CMBR Polarization Measurements: Challenges and Current Status

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1 INTRODUCTION

Recently the emphasis of Cosmic Microwave Background Radiation (CMBR) experiments has shifted from measuring temperature anisotropies to detection of its polarization. Now that CMBR polarization has been observed with both bolometric and coherent detectors, we entering the phase of precision measurements, with the goal of determining parameter values of cosmological models. The cosmological information is encoded in the Stokes I, Q and U parameters of the CMBR polarization anisotropy signal over a wide range of angular scales, and has a maximum amplitude of several micro Kelvin. The experimental situation is made more difficult by dust and synchrotron foreground emission, both which are polarized and can be orders of magnitude larger then the CMB signal of interest. Separating the polarized CMB signal from the foregrounds therefore requires multi-frequency observations, allowing the differing spectral indicies of the foreground components to be exploited in the modeling and removal of the foreground signal from the measured sky signal. Extracting the small CMBR component from maps with large foreground contamination will thus require high fidelity maps over a broad range of frequencies and angular scales with high signal to noise ratios.

2 EXPERIMENTAL ASPECTS

The small amplitude of the polarized CMBR signal means the high sensitivity receivers will be required to achieve the required signal-to-noise ratio. These sensitivities will be achieve through the use of arrays of large bandwidth detectors. Historically measurements of the CMBR intensity were not limited by the raw sensitivity of the detector systems, but rather by systematic errors inherent in the measurements. The same will probably be true of CMBR polarizations measurements, where systematic errors will have to be reduced at least an order of magnitude below the levels required for temperature anisotropy experiments.

2.1 Sources of Systematic Errors

Key areas of instrument performance related to systematic errors are polarization selectivity, modulation techniques, calibration and optical design. Since the CMB signal of interest is limited to the Stokes I, Q U parameters, the measurement problem reduces to measuring differences between the intensities of linear polarized components of the sky signal, in addition to the total intensity signal.

2.2 Polarimeters

Polarization measurements in practice involve two steps. First, the polarization state to be measured must be established in the optics of the instrument. This can be done either through some type of polarization defining filter, of through a transducer which directly couples a given input polarization state into a single moded structure. Secondly, there must be a method of modulating the polarization state being measured to allow for a subsequent demodulation to overcome slow drifts inherent in the detector system. Imperfections in either of these steps can lead to corrupted measurements. The simplest case arises when a linear polarizer is switched such that it alternately couples two orthogonal linear polarizations from the sky onto a detector. Such a system can be implemented in numerous ways, ranging from optical components such a wire grid polarizers and quarter wave plates, to phase switching in correlation polarimeters. In any case, if the efficiency of the coupling of the input power to the detectors differs in the two states a false polarization signal can be generated, coupling intensity variations of the sky signal into the polarimeter outputs. Such *intensity leakage* is often reduced by adding additional loss in one of the polarization switch states to equalize the coupling efficiencies in the two states. This approach becomes problematic, however, when the input signal consists on multiple components with varying spectral indices. In this situation not only must the band average coupling efficiencies be equal in the two states, but they must be equal at all frequencies, so that intensity leakage will not occur for input signals with arbitrary spectral shapes. *Bandpass mismatch* between the two state of the instrument therefore becomes another source of intensity leakage. Matching the bandpasses over the large bandwidths used by these polarimeters to achieve high sensitivity can be very difficult. Currently intensity leakage for polarimeters use for CMB measurements are about 1%, limiting the accuracy of polarization measurements to about 1% of the total sky intensity at any given point.

The previous discussion assumed that the same detector was used to measure the intensity of the two linear polarization signals to be differenced. Often this is not the case, and different detectors are used to measure the two signal components. In this case the relative calibration accuracy of the two detectors contributes to intensity leakage. Again, calibration accuracies of the best systems are approximately 1%, and often this is only a 'mean' calibration determined by comparing the final data product to other measurements of observed calibration objects. To eliminate the intensity leakage, high accuracy calibrations need to be established on time scales over which the detector gain can drift to ensure rejections of intensity fluctuation in the differencing process. Bandpass mismatch often is a more serious problem for polarimeters which difference signals from different detectors, since they typically use fewer shared components to process the two polarization signals.

The rapid spacial scanning used as a modulation technique by CMBR temperature anisotropy measurements may not be appropriate for precise polarization measurements since it modulates the intensity and polarization signals on comparable timescales. Consider the case of measurement of the large spatial modes with multipoles $l < 10$. If a rapid spacial scanning technique is employed, a temperature dipole signal with an amplitude of approximately 3000 micro-Kelvin will be input to the polarimeter while the polarization signal of interest on these angular scales can be in the nano-Kelvin regime. This would require an exceptionally low intensity leakage to recover the polarization signal. In such situations a modulation technique which does not involve spacial scanning seems preferable.

2.3 Optics

The optical systems used to couple the sky signal to the detectors can also corrupt measurements. If the beam patterns of the two polarization components being differenced do not coincide exactly, spatial temperature anisotropies will produce spurious polarization signal. This problem typically arises in the feed horns used to couple either directly to the sky or to the optical system of a telescope. Similar problems arise when an instrument sensitive to a single linear polarization is rotated about its beam axis and differences are taken to detect the polarization state of the input signal. Unless the instruments is rotated exactly about the beam axis, and the beam is circularly symmetric, spatial temperature anisotropies of the input signal will lead to variations in the detectors output, which could be incorrectly identified as a polarized component.

The *ground screens* used to shield the optical systems from thermal radiation from terrestrial and unwanted celestial sources will also need to be improved relative to those used in temperature anisotropy measurements. Diffraction over the edges of the screens can produced significantly polarized signals, another source of potential systematic errors.

2.4 Calibration

There are several additional issues related to calibration which are also important. The first an simplest is the overall calibration of the final data product. This is especially important when results from different experiments are to be combined. The CMB temperature dipole is a nearly ideal calibration source for large scale temperature measurements, due to its stability and well understood form. Smaller scale experiments often use planets or other compact objects to perform temperature calibrations. Still, calibrations uncertainties of several percent are still present when using these calibration sources due to uncertainties in foreground removal and/or beam characteristics. The situations is more difficult for polarization measurements since no analog of the CMB temperature dipole exists for polarizations, and well characterized intense polarized point sources rare.

2.5 Experiment Siting

As in the case of CMBR temperature anisotropy measurements, large scale (low multi-pole index l) structure will best performed from balloon of space based platforms to avoid the signal contamination arising from large scale features of atmospheric emission, while smaller angular scale measurements are often performed by ground based experiments due to the cost and difficulty of flying the large optical surfaces required to achieve the small beam sizes.

3 CONCLUSION

The precise measurements needed to characterize the polarization of the CMBR present formidable experimental challenges. Improvements of at least an order of magnitude in the sensitivity and control of systematic errors over those used in temperature anisotropy measurements will be required to fully exploit the cosmological information contained in the polarizations signal. While all the advances needed to perform these measurements seem feasible, incorporating all the needed improvements in a set of comprehensive measurements will keep experimentalists busy for a number of years.