MAXIPOL's Half Wave Plate Polarimetry

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Abstract. MAXIPOL was the first experiment to measure the polarization of the cosmic microwave background with a rotating half wave plate. We discuss the magnitude and sources for instrumental polarization and polarization rotation in the instrument.

1. Introduction

A level of less than ~100 nK is expected for the signal of the B-mode polarization of the cosmic microwave background (CMB) polarization. This level requires that spurious polarization in the instrument will be controlled to levels below ~10 nK. Polarimetry using a rotating half wave plate (HWP) is one attractive technique because with this technique a number of potential systematic errors are controlled in an effective way: (1) all polarization states are measured with the same beam[1] and thus no beam differencing is required, (2) all polarization states are measured with the same detector and thus no detector differencing is required, and (3) the polarization signal is moved to a frequency that is typically above the knee in the 1/f noise of the receiver and thus noise is lower compared to noise at low frequencies, and its spectrum is typically white.

The MAXIPOL balloon-borne instrument (Johnson et al. 2003, Wu et al. 2003) was the first experiment to report measurement of the polarization of the CMB with a rotating HWP. The HWP was turned continuously at 1.86 Hz and simultaneously the sky was scanned at 0.06-0.1 Hz (see Johnson et al (2003) for detailed scan parameters). The combination of the continuous rotation and scan speed puts the polarization signal at sidebands of 7.4 Hz. Generically, the width of the sideband depends on the beam size and on the scan frequency. The mapping of the signals into the frequency domain highlights a useful distinction between different parts of the polarization signals. Those that are 'modulated by the HWP' and hence appear either at 7.4 Hz or near that frequency, and those that are not, and hence appear at lower frequencies. This separation and the corresponding terminology will be used throughout.

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1 The small variations in beam pattern that occur as a function of the rotation of the HWP are neglected here because (1) they are expected to be negligible (although a full calculation is yet to be done), and (2) they are much smaller compared to those found in techniques where beams corresponding to different detectors are differenced.

In this paper we discuss the levels of instrumental polarization and polarization rotation observed with MAXIPOL and how the data was corrected for these effects. The majority of the material also appears in a paper by Johnson et al. (2003). The reader is referred to that paper for a more thorough review of the experiment and the results.

2. Polarimetry Implementation

Figures 1, 2 show an overview of the MAXIPOL instrument and its implementation of polarimetry. A shaft that penetrates the cryostat, the tertiary mirror and the beam rotates the HWP in a continuous rotation. It was a significant challenge to implement mechanical rotation without exciting excessive noise at the bolometric detectors that MAXIPOL employed. We had tested a number of earlier implementations that had gears and bellows, such that the shaft did not penetrate the beam, but they all induced substantial noise from vibrations.

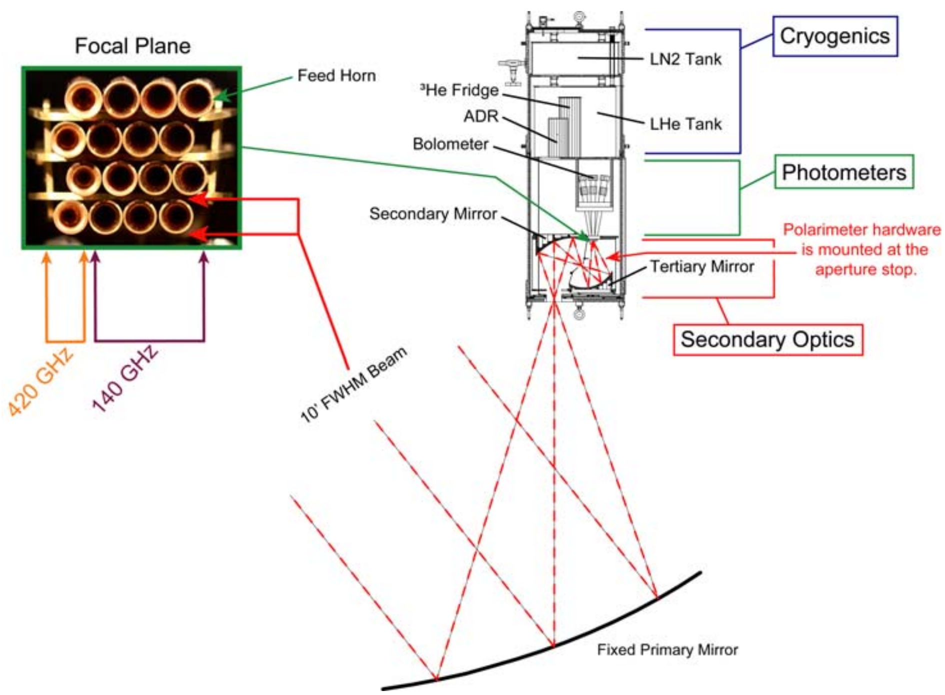


Figure 1. Cross cut view of the MAXIPOL receiver. The photograph on the left gives a photon view of the focal plane. The polarimetry hardware is located between the tertiary mirror and the focal plane (see Figure 2.)

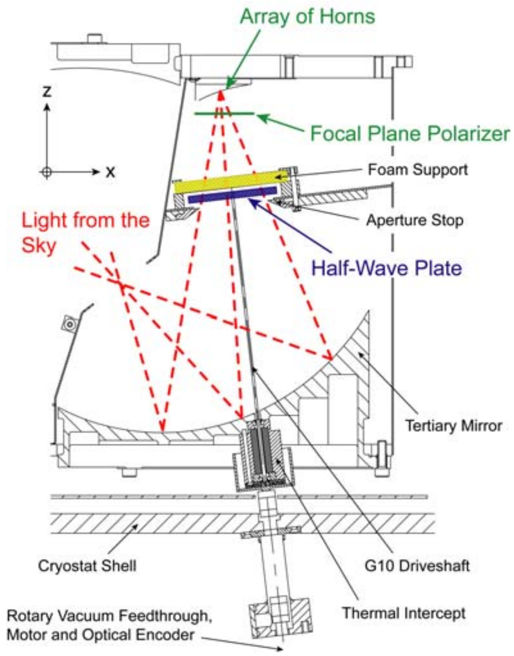


Figure 2. The HWP is mounted at the aperture stop of the MAXIPOL optical system. The polarizing grid is mounted near the focal plane. The HWP is rotated with a shaft that penetrates the cryostat, the tertiary mirror and the beam.

3. Instrumental Polarization

Instrumental polarization is the conversion (by the instrument) of incident intensity to Q, and U Stokes parameters. If the conversion occurs on the sky side of the HWP, the resultant polarization is modulated by the HWP, just like an actual sky signal, and separating spurious effects is more difficult. Instrumental polarization that occurs between the HWP and the detector is not modulated and is therefore not in the signal bandwidth. Instrumental polarization that occurs after the HWP can not be confused with signals from the sky and will not be considered further. There are four sources for instrumental polarization in the MAXIPOL implementation: (i) polarized emission, (ii) polarization through diffraction, (iii) the shaft, and (iv) differential reflection and transmission by optical elements.

3.1. Polarized Emission

Sources of polarized emission include the warm mirror and cold black surfaces inside the cryostat. Consider emission from the primary mirror, which has an ambient temperature of 240 K and emissivity of ~1%. If only 1% of the emission is polarized we have a signal of 24 mK that is modulated by the HWP. Similarly, the signal from a 1%-polarized, 4 K black surface, inside the cryostat, is 40 mK. If this emission is on the sky side of the HWP it is modulated (recall the discussion in Section 1).

Removal of signals that come from polarized emission is relatively straight forward because such signals are expected to be stable throughout the scan. They are not expected to be sky synchronous. In the frequency domain they are expected to appear *at* the 4^{th} harmonic of the rotation frequency, not at side-bands of this harmonic.

3.2. Polarization through Diffraction

An electromagnetic wave that was diffracted by a knife edge can have levels of linear polarization approaching 100%. Consider emission from black surfaces at a temperature of 6 K. Diffraction around sharp edges in the optics that leads to only 10% polarization gives a polarized signal of 600 mK.

Although this is a very large signal compared to the polarization of the CMB, it is stable on long time scales and is not sky synchronous.

3.3. The Shaft

Octupole temperature and emissivity anisotropy around the shaft would give rise to signals that have a 90 degree periodicity as the shaft turns. Thus these signals appear in the detector time stream at the 4^{th} harmonic of the rotation frequency. As such they mimic polarized signals even though they don't arise from polarized signals.

Translational and angular motions of the shaft throughout its rotation modulate the antenna pattern of the detectors. Such motions that have a periodicity of 90 degrees give rise to a signal in the time domain of the detector at the 4^{th} harmonic of the rotation frequency. Again, these mimic polarized signals.

The signals induced by the shaft are not strictly instrumental polarization because they don't convert intensity to Q or U Stokes parameters. Nevertheless, from a signal contamination point of view they are equivalent to instrumental polarization.

Both of the effects from the shaft are similar to polarized emission and to polarization by diffraction in that they are expected to be relatively stable with time (changes are on timescales longer than that of a scan) and they are not sky synchronous.

3.4. Differential Reflection and Transmission

The largest source for conversion of sky intensity to Q, U Stokes parameter in the MAXIPOL optical path is differential transmission through the 50 micron thick polypropylene vacuum window of the cryostat. Rays from a single beam are incident on the highly curved window with incidence angles between ~20 and ~55 degrees, for photometers close to the edge of field of view. Calculation of the difference in reflection for the two polarization states for this range of angles gives a difference of about 1%. This different reflection between the two polarization states is also differential transmission, which gives instrumental polarization. A level of 1% instrumental polarization of the 2.7 K CMB gives a polarized signal of 27 mK that is modulated by the HWP. This signal is constant throughout the sky and is not scan modulated.

Emission from the primary mirror that passes through the vacuum window contributes ~24 mK, assuming a 240 K temperature, 1% emissivity and 1% polarization. This contribution is also not modulated by the scan.

The ~100 μK CMB temperature anisotropy signal produces ~1 μK of scan synchronous spurious polarization through differential transmission. In principle, the spurious scan synchronous signal must be characterized quantitatively and if necessary removed. We discuss the characterization in Section 5. The conclusion is that for MAXIPOL the effect was small relative to other uncertainties so that no subtraction was necessary.

4. Data – Rotation-Synchronous Instrumental Polarization

Figure 3 shows the power spectrum of one 16 minutes section of the MAXIPOL data. It also shows the bandwidths where polarized and unpolarized signals are expected. The peaks at the 1^{st}, 2^{nd}, 3^{rd}, and 4^{th} harmonic of the rotation frequency are stronger by a factor of few hundred to a thousand compared to the white noise level. The peak at ~1.86 Hz corresponds to signals that are synchronous with rotation, most likely from the shaft. The peak at 3.7 Hz is signal produced by differential reflection at the vacuum/HWP interface. It has half the periodicity of the rotation because of the birefringent nature of the HWP. The peak at 5.6 Hz is a 3rd harmonic of the first. The peak at 7.4 Hz is due to all the effects discussed in Section 3. The broad wings of the peaks are caused by long term variations in these signals. ‘Long term’ here refers to time scales much longer than a scan period.

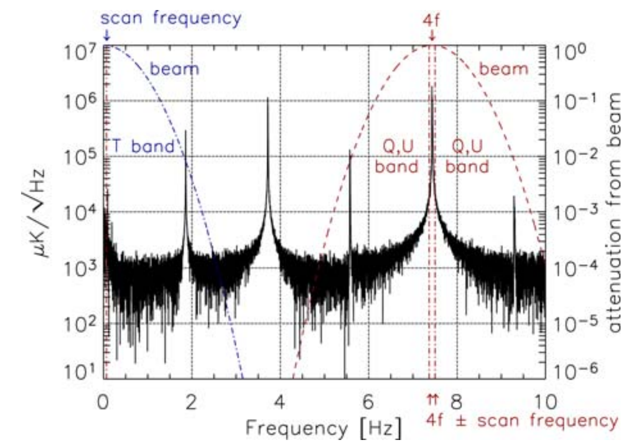
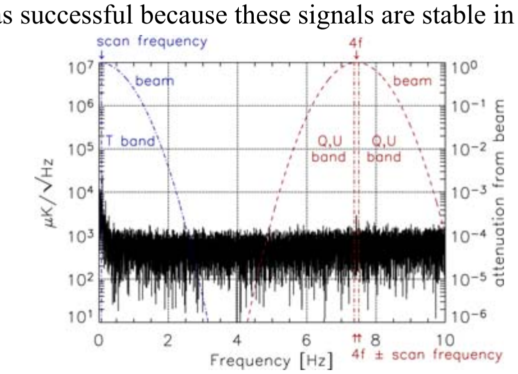


Figure 3. Power spectrum of a 16 minute section of the MAXIPOL time stream. Overlaid in dash blue and red are the bandwidths where the temperature and polarization signals are expected, respectively.

Johnson et al. (2003) describe in detail how the rotation synchronous signal was characterized and removed from the time stream. In brief: sections the time domain data were fit with the following functional form

$$HWPSS(t) = \sum_{n=1}^{8} (C_{1n} + C_{2n}t)\cos(n\beta(t)) + (S_{1n} + S_{2n}t)\sin(n\beta(t)),$$

where *HWPSS* stands for ‘Half Wave Plate Synchronous Signal’, and β is the orientation angle of the HWP. In other words, the data were fit with 8 harmonics of the rotation angle and the amplitude of each harmonic was allowed to vary linearly with time. The fitted amplitudes were subtracted from the time domain data. The outcome of this process is shown in Figures 4 and 5, which show the power spectra of the same temporal section after removal of the rotation synchronous signal. Figure 4 shows the data before demodulation and Figure 5 shows the Q data after demodulation[2]. The key conclusion can be read off Figure 5: the Q and U power spectra are white to frequencies below 10 mHz. Calculations show that the white noise level is consistent with detector noise. In other words: the large (~few hundreds of mK) rotation synchronous signals have been removed successfully. The removal was successful because these signals are stable in time, as expected.



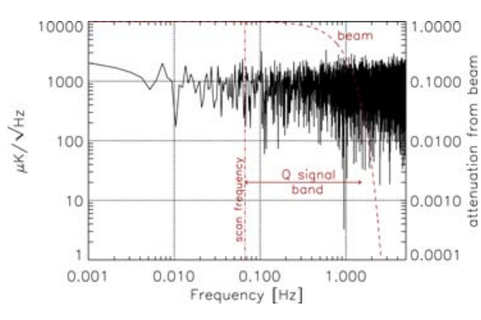


Figure 4. Power spectrum of the same time domain data as in Figure 3 after

Figure 5. Power spectrum of the time data as in Figure 3 after removal of the

[2] The term ‘demodulation’ refers to the extraction of the polarized data from the time domain data. For more details see Johnson et al. 2003.

removal of the rotation synchronous signal.

rotation synchronous signal and after Q demodulation, where Q refers to the Stokes parameter). This is the power spectrum of the Q polarization data.

5. Data – Scan-Synchronous Instrumental Polarization

The magnitude of the spurious *scan-synchronous* component was assessed from scans of Jupiter. Figures 6 and 7 show the total intensity and the U Stokes parameter images, respectively, from one of the MAXIPOL photometers. The absence of signal in the U image puts a limit on spurious polarized scan synchronous signal in the MAXIPOL data. For the 10 of the 12 150 GHz photometers the instrumental polarization was less than 1%. For the other two, which were at the edge of the field of view, we measured an instrumental polarization of 4 and 5%. Simulations show that even if *all* the photometers had a scan synchronous instrumental polarization of 4%, the effect on the final results would be negligible. No correction was applied.

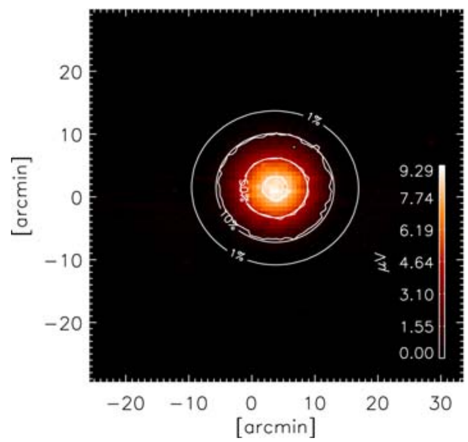


Figure 6. Jupiter in total intensity. The data is from one of the MAXIPOL 150 GHz photometers.

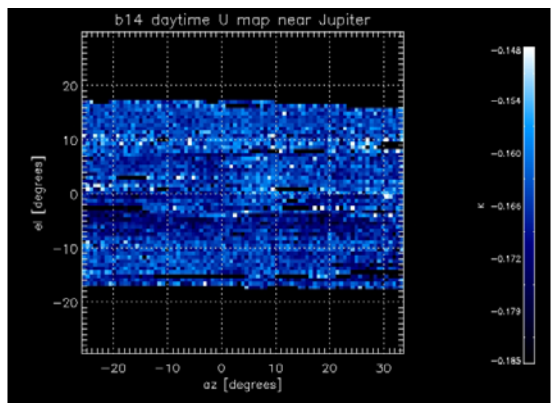


Figure 7. U Stokes parameter from the same data used to make the image in Figure 6. This data was used to place limits on scan synchronous instrumental polarization.

6. Polarization Rotation

Polarization rotation, which is sometimes referred to as 'cross-polarization', is the mixing of Q and U signals by the instrument. In other words, the orientation of an incident polarized signal is rotated by the instrument. Errors due to polarization rotation in MAXIPOL arise from uncertainty in the rotational orientation of the shaft rotating the HWP, from uncertainty in the relative orientation of the HWP and the transmission axis of the grid and from the off-axis nature of the telescope.

Simulations show that 5 degrees of instrumentally induced rotation of the incident polarization vector would cause a ~0.2 μK reduction in the EE polarization signal (and a corresponding increase in the BB signal). Given that receiver noise contributes in excess of 2 μK to the final EE error bar, a limit of 5 degrees on polarization rotation would be adequate for MAXIPOL.

We used a 16 bit angular encoder to encode the rotational position of the shaft turning the HWP and thus uncertainty from that measurement is negligible. Using a fully polarized source that was placed near the entrance window of the cryostat we calibrated the angle of rotation of the HWP relative to the transmission axis of the grid to within an error of 1 degree. This measurement together with simulations of the optical system was also used to determine the contribution of polarization rotation from the secondary and tertiary mirrors, and to place a limit on potential polarization rotation from the primary mirror. The combined uncertainty on polarization rotation due to the off-axis nature of the telescope is less than 3 degrees. We conclude that the error on the EE power spectrum coming from polarization rotation is substantially smaller than the contribution from receiver noise.

Figure 8 shows the rotation angle induced by the secondary and tertiary mirrors as determined from the measurement with the fully polarized source (which does not include the primary mirror), and predictions for the rotation angle coming from all three mirrors as obtained from an optics simulation. An overall offset has been subtracted from the measurements; this offset corresponds to the orientation of the HWP and grid relative to instrument coordinates. All angles are multiplied by 10 to magnify differences. The mean absolute difference between predictions and measurements is 1.2 degrees, showing that polarization rotation from the primary mirror is constrained to that level on average over the entire focal plane. The qualitative agreement between simulations and measurements also gives confidence in the measurements of rotation angles due to the cold optics.

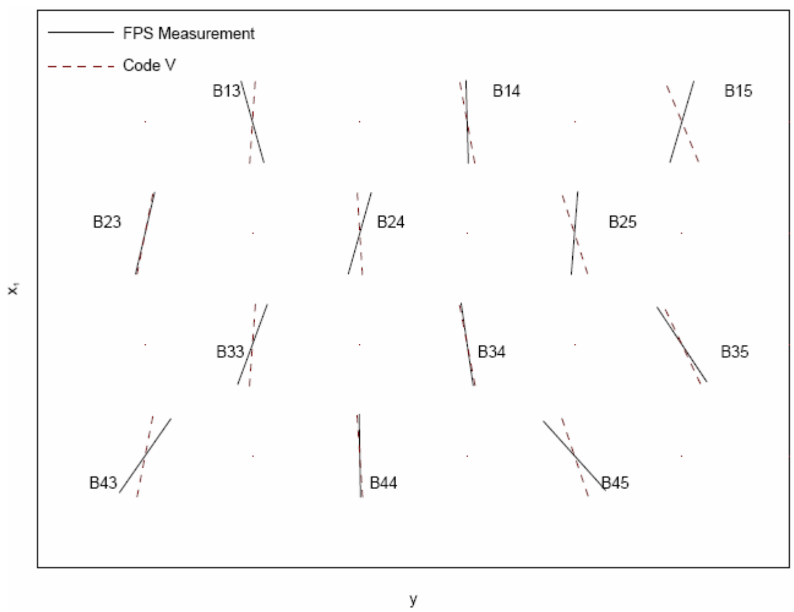


Figure 8. Orientation angle of the rotation synchronous signal for each of the photometers in the MAXIPOL focal plane (solid) and predictions for this orientation using a ray optics simulations package (dash). The difference between measurements and simulations has been amplified by a factor of 10.

7. Summary and Conclusions

Stable 'offsets' in the MAXIPOL data, namely stable rotation-synchronous, but not sky-synchronous signals were removed with no detectable residuals. Most of the Q, U temporal power spectra were white to frequencies below 10 mHz. Residual scan synchronous instrumental polarization and polarization rotation were negligible.

MAXIPOL demonstrated a successful implementation of HWP polarimetry in a CMB experiment.

8. References

[1] B. R. Johnson, et al., 2007, *Astrophysical Journal*, 665, 42

[2] J. H. P. Wu, et al, 2007, *Astrophysical Journal*, 665, 55