obtained on the second run due to less depolarizing effects from the source aperture.

The signal from each raster map is integrated to provide a single data point on a plot of measured signal versus relative grid / PSB orientation angle (Figure 2). These data points are then fitted to a sine wave. The cross-polar leakage, ϵ , is given by the difference between the sine wave minimum and the x

axis. The absolute orientation angle of the PSB is given by the phase angle of the sine wave.

We find that the average cross-polar leakage of all the channels that are used in the season 2/3 analysis is 0.08. In order to check for systematics in the measurement of ϵ and θ , the results from the two calibration runs can be compared, and additionally each calibration run can be split into two halves, since half of the data points were taken with the source grid aligned horizontally and half vertically. By comparing the results obtained from independently analyzing the “grid horizontal” and “grid vertical” data subsets, and the results from the two separate calibration runs, an uncertainty on the mean value of ϵ of $\approx \pm 0.02$ is obtained.

The RMS scatter of the PSB angles about their nominal orientation was found to be 1.2° , and the deviation from orthogonality within a pair was similarly of order 1° . Several mechanisms contribute to the errors in PSB orientation including machining tolerances of the focal plane plate and PSB modules, transmission through the cryostat optical chain, and the alignment of the absorber within the PSB module. Simulations show that random offsets in the PSB angles at this level average down and have no effect on the resulting CMB polarization power spectra for QUaD’s level of sensitivity.

4. Conclusion

We have described the polarization calibration procedure for the QUaD experiment. More detail on the instrument and calibration procedure is provided in Hinderks et al. (2009). Scientific results are presented in Ade et al. (2008) and Pryke et al. (2009).

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