A measurement at the first acoustic peak of the cosmic microwave background with the 33-GHz interferometer

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ABSTRACT
This paper presents the results from the Jodrell Bank–Instituto de Astrofísica de Canarias (IAC) two-element 33-GHz interferometer operated with an element separation of 32.9 wavelengths and hence sensitive to 1°-scale structure on the sky. The level of cosmic microwave background (CMB) fluctuations, assuming a flat CMB spatial power spectrum over the range of multipoles \( \ell = 208 \pm 18 \), was found using a likelihood analysis to be \( \Delta T_\ell = 63^{+5}_{-6} \mu K \) at the 68 per cent confidence level, after the subtraction of the contribution of monitored point sources. Other possible foreground contributions have been assessed and are expected to have negligible impact on this result.

Key words: instrumentation: interferometers – cosmic microwave background – cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION
Observations of the angular power spectrum of cosmic microwave background (CMB) temperature fluctuations are a powerful probe of the fundamental parameters of our Universe. The amplitude and spatial distribution of these fluctuations can discriminate between competing cosmological models. Most inflationary models predict more power on scales of 0°.2–2°, in the form of a series of peaks. These are caused by acoustic oscillations in the photon–baryon fluid, which are frozen into the CMB at recombination, with the peaks corresponding to regions of maximum compression and troughs to regions of maximum rarefaction. Hence, the position of the first acoustic peak is a strong test for the geometry of the Universe, because it corresponds to a fixed physical scale at the time of recombination projected on to the sky.

The previous result from the Jodrell Bank–IAC 33-GHz interferometer of \( \Delta T_\ell = 43^{+13}_{-12} \mu K \), reported in Dicker et al. (1999), corresponds to an angular spherical harmonic \( \ell \sim 110 \), equivalent to \( \sim 2° \) structure. To investigate smaller angular scales, the baseline was doubled; in this paper we analyse the data from this wide spacing configuration, which corresponds to an angular spherical harmonic \( \ell \sim 210 \). The data presented here were taken at the Teide Observatory, Tenerife, between 1998 May 27 and 1999 March 9. The paper is organized as follows. The instrumental configuration is summarized in Section 2; a full description can be found in Melhuish et al. (1999). The basic data processing is outlined in Section 3; for a more complete discussion see Dicker et al. (1999). The calibration method is also discussed in Section 3 and the data analysis in Section 4. A derivation of the fluctuation amplitude, after an estimate of the contribution of possible foregrounds, is given in Section 5.

2 THE 33-GHZ INTERFEROMETER
The interferometer consists of two horn-reflector antennas positioned to form a single E–W baseline, which has two possible lengths depending on the separation of the horns. The narrow spacing configuration has a baseline of 152 mm, while in the wide spacing configuration the horns are 304 mm apart. For the observations presented here, the baseline was 304 mm. Observations were made at a fixed declination of Dec. = +41°, using the rotation of the Earth to ‘scan’ 24 h in RA each day. This ‘scan’ runs through some of the lowest background levels of synchrotron, dust and free–free emission. The horn polarization is horizontal, parallel with the scan direction. There are two data outputs representing the cosine and sine components of the complex interferometer visibility. The operating bandwidth covers 31–34 GHz, near a local minimum in the atmospheric emission spectrum; the antenna spacing corresponds to 32.9 wavelengths. The low level of precipitable water vapour, which is typically around 3 mm at Teide Observatory, permits the collection of high-quality data. Only 16 per cent of the data have been rejected, because of bad weather and the daily Sun transit.

The measured response of the interferometer is well approximated by a Gaussian with sigma values of \( \sigma_{RA} = 2°.25 \pm 0°.03 \).

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3 Basic Data Processing and Calibration

The first step in the analysis is the removal of any variable baseline offsets from the data and the correction of a small departure from quadrature between the cosine and sine data. The data are calibrated relative to the CAL signal and rebinned into 2-min bins to ensure alignment in RA between successive scans. The data affected by the Sun and bad weather are removed and processed data was equal to the predicted value. Using 27 observations of the Moon, an average amplitude for CAL of 14\(\pm 2\) was found. The error consists of a 1.4 per cent error in the Moon and Dec. beam sigma values (dispersion) and \(f\) is the fringe spacing.

Regular observations of the Moon were made; for each observation, equation (2) was evaluated numerically and an amplitude for CAL found such that the amplitude of the Moon in the processed data was equal to the predicted value. Using 27 observations of the Moon, an average amplitude for CAL of 14.7 ± 0.8 K was found. The error consists of a 1.4 per cent error in the measurements and an estimated 5.5 per cent error in the Moon model (Gorenstein & Smoot 1981). Fig. 2 shows our observations and how the measured brightness temperatures of the Moon change with phase.

The Moon model used in this paper differs from the model given in Dicker et al. (1999). These data, together with the additional data taken using narrow spacing (Section 6), will be the subject of a forthcoming paper, using the Moon model given in this paper.

4 Likelihood Analysis

4.1 Theory

The temperature anisotropies of the CMB fluctuations are described by a two-dimensional random field on the sky, the properties of which can be determined from the two-point correlation function \(C^{\text{CMB}}(\theta)\), where \(\theta\) is the angular separation...
of the two points:

$$C_{\text{CMB}}(\theta_j) = \left( \frac{\Delta T_i}{T_i} \right) \left( \frac{\Delta T_j}{T_j} \right)^*,$$

(3)

which can be expanded in terms of spherical harmonics as

$$C_{\text{CMB}}(\theta_j) = \sum \frac{(2 \ell + 1)}{4\pi} C_\ell \cos(\theta_j).$$

(4)

In our analysis the form of the likelihood function is given by:

$$L \propto \frac{1}{|C|^2} \exp(-\frac{1}{2}D^T C^{-1} D),$$

(5)

where $D$ is the data set and $C$ is the covariance matrix, which represents the model of the CMB sky modulated by our observing strategy. The covariance matrix is composed of two terms, $C = S + N$, where $S$ is the signal and $N$ is the noise correlation matrix. The signal is the convolution of the two-point correlation function and the autocorrelation function of the primary beam function of the interferometer:

$$S_{ij} = C_{\text{CMB}}(\theta_j) \otimes S_{\text{beam}}(\theta_j).$$

(6)

Using the band-power approximation, where $\Delta T_\ell = \sqrt{\ell(\ell + 1)} C_\ell / 2\pi$ is assumed to be constant across the range of $\ell$ covered by the window function,$^1$

$$C_{\text{CMB}}(\theta_j) = \frac{1}{2} (\Delta T_\ell) \sum_{\ell = \ell_{\text{min}}}^{\ell_{\text{max}}} \frac{(2 \ell + 1)}{\ell(\ell + 1)} P_\ell \cos(\theta_j),$$

(7)

where $\ell_{\text{max}}$ is the limit of the summation.

The sensitivity at an individual value of $\ell$ is given by the window function of the interferometer in Fig. 3. The window function was computed using the method of Mucciaccia, Natoli & Vittorio (1997) to decompose the beam into spherical harmonics. The resulting function can be modelled by

$$W_\ell(\ell) = 0.0377 \times \exp \left[ - \frac{(\ell - 208)(\ell - 209)}{694} \right].$$

(8)

$W_\ell(\ell)$ falls to half power at $\ell = 208 \pm 18.$

$^1$There is a typographical error in Dicker et al. (1999): in the denominator the $8\pi$ should be $2\pi$ as written here.

**Figure 2.** Measured value of the Moon’s brightness temperature as a function of phase. Phase is measured from the full Moon. The solid line is the prediction of the model given by Gorenstein & Smoot (1981): $T_b = 202 + 27 \cos(\phi - \psi)$ in K. Each observation has been calibrated using CAL = 14.7 K.

**Figure 3.** The window function of the interferometer in its wide spacing configuration (304 mm - 32.9 wavelengths), which is well fitted by $W_\ell(0) = 0.037 \exp[-(\ell - 208)(\ell - 209)/694].$

The covariance matrix can now be calculated, by numerically evaluating equations (6) and (7). Equation (7) is evaluated to $\ell_{\text{max}} = 300,$ where the sensitivity of the interferometer, $W_\ell(0)$, is negligible. The result of equation (7), $C_{\text{CMB}}(\theta_j)$, is used to calculate the required value of $S_j$ using equation (6). The covariance of two points with an angular separation of $\theta_j$ is then given by $C_{ij} = S_j + N_{ij}.$

### 4.2 The Results and the Galactic Cut

Any analysis should take account of likely Galactic emission. At Dec. $+41^\circ$ the ranges $21^h 48^m - 3^h 48^m$ RA and $6^h 12^m - 19^h 30^m$ RA are at Galactic latitude $b \approx 10^\circ.$ To find regions free of significant Galactic emission, 48 intervals of 5 h in RA were analysed as described above, stepping every 0.5 h. It was found that the above cut was in general agreement with the higher latitude results, except the region $2^h 48^m - 3^h 48^m,$ which was excluded; this is because of the Galactic plane emission and difficulties in subtracting the contribution of 3C84; see Section 5.1.

The likelihood analysis of the ranges $21^h 48^m - 2^h 48^m$ RA and $6^h 12^m - 19^h 30^m$ RA gives $\Delta T = 78.5_{-12.0}^{+12.0}$ K and $69.5_{-12.0}^{+12.0}$ K for the cosine channel and the sine channel respectively. The likelihood analysis using both channels simultaneously gives $\Delta T = 70.0_{-6.5}^{+7.0}$ K at the 68 per cent confidence level.

### 5 The Effect of Foregrounds on the Results

#### 5.1 Point sources

The five strongest sources with $S(33 \mathrm{GHz}) \geq 2 \mathrm{Jy}$ within a $4^\circ$ strip centred on Dec. $+41^\circ$, listed in Table 1, are routinely monitored by the University of Michigan at 4.8, 8.0 and 14.5 GHz and in the Metsahovi programme at 22.0 and 37.0 GHz. Using these data over the period of our observations, it was possible to assess their approximate flux densities at 33 GHz. These were then convolved with the two-dimensional interferometer beam pattern centred on Dec. $+41^\circ$ and converted to antenna temperatures using the factor 6.90 $\mu\text{K}\text{Jy}^{-1}$; in this form these sources may be subtracted from the data.

The data ranges $21^h 48^m - 2^h 48^m$ RA and $6^h 12^m - 19^h 30^m$ RA were analysed together, subtracting the point sources as discussed above. Each channel was analysed independently and then combined for a joint analysis. For the cosine channel $\Delta T = 69.5_{-12.0}^{+12.0}$ K, for the sine channel $\Delta T = 62.5_{-11.5}^{+11.0}$ K, and combining both channels gives $\Delta T = 64.0_{-6.0}^{+7.0}$ K at the 68 per cent confidence level.

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Table 1. Sources within a 4° wide Dec. strip centred on +41°.

| Name      | RA2000 | Dec.2000 | Mean Flux (Jy) |
|-----------|--------|----------|----------------|
| 3C 84     | 03h19m48\(^\circ\) | +41°30'42" | 11.8           |
| DA 193    | 08h55m31\(^\circ\) | +39'48"49' | -             |
| 4C 39.25  | 09h27m03\(^\circ\) | +39°02'21" | 9.5            |
| 3C 345    | 16h42m59\(^\circ\) | +39°48"57' | 9.0            |
| BL Lac    | 22h02m43\(^\circ\) | +42'16"40" | 3.7            |

Figure 4. The likelihood curve of the joint analysis of both channels of the point-source-subtracted data. \(\Delta T = 64.0^{+7.0}_{-6.0}\) μK at the 68 per cent confidence level and \(64.0^{+14.0}_{-13.0}\) μK at the 95 per cent confidence level.

cent confidence level and \(64.0^{+14.5}_{-14.0}\) μK at the 95 per cent confidence level. The likelihood curve of this analysis is shown in Fig. 4.

The contribution of unresolved point sources was estimated according to the results of Franceschini et al. (1989). At a 33-GHz resolution of 0.8° this is expected to be ~11 μK, which adds in quadrature to the CMB signal. The contribution of unresolved sources then accounts for approximately 1 μK of the total signal and accordingly the best estimate of the intrinsic CMB fluctuation amplitude is \(\Delta T = 63.0^{+7.0}_{-6.0}\) μK at \(\ell = 208\).

5.2 Spinning dust

de Oliveira-Costa et al. (1998) estimated the contribution of spinning dust in a 19-GHz map of 3° resolution by correlating it with the DIRBE sky maps, finding \(\Delta T \sim 66 \pm 22\) μK. Using the IRAS 100-μK map, Gautier et al. (1992) investigated the spatial index of the dust, finding on scales between 8° and 4 arcmin that \(\Delta T \propto \ell^{-3/2}\). This, combined with the expected spectral index of the spinning dust of \(-3.3 < \beta_{\text{dust}} < -4\) (de Oliveira-Costa et al. 1998), allowed the estimation of the contribution of spinning dust at 33 GHz and 0.8° resolution. The expected signal in our data arising from spinning dust was found to be \(\Delta T_{\text{dust}} = 1.5 \pm 0.5\) μK. This again adds in quadrature to the total signal, therefore the contribution from spinning dust is expected to be negligible.

5.3 Diffuse Galactic emission

An estimate of the amplitude of the diffuse Galactic component in our data can be computed using the results obtained in the same region of the sky by the Tenerife CMB experiments (Davies & Wilkinson 1998; Gutiérrez et al. 2000). At 10.4 GHz and on angular scales centred on \(\ell = 20\), the maximum Galactic component was estimated to be \(\leq 28\) μK. Assuming that this contribution is entirely caused by free–free emission (\(\beta = -2.1\)) and a conservative Galactic spatial power spectrum of \(\ell^{-2.5}\), the predicted maximum Galactic contamination in the data presented here is 0.8 μK, less than 2 per cent of our measured value. Any such contribution would add in quadrature to that from the CMB, and so is insignificant. The true make-up of the 10.4-GHz Galactic foreground emission will have a steeper average spectral index, because synchrotron radiation with \(\beta < -3\) will contribute to the measured value; therefore the contribution to our result will be even lower than stated.

6 CONCLUSIONS

In this paper we describe the results taken with the Jodrell Bank–IAC 33-GHz interferometer in its wide spacing configuration, which is sensitive to structure at \(\ell \sim 200\). In the final result of \(\Delta T = 63.0^{+7.0}_{-6.0}\) μK, possible foreground contributors have been considered, the most significant of which are point sources. In Section 5.1 the contribution of strong, monitored sources is removed from the data. To allow for the contribution of unresolved sources, the lower limit on \(\Delta T\) has been increased. In Sections 5.2 and 5.3, the contributions from dust and diffuse Galactic emission are found to be negligible. We believe our result represents the intrinsic CMB fluctuation signal at \(\ell = 208\). The quoted error in our result is dominated by sample variance, resulting from the finite number of beam areas observed.

Table 2 and Fig. 5 show our result alongside others published in the last year from experiments covering similar angular scales. These experiments have been made for a range of different frequencies and regions of the sky. Our result is in good agreement with the published data around \(\ell \sim 200\). The results at \(\ell \sim 200\) appear to be converging on a value of \(\Delta T = 60-70\) μK. However, over the wider \(\ell\) range of 50–300, discrepancies appear in the data sets significantly greater than the quoted errors. There appears to be evidence for unknown systematic effects and possible foreground contamination remaining in the data sets.

Our interferometer results show a rise in the amplitude of the power spectrum between \(\ell \sim 100\) and \(\ell \sim 200\). This is intrinsic to the CMB, because the parameters of the interferometer system, particularly the calibration, remain the same except for the spacing. The data in Fig. 5, despite the discrepancies referred to above, are strongly indicative of a peak in the power spectrum at \(\ell \sim 200\).

The interferometer is currently in its narrow spacing configuration (\(\ell \sim 110\)), observing declinations spaced by 1°2 from Dec +37.4 to +43.4; these data will significantly reduce the sample variance of the result published by Dicker et al. (1999) to the order of 5 per cent.
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APPENDIX A: NOTE ADDED IN PROOF

Our result of $\Delta T = 63.0^{+7.0}_{-6.0} \mu K$ at $\ell = 208$ is competitive in accuracy with the latest published results from the Boomerang experiment, which found an amplitude for the first peak of $\Delta T = 69 \pm 8 \mu K$ at $\ell = 197 \pm 6$ (de Bernardis et al. 2000), and the Maxima experiment, which found a peak at $\ell = 220$ of amplitude $\Delta T = 78 \pm 6 \mu K$ (Hanany et al. 2000).

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