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Bolometric interferometry: the millimeter-wave bolometric interferometer

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Abstract

Bolometric interferometry is not a new idea, but this technique has not been demonstrated at millimeter wavelengths. The millimeter-wave bolometric interferometer combines the advantages of two well-developed technologies – interferometers and bolometric detectors – and will open a new region of sensitivity and angular resolution not previously accessible to other instruments.

1. Introduction

We are in the process of building an instrument called the millimeter-wave bolometric interferometer (Ali et al., 2002). Initially we are building a small baseline (<1 m) version of the instrument, which is called MBI-B. Given the small baseline, this instrument will probe relatively large angular scales (>1°). MBI-B will demonstrate bolometric interferometry at millimeter wavelengths. Later we hope to build a longer baseline (~few m) version of this instrument, which is called simply MBI. Concepts for MBI-B and MBI are illustrated in Fig. 1.

The scientific goals of MBI-B are to search for primordial B-mode polarization in the CMB and to map magnetic fields near the core of the galaxy. MBI addresses somewhat different scientific goals. It is designed to: (1) characterize the polarization of the CMB, (2) characterize clustering in the far-infrared background (FIRB), (3) measure wavelength dependent properties of dust polarization, and (4) conduct searches for and characterize the Sunyaev-Zel'dovich effect.

The technology goals for both MBI-B and MBI are to: (1) demonstrate aperture synthesis at millimeter wavelengths using an array of bolometers, (2) demonstrate deep integration on a single field without spatial chopping, (3) demonstrate advantages of millimeter-wave interferometry for the control of systematic effects.

2. Bolometric interferometry

A bolometric interferometer is an adding interferometer as opposed to a multiplying interferometer (Rohlfs and Wilson, 1996) as illustrated in

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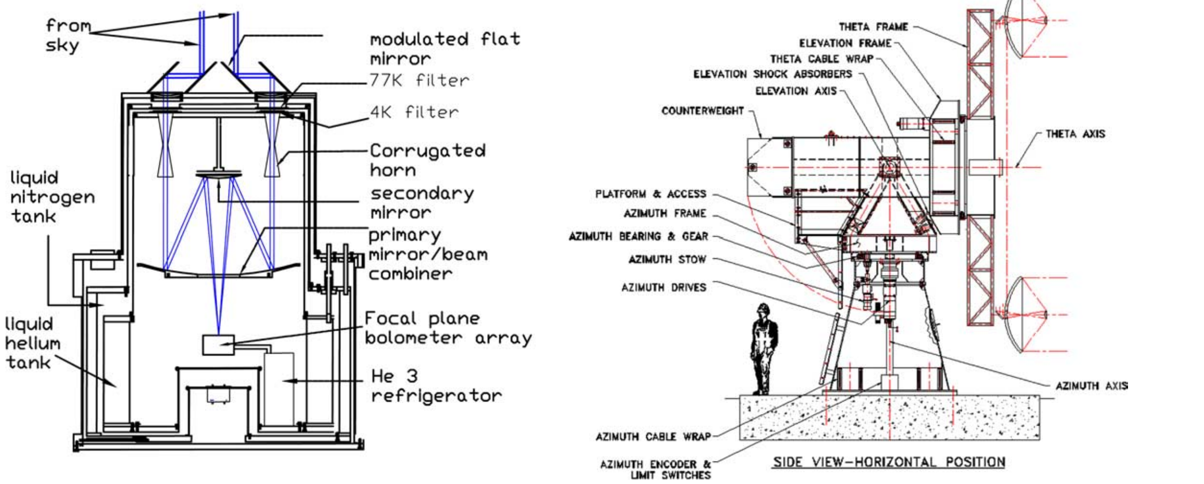

Fig. 1. Concepts for the MBI-B (left) and MBI (right) optical design. In the MBI-B design light from the sky is first reflected from two flat mirrors at 45°. The position of one of each pair of flat mirrors is modulated by a few wavelengths at a unique low frequency. Light enters the cryostat from the top, passing through blocking filters. The interferometer beams are defined with back-to-back corrugated feed horns; for clarity only two horns are shown. The beams are combined with a primary and secondary mirror in a Cassegrain telescope configuration. The interference pattern is imaged by a bolometer array in the focal plane. The bolometer array is cooled to below 0.3 K with a ^{3}He refrigerator. The MBI design is similar to the MBI-B design except that light enters the side of the cryostat and strikes a flat mirror at 45°. The light comes from Cassegrain telescopes located up to several meters away.

Fig. 2. To measure the cosine "cross-term" requires the use of a phase shifter to reject the DC component. In MBI and MBI-B the phase shifts will be accomplished with mirrors that modulate the path length of the beams by a few wavelengths. However, we are also investigating low-loss electronic phase shifters. Adding and multiplying interferometers recover the same visibility.

2.1. Beam combination

There are two approaches to beam combination, each with its own advantages and drawbacks. The two different types of beam combination are pupil-plane and image-plane. An interferometer which uses pupil-plane beam combination is also known as a Michelson interferometer. Image-plane beam combination is also known as Fizeau combination.

A Michelson interferometer is an example of a pupil-plane interferometer – the interference of the beam occurs in the pupil-plane. This type of interferometer is typically made using wire grids or dielectric beam splitters. The challenge in this type of instrument is to find a configuration that permits the combination of beams from more than a few baselines simultaneously.

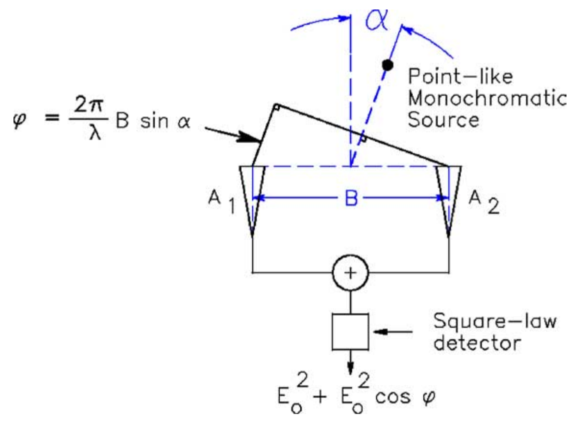

Fig. 2. Adding interferometer. At antenna A_2 the electric field is E_0, and at A_1 it is $E_0 e^{i\phi}$, where $\phi = kB \sin\alpha$ and $k = 2\pi/\lambda$. B is the length of the baseline, and α is the angle of the source with respect to the symmetry axis of the baseline, as shown. (For simplicity 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 $E_0^2 + E_0^2 \cos\phi$.

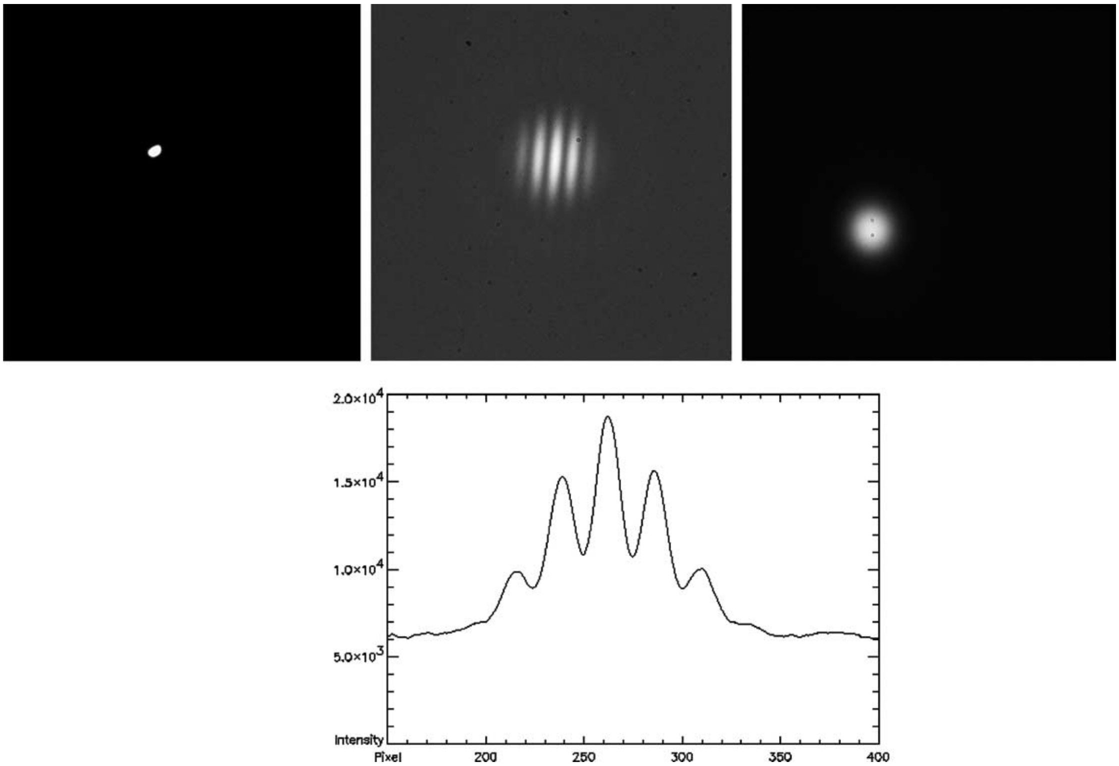

Fig. 3. Interferograms of Venus obtained using an optical Fizeau interferometer. The upper left shows an image of Venus obtained using a standard 1400 mm diameter Cassegrain telescope. The upper right panel shows an image of Venus but with the aperture stopped down to 2.4 mm. The lower left panel shows an interferogram of Venus obtained with two 2.4 mm apertures separated by 8 mm. The lower right panel is a cross-section through the interferogram.

A Fizeau interferometer combines the beams from various baselines in the image plane. A Fizeau interferometer operating at optical wavelengths can be obtained by putting two pinholes in a mask in front of a Cassegrain telescope. The results from such a demonstration are shown in Fig. 3. Efficient image reconstruction from Fizeau interferograms is an area of active research.

Table 1
MBI-B characteristics and sensitivity

λ (mm)	MBI-B 20×20 array		MBI-B 20×1 array		MBI-B		MBI	
	Sensitivity (mK $\sqrt{s}$)	Days to reach 3 μK/sky pixel	Sensitivity (mK$\sqrt{s}$)	Days to reach 3 μK/sky pixel	θ (deg)	ϕ (deg)	θ (arcmin)	ϕ (arcmin)
3	0.6 (1.1)	0.5 (1.4)	2.5 (4.7)	8 (28)	7	1.4	10	2.0
2	0.7 (1.3)	0.6 (2.2)	3.0 (5.7)	12 (43)	7	1.4	7.2	1.4
1	2.9 (5.4)	11 (37)	13 (24)	207 (740)	7	1.4	3.6	0.7

Note. Calculations assume equivalent temperature of atmosphere, optics and CMB is 40 K. Each interferometer views 25 pixels on the sky simultaneously. The NET is the sensitivity for each sky pixel to fluctuations in a 2.7 K blackbody. Sensitivity numbers and integration times are for background-noise-limited and, in parentheses, (detector-noise-limited) cases.

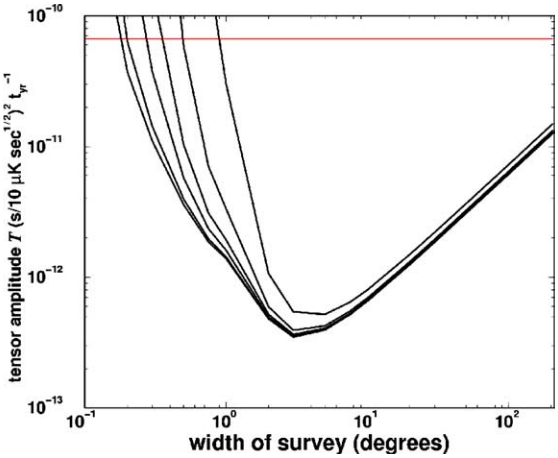

Fig. 4. The smallest tensor amplitude that could be detected at 3σ with an experiment with a detector sensitivity of 10 μK $\sqrt{s}$ that observed for one year and maps a square region of sky of given width. The result scales with the square of the detector sensitivity and inversely with the duration of the experiment. The curves are (from top to bottom) the FWHM beamwidths of 1.0°, 0.5°, 0.3°, 0.2°, 0.1° and 0.05°. The horizontal line shows the upper limit to the tensor amplitude from COBE. MBI-B will improve the COBE measurement by more than a factor of 10. (Reproduced from Jaffe et al., 2000.)

2.2. Sensitivity

The main characteristics of MBI-B are presented in Table 1. The field-of-view (FOV) of each interferometer element is denoted by θ and the size of the synthesized beam by ϕ.

For a noise-limited experiment the best observation strategy for detecting B-mode polarization is to spend more observation time on a restricted part of the sky rather than to survey a large part of the sky (Jaffe et al., 2000). A beam size smaller than ~1° does not significantly improve the sensitivity to detecting B-mode polarization. At a wavelength of 3 mm MBI-B has a FOV of ~7° and an effective resolution of 1.4°. This choice of FOV and resolution represents a trade-off to most effectively probe the B-mode polarization signal. Fig. 4 illustrates the trade-off between survey size and angular resolution and shows the choice of instrument parameters for MBI-B is nearly optimal.

Acknowledgements

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