ON STOKES POLARIMETERS FOR HIGH PRECISION CMB MEASUREMENTS AND MM ASTRONOMY MEASUREMENTS

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Several on-going and future experiments use a Stokes polarimeter (i.e. a rotating wave plate followed by a steady polarizer and by an unpolarized detector) to measure the small polarized component of the Cosmic Microwave Background. The expected signal is typically evaluated using the Mueller formalism. In this work we carry-out the signal evaluation taking into account the temperatures of the different optical devices present in the instrument, their non-idealities, multiple internal reflections, and reflections between different optical components. This analysis, which exploits a new description of the radiation transmitted by a half wave plate, can be used to optimize the experimental setup as well as each of its optical components. We conclude with an example of application of our analysis, studying a cryogenic polarization modulator developed for detecting the interstellar dust polarization.

1 Introduction

The most ambitious challenge in Experimental Cosmology today is the precision measurement of the polarized signal of the Cosmic Microwave Background (CMB). Given the tiny amplitude of the polarized component with respect to the unpolarized one, its extraction is very complicated. Several on-going and future CMB experiments, like EBEX, BRAIN, BICEP-2, QUBIC, SPIDER, LSPE, B-Pol, CMB-Pol, and astrophysical ones, like PILOT and BLAST-pol, will detect the polarized component of the signal of interest (CMB or interstellar dust polarization) by means of a rotating a Half Wave Plate (HWP) followed by a fixed polarizer, both located in front of the detector.

Using the Stokes parameters and the Mueller matrix formalism, the power detected when an ideal HWP rotates at angular speed $\omega$ in front of an ideal polarizer is:

$$ S_{\text{ideal}}(\theta) = \frac{1}{2} [S_0 + S_1 \cos 4\theta + S_2 \sin 4\theta]; $$

where $\theta = \omega t$ and $S_i$ are the Stokes parameters of the radiation under analysis. The linearly polarized radiation is thus modulated at frequency $4f = 2\omega/\pi$. Only the radiation transmitted by the HWP + polarizer stack have been included. In general, we need to include in the analysis also the thermal emission from all the optical devices and from the radiative background. Moreover the non-ideality of the devices, the multiple internal reflections and the reflections between distinct devices modify the signal detected by the polarimeter. In Sec.2 we describe the behavior of a real polarimeter. We provide simulations of the signal detected by a typical CMB experiment in Sec.3. Before concluding summarizing our results (Sec.5), we present the Cryogenic Waveplate Rotator (CWR), a system which will modulate the polarized component of the interstellar dust in the PILOT balloon-borne experiment (Sec.4).
Figure 1: Simulation of the different contributions to the power detected in a Stokes polarimeter at 150 GHz, vs rotation angle of the waveplate. From top left to bottom right: CMB polarization, unpolarized radiative background with temperature 2.7 K, polarized emission of the HWP at 50 K transmitted to the polarizer and the same reflected back by the polarizer, polarized emission of the polarizer ($T_p = 2.5K, \epsilon_p = 0.01$), total signal detected by the bolometer.

2 Modeling a real polarimeter

The Mueller formalism as used above provides a simplistic description of the radiation transmitted by an ideal HWP; in particular, it assumes that the 100% of the incident radiation is transmitted, independently of the incidence angle, and that the phase difference $\phi$ is frequency-independent. In the Adachi formalism\cite{12}, instead, the phase difference depends on the frequency of the incident wave, on the thickness of the crystal $d$, on the extraordinary $n_e$ and ordinary $n_o$ refraction index of the birefringent crystal.

Here we use a new description of the HWP\cite{13} that takes into account multiple internal reflections. These depend on the optically activity of the anisotropic HWP crystal (OAMR, Optically Active Multiple Reflections), and we also include the frequency dependence of the refraction indices. From the total transmitted and reflected electric fields we have built two new Mueller matrices: one for the transmitted stokes vector and the other for the reflected one; the matrix elements depend on $n_e$, $n_o$, $\phi$, the reflectivity, and the transmissivity of the anisotropic medium in a complex way. For a real HWP, $M_{\text{real HWP}}$, in normal incidence approximation the multiple reflections create non-vanishing off-diagonals terms, not present in the ideal one, $\text{diag}(M_{\text{ideal HWP}}) = (1, 1, -1, -1)$. For example, at 150 GHz, a typical Mueller matrix for the HWP is:

$$M_{\text{real HWP}} = \begin{pmatrix}
0.773 & -0.006 & 0 & 0 \\
-0.006 & 0.773 & 0 & 0 \\
0 & 0 & -0.773 & -0.033 \\
0 & 0 & 0.033 & -0.773
\end{pmatrix}.$$  \hspace{1cm} (2)

We also take into account the spectral dependence of the refraction indices and of the absorption coefficients which are assumed to decrease linearly with the temperature of the HWP.

A polarizer emits linearly polarized radiation; in the Stokes polarimeter this emission is reflected back by the rotating HWP, and after the crossing through the polarizer, is modulated at a frequency $4f$. The unpolarized radiative background, following the same optical path of the astrophysical signal, is instead modulated at $2f$ by small non-idealities in the wave plate. Small
Figure 2: Accuracy for the detection of linear CMB polarization versus the temperature of the radiative background (left) and of the HWP (right).

Table 1: Features of the spurious signals produced by a real polarimeter.

| EFFECT                                                      | MOD. | AMPL.  |
|--------------------------------------------------------------|------|--------|
| radiative background at 2.7 K                               | 2f   | 15 mK  |
| polarized emission of the polarizer at 2.5 K reflected by the HWP | 4f   | 2.1 µK |
| polarized emission of the HWP at 50 K transmitted by the polarizer | 2f   | 22 mK  |
| polarized emission of the HWP at 50 K reflected by the polarizer | 4f   | 3 µK   |
| polarized emission of the HWP at 4 K reflected by the polarizer | 4f   | 0.6 µK |

differences in the absorption coefficients of the HWP, fewer $10^{-3}$, produce a polarized emission; it is modulated at $2f$ ($4f$) when is transmitted (reflected back) by a polarizer (and successively by the HWP).

For a Λ-CDM model, with tensor to scalar ratio $r = 0.1$, the expected detected signal due only to the CMB, has a typical (rms) amplitude of about $0.7\mu$K. We consider the normal incidence approximation and an incoming monochromatic ray at 150 GHz. Going through a real absorbing HWP the signal amplitude does not change much ($0.6\mu$K), but the heights of the peaks become uneven, due to a spurious $2f$ component (Fig. 1). From our model, we find a number of spurious effects, as quantified in Tab. 1.

The result of the sum of these emissions, with respect to the CMB signal, depends on the relative angle between the CMB polarization angle and the orientation of the wire grid. Despite the large amplitude of the $2\theta$ components, they are easily removable from the cosmological signal by means of a high-pass filter. The $4f$ spurious signals, on the contrary, cannot be removed; being at the same frequency, they contaminate the cosmological signal by an amount which depends on the physical temperature of the optical components: at 2.5 K the spurious signal is about 4 times the CMB one, while at 1 K it decreases below 4% of the CMB one. We conclude that it is certainly necessary to cool down the polarizer and the HWP, and to reduce the radiative background.

3 Saturation effects

Bolometric detectors, used at these frequencies, are non linear and start to saturate if the detected signals become too large. In a slightly saturated bolometer a pure $2\theta$ signal acquires a $4\theta$ component, plus higher order terms. Therefore, non linearities place upper limits on the radiative background we can tolerate in a CMB polarization experiment. Given a 1% saturation
for signals of the order of $200 \, mK_{\text{CMB}}$, we find that if we want to detect the $S_1$ and $S_2$ parameters with, at least, 10\% accuracy, we must reduce the radiative background below 4.5 K (Fig. 2).

A possible solution for removing these troublesome spurious signals could be using an array of polarizers, one per detector, with different wire grid orientations, in place of a single wire grid covering all the array. In this way, the spurious emissions having different phases partially cancel each other. PSBs are naturally providing this advantage, if properly oriented in the array.

4 The Cryogenic Waveplate Rotator

In the near future PILOT\cite{9}, a balloon experiment with 1024 bolometers cooled down to 0.3 K, will observe the polarized emission from the Galactic plane and the cirrus clouds at high Galactic latitudes, in two bands centered on 545 and 1250 GHz. The cryogenic waveplate rotator (CWR)\cite{14,15} will modulate the astrophysical signal at a frequency of $4f$, rotating a 4K HWP. The CWR works in a step and integration mode, exploiting an innovative mechanical system driven by a step motor running at room temperature. The CWR controls, in a completely automated way, the position of the crystal with an accuracy better than 0.03°, stopping in pre-selected positions sensed by a 3-bit optical encoder made with optical fibers.

5 Conclusions

We have shown a few examples of contamination of Stokes Polarimeter data due to the polarized emission of the polarizer reflected back by the rotating HWP, to the unpolarized radiative background, which follows the same path of the target signal, going through a non-ideal waveplate, and to the polarized emission of the HWP reflected and transmitted by a polarizer. This study has used a new description of the HWP which takes into account the optically active multiple reflections inside the crystal and which describes the radiation transmitted and reflected from the birefringent medium. The non linear behavior of the bolometric detector produces a 4θ signal from the large $2f$ spurious signals; this means that even if the $2f$ signal can be removed post-detection, its level should be kept low enough that the linearity of the detector is not challenged. This sets upper limits, less than about 10 K, for the allowed radiative background in a given experiment. Our simulations also show the necessity of cooling the polarizer down to about 1 K and the HWP to 4 K.

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