Observing the CMB with the AMiBA

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Abstract. I discuss the capabilities and limitations of the AMiBA for imaging CMB anisotropies. Michael Kesteven (ATNF-CSIRO) has proposed drift-scanning as an observing strategy for measuring and rejecting any instrumental response that the close-packed interferometers may have to the local environment. The advantages of mosaic imaging CMB anisotropies using a co-mounted interferometric array in a drift-scanning observing mode are discussed. A particular case of mosaic imaging a sky strip using a two-element AMiBA prototype interferometer is considered and the signal-to-noise ratio in the measurement of sky anisotropy using this observing strategy is analysed.

1. Introduction

The ASIAA, Taiwan, is building an Array for Microwave Background Anisotropy (AMiBA) in collaboration with the National Taiwan University. The science goals are discussed by Lo et al. (2001). The telescope would be an interferometric array of 19 elements co-mounted on a single fully steerable platform. The array may be configured using either elemental apertures of 1.2 or 0.3 m diameters. Dual polarization receivers would have 20 GHz bandwidth centered at 95 GHz and the system temperature is expected to be about 75 K.

2. Imaging capabilities of the AMiBA

Surveys with the AMiBA are proposed to be made with the 19 apertures configured as a hexagonal close-packed array on the platform to maximize the surface brightness sensitivity of the interferometers. The configuration gives a well filled sampling of the u,v-domain with a radial density which peaks at the spacing corresponding to the distance between the centres of the adjacent apertures (which, for engineering reasons, is somewhat larger than the aperture diameters) and tapers off to zero at a u,v-distance five times larger. When the visibility data from single sky pointings are ‘naturally weighted’ — for maximum flux sensitivity — and images are synthesized, the synthetic beam has FWHM of 2.6 arcmin when the 1.2 m apertures are used and 10.4 arcmin when the 0.3 m apertures are used. The primary beam is expected to have HPW of 11 arcmin (1.2 m apertures) and 44 arcmin (0.3 m apertures). The absence of a ‘zero-spacing’ measurement in the interferometer array results in a ‘hole’ in the u,v-coverage at the origin whose size depends on the taper in the illumination at the edges of
the apertures. As a result, the main lobe of the synthetic beam is surrounded by a negative bowl which limits the surface brightness sensitivity.

Assuming aperture efficiencies of 0.6, we expect the 1.2 and 0.3 m apertures to have sensitivities about 4100 and 65100 Jy K$^{-1}$ respectively; antenna temperatures from planets Jupiter and Saturn would be detectable with high signal-to-noise ratio, for calibration, in seconds integration time. When all four cross products are measured between the dual polarization channels of every antenna pair, and images are synthesized in the Stokes parameters using ‘naturally’ weighted visibility data of all the 171 baselines, the rms thermal noise after 1-hr integration time is expected to be 1.4 and 22 mJy beam$^{-1}$ respectively when 1.2 and 0.3 m apertures are used.

3. Confusion limits

I adopt the 90-GHz source counts derived by Holdaway, Owen & Rupen (1994), with 180 sources all sky exceeding 1 Jy and 4400 sources all sky exceeding 100 mJy. The rms confusion noise, owing to these discrete synchrotron sources, is expected to be less than 70 and 2 $\mu$Jy beam$^{-1}$ in the images made respectively with the 0.3 and 1.2 m aperture arrays. The thermal noise will not reach this confusion noise for any reasonable integration time: the images will always be thermal noise limited. Consequently, extragalactic synchrotron sources will only appear in AMiBA images above the instrument thermal noise as well separated discrete sources. The source counts imply that we may expect to detect a source above 1-$\sigma$ thermal noise, in any AMiBA pointed observation, only after integration times of 50 and 300 hr respectively with the arrays made of 0.3 and 1.2-m apertures.

Confusion from the primary CMB anisotropy may limit the SZE-cluster survey sensitivity. In Stokes I images made with the 171-baseline array of 1.2-m apertures, the primary CMB contributes an rms image noise of about 2 mJy beam$^{-1}$ which exceeds the thermal noise in 1-hr integration. However, the T-mode primary anisotropy is expected to vanish at multipoles exceeding $l \sim 2500$ corresponding to a u,v-distance of 400: all of the T-mode power will be confined to the 1.2-m baselines and may be discriminated using appropriate filtering in $l$-space.

4. AMiBA sensitivity

I have adopted cosmological parameters $\Omega_m = 0.37$, $\Omega_\Lambda = 0.63$, $\Omega_B h^2 = 0.02$ and $h = 0.7$ for computing CMB anisotropy spectra in order to estimate the expected signal variance in AMiBA images. A $C_l$ power spectrum decomposition of the SZE anisotropy expected in this cosmological model was provided, for these calculations, by Ue-Li Pen (private communication).

In sky images synthesized using the 0.3 m aperture array, the E-mode CMB polarization signal is expected at appear with an rms of about 5 mJy beam$^{-1}$. The 171-baseline array with these apertures may image this linearly polarized signal, at 1-$\sigma$, in about 18 hr integration per pointing.

An SZE cluster survey with the 171-baseline array made of 1.2-m apertures would be confusion limited, in about 1 hr, because the thermal noise contri-
bution in this time would equal the T-mode confusion noise in the synthetic images. Added in quadrature, the rms image noise in 1-hr integration time would be 2.0 mJy beam$^{-1}$ and the rms anisotropy signal owing to cosmological clusters, with a contribution about 0.5 mJy beam$^{-1}$, would be buried in the noise. However, a simpleminded filtering by rejecting the 42 1.2-m baseline data would reject the T-mode confusion and in images synthesized using the (171 − 42) baseline visibilities, the 0.3 mJy beam$^{-1}$ SZE signal may be detectable at 1-$\sigma$ in about 30 hr integration in any pointing. It may be noted here that the cosmological evolution in cluster gas properties is poorly understood and predictions of the $C_l$ spectra expected from cosmological clusters may have large uncertainties. Consequently, estimates of integration times required for detection of the SZE $C_l$s are crude.

5. Mosaicing

Scanning the sky with interferometers has long been recognized as a method for decomposing visibility measurements made with finite apertures into equivalent visibilities which may be obtained by dividing the apertures into smaller sections (Ekers & Rots 1979, Rao & Velusamy 1984). Interferometric measurements of CMB anisotropy, which are made with single pointings, provide estimates of the CMB anisotropy power spectrum integrated in $l$-space over a range (defined by a telescope filter function) which corresponds to the auto-correlation function of the aperture illumination. A mosaic-mode observation of the CMB anisotropy is a method for decomposing the anisotropy measurements in $l$-space (White, Carlstrom, Dragovan & Holzapfel 1999) and improving the $l$-space resolution.

Short spacing interferometers have usually been used in interferometric CMB anisotropy measurements to give higher surface brightness sensitivity. However, these suffer from an undesired response to the environment (brightness variations across the ground-sky interface and across terrestrial objects) and are also susceptible to cross-talk (Subrahmanyan 2002). The unwanted response usually dominates the visibility due to the CMB anisotropy. The suggested observing strategy with the AMiBA is drift scanning: the co-mounted array is to be kept stationary with respect to the environment, and the apertures are kept stationary with respect to each other, during the data acquisition. The unwanted environmental response and cross-talk is then to be filtered out of the data stream as a constant.

We believe that this observing strategy has its advantages as compared to tracking arrays with independently mounted elements as well as tracking platforms with co-mounted apertures. First, although tracking arrays may differentiate between the sky signal and spurious coupling by the difference in their fringe rates, the summed environmental coupling and cross-talk would give an unwanted visibility contribution which would inevitably have a slow time varying amplitude. However, for a drift-scanning array of co-mounted elements, the unwanted component would be a constant in amplitude and phase and its subtraction is potentially exact. Second, any baseline in a tracking array which has a small $v$-component, either because the baseline is north-south oriented or because the observation is being made at a large hour angle, would have difficulty separating the sky signal from the unwanted response.
Scanning with interferometers has added advantages: as noted above, the time stream may be processed to improve the \( l \)-space resolution. This creates the possibility that the spurious correlations and cross-talk, which are expected to arise in the correlations between the fields in those parts of the two apertures which are the nearest, may be isolated.

Mosaic-mode observing, followed by a decomposition of the visibility measurements in \( u, v \)-space, gives measurements in regions of \( u, v \)-space which have poor sensitivity to sky anisotropy (because they represent correlations between sections of the apertures which are poorly illuminated by the feed). These measurements provide useful ‘control samples’ and may be used to estimate the instrument thermal noise from the data.

5.1. Sensitivity in Mosaic-mode observations

The signal and noise are distributed differently across \( l \)-space or, equivalently, \( u, v \)-space. The decomposition of the data obtained in multiple sky pointings — perhaps during a scanning of a sky region with the primary beam — into data distributed in \( l \)-space results in a separation of data with different signal-to-noise ratios. The signal-to-noise ratios in the individual \( l \)-space filters depends on the \( C_l \) spectrum of the CMB anisotropies and on the aperture illumination function.

As an illustration of the mosaic-mode observing, a particular case is considered here. A two element interferometer is considered, which is made of two 0.3-m apertures, and which are configured close-packed on a common steerable platform to give a 0.3 m baseline. This may represent the interferometer being constructed as a prototype for the AMiBA. Equipped with the 95 GHz AMiBA receivers, the thermal rms noise in the real and imaginary parts of the complex Stokes parameter visibilities is expected to be 0.29 Jy for 1-hr integration time.

A measurement of the CMB anisotropy signal, in a single pointing and with this single baseline, corresponds to a filtering of the CMB anisotropy spectrum with a telescope filter function (TFF) given in Fig. 1. This single filter defines the sensitivity, in \( l \)-space, of the interferometer formed between the pair of 0.3 m

![Figure 1](image-url)

Figure 1. Telescope filter function for a single pointing
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Figure 2. Telescope filter functions for a 11-point mosaic

apotures. Assuming a ‘flat-band’ CMB power with \( l(l + 1)C_l/(2\pi) = 4 \times 10^{-12} \) \((\Delta T/T)^2\); dimensionless), the expected signal is 33 mJy rms in the real and imaginary visibilities. In an observation of a single pointing, 39 hr integration would be expected to yield one estimate of the anisotropy power — averaged in \( l \)-space over the range defined by the aperture extent — with unity signal-to-noise ratio.

Consider next a mosaic-mode observation with the two-element interferometer in which an RA strip of the sky is observed in a sequence of eleven pointings spaced 18.1 arcmin apart (the primary beam FWHM is about 44 arcmin). I assume that the platform is steered, in RA, declination, and about a rotation axis, to keep the baseline oriented parallel to the scan direction. Assuming an integration time of 39/11 hr in each pointing (and 39 hr in total), each of the 11 complex visibilities would have a thermal rms noise of 0.15 Jy in the real and imaginary components.

The 11 complex visibilities \( X(n), n = -5, -4, ..., 4, 5 \) are discrete Fourier transformed:

\[
Y(k) = \sum_{n=-5}^{n=+5} [X(n)e^{i2\pi n\frac{k}{N}}],
\]

with \( N = 11 \), to give eleven complex visibilities \( Y(k), k = -5, -4, ..., 4, 5 \), distributed in \( l \)-space. These eleven visibilities are measures of the sky anisotropy signal as viewed through a bank of filters, shown in Fig. 2, which span the \( l \)-space range covered by the pair of apertures forming the interferometer.

Adopting once again a ‘flat-band’ CMB anisotropy spectrum, with \( l(l + 1)C_l/(2\pi) = 4 \times 10^{-12} \), the expected rms signal amplitudes, and the signal-to-noise ratios, for the estimate of the signal in each filter, for the eleven measurements \( Y(k) \), are given in Table 1.

The rms thermal noise in each of these measurements, assuming 39/11 hr integration on each of the 11 pointings, is \( 0.15 \times \sqrt{11}/\sqrt{2} = 0.36 \) Jy.
Table 1. Signals (S in mJy) and the signal to noise (S/N) expected in the $l$-space filter bank

| Filter num. | −5 | −4 | −3 | −2 | −1 | 0  | 1  | 2  | 3  | 4  | 5  |
|-------------|----|----|----|----|----|----|----|----|----|----|----|
| S           | 36 | 80 | 131| 152| 170| 169| 125| 82 | 52 | 31 | 27 |
| S/N         | 0.1| 0.2| 0.4| 0.4| 0.5| 0.5| 0.3| 0.2| 0.1| 0.1| 0.1|

In place of the eleven measurements $X(n)$, each with a signal-to-noise ratio of $1/\sqrt{11}$ and with independent noise, the mosaic-mode analysis which combines the information from the multiple pointings simultaneously provides eleven estimates $Y(k)$ of the CMB anisotropy power spectrum distributed in $l$-space with varying signal-to-noise ratios and with independent noise.

It may be noted that the central filters detect the CMB flat-band power with signal-to-noise exceeding $1/\sqrt{11}$ where as the edge channels respond poorly to sky anisotropy. However, the signal-to-noise in the detection of anisotropy in any of the $l$-space filters generated via the mosaic-mode observation does not exceed the signal-to-noise attainable if the total time were used in a single pointing. The sum of the squares of the signal-to-noise ratios in the 11 filters, listed in Table 1, is unity, and this is true for any plausible form for the $C_l$ spectrum. The mosaicing strategy evaluated here effectively redistributes the observing time equally among the synthetic $l$-space filters so that the sum of the squares of the signal-to-noise ratios over all independent filters is invariant and is proportional to the total observing time.

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