Half-Wave Plate Polarimetry with MAXIPOL

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We discuss the use of half-wave plate (HWP) polarimetry for bolometric measurements of the polarization anisotropy of the cosmic microwave background radiation (CMB). The information presented here comes from experience gained during a balloon-borne experiment called MAXIPOL, which is the instrument from the CMB temperature anisotropy experiment, MAXIMA, retrofitted with a rotating HWP and wire-grid analyzer. We describe the HWP polarimetry technique and associated systematic errors. For MAXIPOL, we found the method worked well and that after appropriate corrections, any residual HWP systematic errors were less than the statistical noise. Therefore, the method appears to be promising for E and B-mode characterization. The hardware and data analysis techniques developed for MAXIPOL may be useful for the development of future B-mode experiments.

1 Introduction

Interest in precise millimeter-wave polarimetry is growing because measurement of the anticipated B-mode gravitational wave signature of inflation in the CMB is becoming technologically possible. Newly developed detector arrays with multiplexed readouts promise to deliver sufficient sensitivity for detection of the faint B-mode signals;[1,2] heretofore, receiver sensitivity has limited measurements to the E-mode.[3,4,5,6,7] Once sufficient sensitivity is available, identifying methods for mitigating systematic errors becomes the paramount issue for next-generation experiments. Now is the time to characterize polarimetry techniques precisely, and identify those that will both be compatible with the new detector arrays, and produce acceptable levels of manageable systematic error. This paper is dedicated to the discussion of half-wave plate polarimetry, which is one candidate technology. This technique along with important sources of systematic error are described in Section 2. A measurement used to characterize this type of polarimeter is described in Section 3.

We used the MAXIMA instrument as a pathfinder to learn about CMB polarization measurements which use a rotating HWP as a polarization modulator. The optical arrangement of MAXIMA allowed HWP hardware to be installed and the high sensitivity of the receiver made detection of the E-mode polarization plausible in a ~24 hour flight. The retrofitted experiment is called MAXIPOL, and it is the first CMB experiment to observe the sky with a HWP polarimeter. In this paper we discuss some of the lessons learned from MAXIPOL about the systematic errors in HWP polarimetry, with the intention that this information will inform the design of future experiments. We find that any residual HWP systematic errors were less than the statistical noise in the time and map domain for MAXIPOL so the technique remains

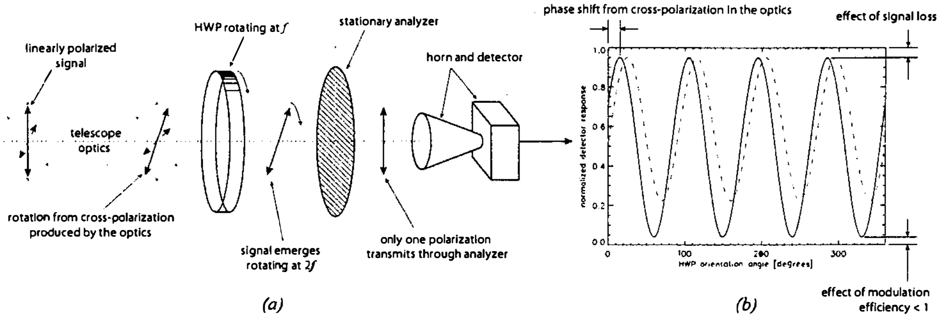

Figure 1: (*a*) Schematic drawing of HWP polarimeter hardware. (*b*) Two simulations of the detector output. The length of the signal vector in (*a*) corresponds to the degree of polarization. The effect of a few kinds of non-ideal performance is highlighted in (*b*). The modulated signal from a perfect polarimeter measuring a perfectly lineraly polarized source would extend from 0 to 1 in (*b*).

promising for E and B-mode characterization. The MAXIMA instrument and observations have been described in previous publications.[8,9,10,11,12,13,14,15,16,17,18,19] Detailed descriptions of the MAXIPOL results are being prepared.[20,21]

2 Half-Wave Plate Polarimetry

Linearly polarized light that propagates through a HWP rotating at a frequency f emerges linearly polarized with its orientation rotating at $2f$. If this light then passes through a fixed polarization analyzer and its intensity is subsequently detected, the output data stream will be modulated sinusoidally at $4f$. Perfectly polarized light will maximize the $4f$ amplitude and unpolarized light will yield no modulation. The phase of the output data is determined by the orientation of the incident polarization. Figure 1 shows a drawing of a HWP polarimeter and a simulated detector response. The fact that the detected signal is modulated at $4f$ is very important for several reasons. The modulation imposed by the HWP, combined with telescope scanning moves sky signals to a user-defined band in the frequency domain, which can be shifted away from any detector $1/f$ noise or other spurious instrumental signals. Unwanted signals at f, $2f$, and $3f$ from the HWP or its drive mechanism can easily be rejected. The HWP operates on polarized radiation only so polarized and unpolarized signals are cleanly separated. Further, a single detector rapidly measures the modulated Q and U Stokes parameters simultaneously, so systematic errors that complicate detector differencing techniques are avoided. The systematic errors that must be corrected in order to successfully use the technique are explained in detail below.

2.1 Cross-Polarization

Cross-polarization is an effect where power from one polarization state is moved to the orthogonal polarization. This phenomenon produces $Q \leftrightarrow U$ mixing if the phase of the two polarizations is preserved during the operation and $Q, U \leftrightarrow V$ mixing if it is not. For CMB measurements $Q \leftrightarrow U$ mixing is important because it leads to $E \leftrightarrow B$ mixing. HWP polarimeters like MAXIPOL are insensitive to V. Typical sources of cross-polarization are the reflective telescope optics and the horns, though the effect of the horns is not detectable if they follow the analyzer, which was the case for MAXIPOL. The MAXIPOL HWP should not produce spurious cross-polarization. However, achromatic HWPs under consideration for future experiments can produce spurious cross-polarization.[22]

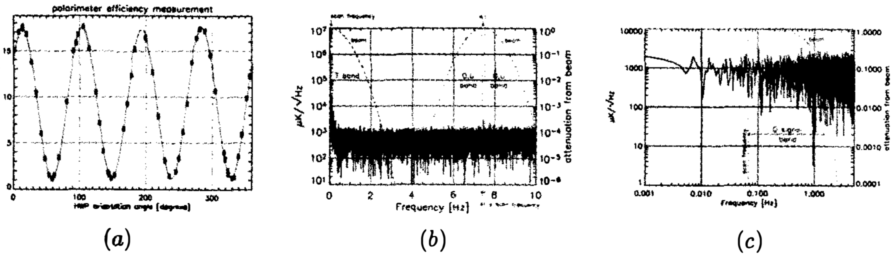

Figure 2: MAXIPOL polarimeter data from a typical photometer. (a.) Results from the pre-flight characterization of the polarimeter. (b) The power spectrum of 16 minutes of time-ordered flight data with the known systematic errors corrected. (c) The power spectrum of the demodulated time ordered polarization data for Q. Zero-frequency in (c) is $4f$ in (b). Sky signals appear in sidebands bounded by the dashed lines marking the telescope scan frequency and the frequency-domain representation of the telescope beam in panels (b) and (c). Nominal instrument noise is recovered in all cases.

Systematic errors arising from cross-polarization can be mitigated during data analysis by applying a calibration like the one ascertained by the measurement described in Section 3. Other instrumental effects that mimic cross-polarization are phase shifts from the bolometer time constant and offsets produced by misalignment between the crystal axes and the encoder. The combined effect of the MAXIPOL cross-polarization from the secondary and tertiary telescope mirrors and a HWP encoder offset appears as the phase shift in the modulation data in Figure 2(a).

2.2 Instrumental Polarization

Unpolarized incident light can become partially polarized inside the instrument through diffraction, oblique reflection, and by combining the incident signals with polarized emission. Sources of instrumental polarization that affect the transmitted signal are most serious because they operate on sky signals which have been modulated by the telescope scanning. For example, unpolarized CMB temperature anisotropies become spurious sky-stationary polarization anisotropies. Polarized signals radiated from telescope baffles located between the sky and the HWP are less serious, provided the baffle temperature changes are slow compared with the rate of modulation of sky-stationary signals. For MAXIPOL the instrumental polarization in transmission is $< 1\%$ so any $T_{sky} \rightarrow Q, U$ is not detectable.

2.3 Depolarization

The HWP for MAXIPOL is made from a single layer of anti-reflection coated sapphire. The behavior described in Section 2 applies only to frequencies $\nu = mc/2t\Delta n$ where Δn is the difference between the ordinary and extraordinary indices of refraction in the birefringent crystal, t is the propagation length through the crystal, m is an odd integer and c is the speed of light. Linearly polarized light at other frequencies emerges elliptically polarized from the HWP($Q, U \rightarrow V$ conversion). Typical analyzers like wire-grid polarizers do not mix V to I and total power detectors like bolometers are only sensitive to I emerging from the analyzer so the spurious V signal created by the HWP is rejected. However, the Q and U that are detected are smaller than the true Q and U of the actual signal, which means the polarimeter has partially depolarized the signal. The level of depolarization is described by a modulation efficiency. A typical photometer in the MAXIPOL polarimeter had a modulation efficiency of 92%, which means a perfectly polarized signal was measured to be 92% polarized by the instrument.

2.4 *Other HWP Errors*

Other known HWP systematic errors exist though they are less serious because they appear out of the Q, U signal sidebands on either side of $4f$ (see dashed curves in Figures 2(b) & 2(c)). For example, differential transmission resulting from use of a non-birefringent anti-reflection coating will produce a $2f$ signal. For MAXIPOL, thermal emission from the hardware used to rotate the HWP produced signals that appeared in the data stream at the harmonics of f. The most serious case was the $4f$ harmonic. Like the instrumental polarization signal from emission at $4f$, it could be separated from the sky stationary signals using the fact that the thermal emission signal drifts very slowly compared to the time scale of the sky signals. The power spectra in Figures 2(b) and 2(c) show that after correction of the known errors, the nominal detector noise is recovered.

Absorptive loss at 140 GHz in the HWP is low. The transmission is 98% for 3.18 mm of sapphire at 4 K. The absorption coefficient does not change significantly between 5.8 and 76 K so for MAXIPOL the exact HWP temperature was not important, provided it was stable on time scales that were long compared to the HWP rotation period.[23]

3 Polarimeter Characterization

The MAXPOL polarimeter was characterized with measurements in the laboratory before the flight. We made two measurements using a thermal source, which filled the beam and was chopped between 273 K and 300 K. First, the radiation was linearly polarized with a wire-grid mounted on the window of the cryostat. The orientation of the transmission axis of this polarizer and the analyzer were aligned to within a few degrees. The amplitude of the chopped signal was then measured at 54 orientations of the HWP angle, as shown in Figure 2(a). This test yielded the cross-polarization of the optical elements between the cryostat window and the HWP and the modulation efficiency of the polarimeter. Second, the same test was repeated with the window polarizer removed to give the transmission component of the instrumental polarization, which was constrained to be $< 1\%$.

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