The Millimeter-wave Bolometric Interferometer and the Einstein Polarization Interferometer for Cosmology: Systematics

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Abstract. The Millimeter-wave Bolometric Interferometer (MBI) is a prototype instrument developed in part as a pathfinder for a future space-based cosmic microwave background (CMB) polarization measurement, the Einstein Polarization Interferometer for Cosmology (EPIC). MBI uses adding interferometry to measure CMB polarization; this is a distinctly different and possibly more advantageous approach than directly imaging the sky. The adding interferometer has sensitivity comparable to that of an imaging experiment, but the adding inteferometer has different systematic effects than an imaging experiment. We explore and compare some of those effects here.

1. Introduction

Interferometers have long been used to measure the CMB temperature and polarization anisotropy power spectra. The first detection of polarization in the CMB was made by an interferometer, DASI[1].

MBI is a prototype instrument which has started making preliminary measurements of the sky to verify models of sensitivity and control of systematic effects. For details of the MBI instrument see [2]. More observations will be required to fully verify these models. While simulations of many imaging instruments for observing the CMB are well developed, this is not as true for adding interferometric instruments. A simulation relevant to MBI has been carried out by [3].

2. The Adding Interferometer

In interferometers that use incoherent detectors, such as MBI, the electric field wavefronts from two telescopes are added and then squared in a detector as shown in Fig. 1 — an "adding" interferometer as opposed to a "multiplying" interferometer[4]. The result is a constant term proportional to the intensity plus an interference term. The constant term is an offset that is removed by phase modulating one of the signals. Phase-sensitive detection at the modulation frequency recovers the interference term and reduces susceptibility to low-frequency drifts ($1/f$ noise) in the bolometer and readout electronics. The adding interferometer recovers the same visibility as a multiplying interferometer. Details of the adding interferometer using either bolometers or coherent receivers may be found in [5].

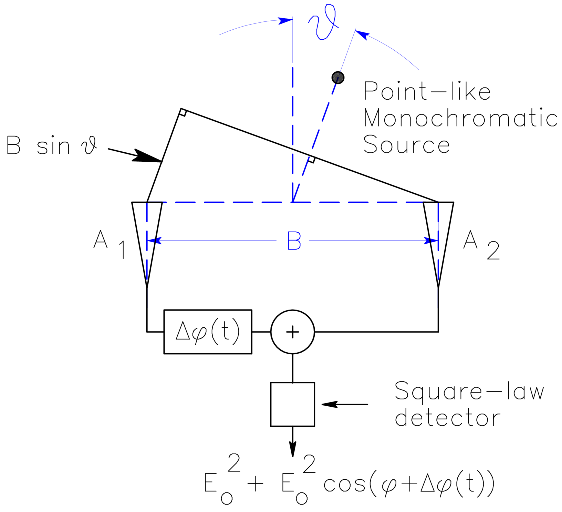

Figure 1. Adding interferometer. At antenna A_2 the electric field is E_0, and at A_1 it is $E_0 e^{i\phi}$, where $\phi = kB \sin\theta$ and $k = 2\pi/\lambda$. B is the length of the baseline, and α is the angle of the source with respect to the symmetry axis of the baseline, as shown. (For simplicity consider only one wavelength, λ, and ignore time dependent factors.) In a multiplying interferometer the in-phase output of the correlator is proportional to $E_0^2 \cos\phi$. For the adding interferometer, the output is proportional to $E_0^2 + E_0^2 \cos(\phi + \Delta\phi(t))$. The desired signal is recovered by introducing a time dependent phase modulation $\Delta\phi(t)$ in one arm of the interferometer.

3. Systematics

Why use an adding interferometer to measure CMB polarization? The short answer is minimization and control of systematic effects. Bunn has carried out a detailed analysis of systematic effects in interferometers[6]; a similar analysis has been undertaken for imaging systems[7].

When using a traditional telescope in conjunction with a focal-plane array to measure CMB anisotropy, there are several design issues. The telescope provides angular resolution, but to get sensitivity a large number of detectors must be placed in the focal plane. Obtaining a low cross-polarization, large field-of-view optical design for such a system is challenging. An interferometer such as MBI observes the sky directly with corrugated horn antennas. This has several advantages:

(i) The optical design is simple and clean. There is no polarization or emission from mirrors observing the sky.

(ii) Corrugated horn antennas have low sidelobes and very symmetric circular beam patterns.

(iii) The corrugated horn antennas are kept at cryogenic temperatures to reduce emission.

(iv) The field-of-view of the interferometer is determined by the instantaneous field-of-view of a single corrugated horn antenna. There are no distortions from off-axis imaging elements.

(v) A large number of corrugated horns antennas, not limited in number by a telescope design, can be used to obtain sensitivity.

Another advantage of the interferometer is related to the scan strategy. Let's consider the case of an instrument staring at a patch of sky. For the interferometer, rotation about the boresite rotates the polarization vectors and provides a clean way to modulate the polarization

Table 1. A Comparison of Systematic Effects

Systematic Effect	*Imaging System Solution*	*Interferometer Solution*
Cross-polar beam response	Instrument rotation & correction in analysis	Instrument rotation & non-reflective optics
Beam ellipticity	Instrument rotation & small beamwidth	No T to E and B leakage from beams; inst. rot'n
Polarized sidelobes	Correction in analysis	Correction in analysis
Instrumental polarization	Rotation of instrument & correction in analysis	Clean, non-reflective optics
Polarization angle	Construction & characterization	No T to E and B leakage from beams; construction & characterization
Relative pointing	Rotation of instrument & dual polarization pixels	No T to E and B leakage from beams; inst. rot'n
Relative calibration	Measure calibration using temperature anisotropies	Detector comparison not req'd for mapping or measuring Q and U
Relative calibration drift	Control scan-synchronous drift to 10^{-9} level	All signals on all detectors
Optics temperature drifts	Cool optics to $\sim$3 K & stabilize to $< \mu$K	No reflective optics
$1/f$ noise in detectors	Scanning strategy & phase modulation/ lock-in	Instant. measurement of power spectrum without scanning
Astrophysical foregrounds	Multiple frequency bands	Multiple frequency bands

signal and recover the Stokes parameters for a single patch. For an imaging instrument, however, such a rotation also rotates the field of view in the image plane so complicates the recovery of the Stokes parameters. The imaging instrument requires a more complex scan strategy so that the instrument scans across each pixel on the sky in multiple orientations.

There are a number of challenges for adding interferometry. One challenge is that a low-loss wide-bandwidth phase shifter that is easily scaled to a large number of elements does not, to our knowledge, exist at the current time. Another challenge is the following: In part, the sensitivity of the adding interferometer results from having a wide bandwidth. A wide bandwidth, however, tends to decrease the fringe contrast.

In a ground-based interferometer such as MBI, the signal is less affected by the atmosphere than in an imaging experiment [8, 9]. Unlike a single-dish imaging telescope, an interferometer instantaneously performs a differential measurement: the effective "beam pattern" of each individual baseline is a set of fringes that sample the sky with positive and negative weights. This differencing removes the need for mechanical chopping or rapid scanning. Only correlated signals are detected, so the interferometer has reduced sensitivity to changes in the total power signal absorbed by the detectors[10].

Table 1 outlines a variety of systematic errors and how they can be managed in imaging and interferometric instruments. The relative importance of these effects is quite different in interferometric systems: some sources of systematic error in imaging systems are dramatically reduced in interferometers. As an example we consider the effects of pointing errors and mismatched antenna patterns.

Some imaging instruments used for CMB polarization measure the power in each linear polarization on separate bolometers and then form the difference of the two signals to determine the linear polarization. This approach requires careful matching of the bolometers. If the signals being differenced come from two different antennas, then the beam patterns and pointing of the two antennas must coincide precisely. Any mismatch converts power from the total intensity into a spurious polarization signal [7]. In an interferometer, differences in antenna patterns for the different horns do not couple intensity to polarization in this way.

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