THE JODRELL BANK – IAC 33 GHz INTERFEROMETER

D.L.Harrison[1], R.A. Watson[1], R.D. Davies[1], R. Rebolo[2], R.J. Davis[1], J. A. Rubiño-Martin[2], J. F. Macias-Perez[1], C. M. Gutiérrez[2]
[1] *University of Manchester, Jodrell Bank Observatory,Macclesfield, Cheshire SK11 9DL, UK*
[2] *Instituto de Astrofisica de Canarias, 38200 La Laguna, Tenerife, Canary Islands, Spain*

This paper presents results obtained with the Jodrell Bank – IAC two-element 33 GHz interferometer, located at the Teide Observatory on Tenerife, which is designed to measure the level of the Cosmic Microwave Background (CMB) fluctuations on angular scales of 1° and 2° . The results, at the 68% confidence limit, from a maximum likelihood analysis of observations taken at Dec +41° are $\Delta T_\ell = 64^{+7}_{-7}\,\mu$K at $\ell = 208 \pm 18$ and $\Delta T_\ell = 56^{+5.5}_{-6.0}\,\mu$K at $\ell = 106 \pm 19$. The contribution of possible foreground contaminants are considered.

1 A Description of the 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, 16.5 wavelengths, while in the wide spacing configuration the horns are 304 mm, 32.9 wavelengths, apart. Observations are made at a fixed declination of Dec=+41° for the data presented here, using the rotation of the Earth to "scan" 24 hours in RA each day. This "scan" runs through some of the lowest Galactic 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 the sine components of the complex interferometer visibility. The operating frequency range is 31–34 GHz, near a local minimum in the atmospheric emission spectrum. The low level of precipitable water vapour, which is typically around 3 mm at Teide Observatory permits the collection of high quality data, limited by the receiver noise for more than 80 per cent of the time.

The measured response of the interferometer is well approximated by a Gaussian with sigmas of $\sigma_{\rm RA}$=$2^\circ\!.25 \pm 0^\circ\!.03$ (in RA) and $\sigma_{\rm Dec}$=$1^\circ\!.00 \pm 0^\circ\!.02$ (in Dec), modulated by fringes with a period of f = $3^\circ\!.48 \pm 0^\circ\!.04$ in RA at a baseline of 152 mm and f = $1^\circ\!.74 \pm 0^\circ\!.02$ in RA at a baseline of 304 mm. This defines the range of sensitivity to the different multipoles ℓ of the CMB power spectrum (C_ℓ) of the narrow and wide spacings to a maximum sensitivity at ℓ = 106 (1°.6) and half sensitivity at $\Delta\ell = \pm 19$, and at ℓ = 208 (0°.8) $\pm$ 18, respectively.

A known calibration signal (CAL) is periodically injected into the waveguide after the horns allowing a continuous calibration and concomitant corrections for drifts in the system gain and phase offset. A full description of the instrument configuration can be found in Melhuish *et al.*[7].

2 Basic Data Processing & 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 re-binned into 2-minute bins to ensure alignment in RA between successive scans. The effects of the Sun and bad weather are removed and individual scans are averaged to form a "stack". The data are calibrated relative to CAL which itself needs to be calibrated by an astronomical source. The small collecting area of the antenna gives a reduced sensitivity to point sources and many days of observation are required to achieve a signal-to-noise ratio sufficient for calibration purposes. Consequently, the Moon is used as the primary calibrator as the power received from a single Moon transit is large enough to give signal-to-noise ratios of $\sim 6000:1$.
The model used for the Moons brightness temperature at 33 GHz is that of Gorenstein & Smoot[4]. Regular observations of the Moon were made; using 27 observations of the Moon, an average amplitude for CAL of 14.7 $\pm$ 0.8 K was found. A more complete discussion of the basic data processing can be found in Dicker *et al.*[2] and of the calibration with respect to the Moon in Harrison *et al.*[5].

3 Analysis of Observational Data

The interferometer has made observations at Dec +41° in both its narrow and wide spacings, over the periods 4 April 1997 - 2 September 1997 and 27 May 1998 - 9 March 1999, which are the subject of the papers published by Dicker *et al.*[2] and Harrison *et al.*[5], respectively. The narrow spacing result has since been revised by the inclusion of extra data, taken over the period 4 February 1998 - 9 March 1998, an improvement in the value of CAL and the use of more of the RA range in the analysis.

The data is analysed using a maximum likelihood approach, the details of which are outlined in Harrison *et al.*[5]. Any analysis should take account of likely Galactic emission. At Dec +41° the ranges 21^h48^m- 3^h48^m RA and 6^h12^m-19^h30^m RA are at Galactic latitude b $\geq$ 10° . The region 2^h48^m- 3^h48^m is also excluded due to 3C84. To show that these RA ranges are free of significant Galactic emission, 48 intervals of 5 hours in RA were analysed using maximum likelihood, stepping every 0.5 hours; these showed no significant changes as a function of RA inside these regions.

The likelihood analysis of the wide spacing data at $\ell = 208$ over these regions gives $\Delta T = 78.5^{+12.5}_{-12.0}\,\mu K$ and $\Delta T = 69.5^{+12.5}_{-12.0}\,\mu K$ for the cosine channel and the sine channel respectively. The likelihood analysis using both channels simultaneously gives $\Delta T = 70.0^{+7.0}_{-6.5}\,\mu K$.

The analysis of the narrow spacing data at $\ell = 106$, over the same RA ranges gives $\Delta T = 49.5^{+10.0}_{-10.0}\,\mu K$ and $\Delta T = 65.5^{+11.0}_{-9.0}\,\mu K$ for the cosine channel and the sine channel respectively. Combining both channels gives $\Delta T = 55.0^{+6.0}_{-5.5}\,\mu K$.

Table 1: Values of ΔT around $\ell \sim 200$ and $\ell \sim 100$ published in the past year.

Experiment	Freq. (GHz)	ΔT (μK)	ℓ	ΔT (μK)	ℓ	Reference
Int33	**33**	$\mathbf{64^{+7}_{-7}}$	$\mathbf{208^{+18}_{-18}}$	$\mathbf{56^{+5.5}_{-6.0}}$	$\mathbf{106^{+19}_{-19}}$	This paper
MSAM1	156	49^{+10}_{-8}	201^{+70}_{-82}	35^{+15}_{-11}	84^{+46}_{-45}	Wilson *et al.*[11]
Viper	40	$66^{+24.4}_{-17.2}$	237^{+111}_{-99}	$61.6^{+31.1}_{-21.3}$	108^{+129}_{-78}	Peterson *et al.*[9]
Boomerang	150	72^{+10}_{-10}	204^{+28}_{-21}	49^{+9}_{-9}	102^{+23}_{-26}	Mauskopf *et al.*[6]
Python V	41	77^{+20}_{-28}	199^{+15}_{-15}	34^{+7}_{-9}	106^{+15}_{-15}	Coble[1]
TOCO98	144	83^{+7}_{-8}	226^{+56}_{-37}	-	-	Miller *et al.*[8]
TOCO97	35	85^{+8}_{-8}	199^{+29}_{-38}	70^{+6}_{-6}	114^{+20}_{-24}	Torbet *et al.*[10]

4 Foregrounds

The sensitivity of the interferometer to foreground contaminants, depends of the baseline configuration. The wide spacing is less sensitive than the narrow spacing to Galactic diffuse emission such as dust, free-free and synchrotron, but is more sensitive to the contribution from point sources.

The 5 strongest sources with S(33 GHz) $\geq$ 2 Jy within a 4° strip centred on Dec +41° 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 flux densities at 33 GHz. These were then convolved with the two-dimensional interferometer beam pattern centred on Dec +41° and converted to antenna temperatures using the factor $6.90\,\mu\mathrm{KJy}^{-1}$; in this form these sources may be subtracted from the data. The wide spacing data over the ranges $21^{\mathrm{h}}48^{\mathrm{m}}$- $2^{\mathrm{h}}48^{\mathrm{m}}$ RA and $6^{\mathrm{h}}12^{\mathrm{m}}$- $19^{\mathrm{h}}30^{\mathrm{m}}$ RA were analyzed together, subtracting the point sources as discussed above. Each channel was analyzed independently and then combined for a joint analysis. For the cosine channel $\Delta T = 69.5^{+12.5}_{-11.5}\,\mu\mathrm{K}$, for the sine channel $\Delta T = 62.5^{+13.0}_{-11.5}\,\mu\mathrm{K}$ and combining both channels gives $\Delta T = 64.0^{+7.0}_{-6.0}\,\mu\mathrm{K}$. The contribution of unresolved point sources was estimated according to the results of Franceschini *et al.*[3]; at the 33 GHz resolution of 0°.8 this is expected to be $\Delta T \sim 11\mu\mathrm{K}$, which adds in quadrature to the CMB signal. The contribution of unresolved sources then accounts for approximately 1 μK of the total signal. Since this contribution can only add we increase, the negative error by 1 μK; giving $\Delta T = 64.0^{+7.0}_{-7.0}\,\mu\mathrm{K}$. In Harrison *et al.*[5] we show that the expected contribution from diffuse Galactic emission including spinning dust is negligible.

For the narrow spacing data we are less sensitive to point sources; after the subtraction of monitored sources we find for the cosine channel $\Delta T = 53.0^{+9.5}_{-9.5}\,\mu\mathrm{K}$, for the sine channel $\Delta T = 65.5^{+11.0}_{-9.5}\,\mu\mathrm{K}$ and combining both channels gives $\Delta T = 56.0^{+5.5}_{-5.5}\,\mu\mathrm{K}$. The expected contribution from unresolved sources is $\Delta T \sim 8\mu\mathrm{K}$ (Franceschini *et al.*[3]) which accounts for approximately 0.5 μK of the total signal, again we increase the negative error by this amount; giving $\Delta T = 56.0^{+5.5}_{-6.0}\,\mu K$. Although the sensitivity to diffuse emission has increased the contribution of free-free, synchrotron and dust is still expected to be negligible, Dicker *et al.*[2].

5 Conclusions

Table 1 and Fig. 1 show our results alongside others published in the last year from experiments covering similar angular scales. These experiments have been made at a range of different frequencies and regions of the sky. Our result has the lowest quoted errors and is in good agreement with the published data around $\ell \sim 200$. The results at $\ell \sim 200$ appear to be converging

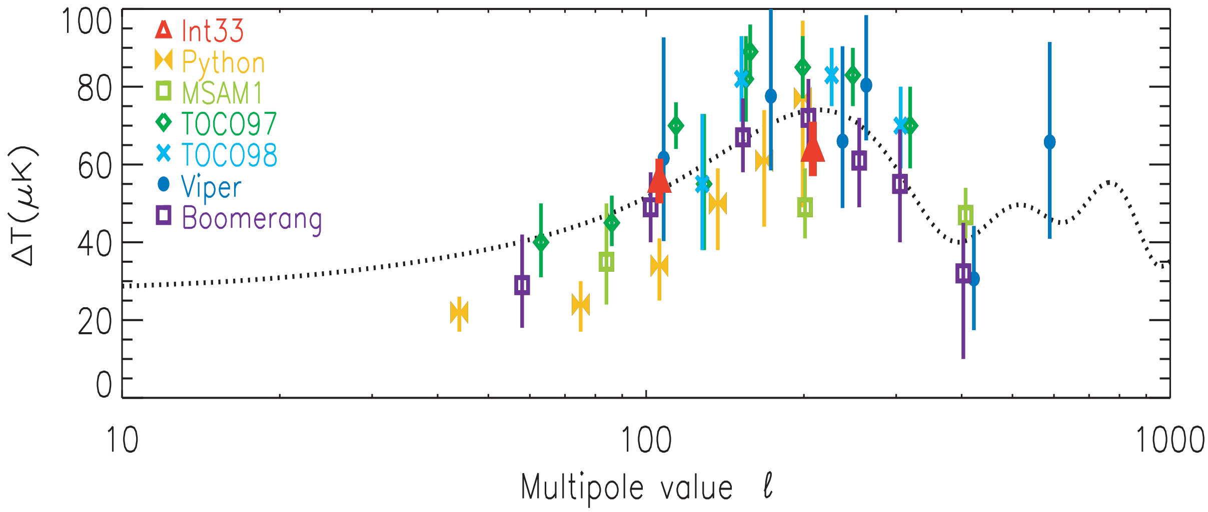

Figure 1: Values of ΔT published in the past year, as a function of ℓ. Our results are shown by the heavy lines at $\ell = 106$ of $\Delta T_\ell = 56^{+5.5}_{-6.0}\,\mu$K and at $\ell = 208$ of $\Delta T_\ell = 64^{+7}_{-7}\,\mu$K. The dotted line represents the model given by $\Omega_b = 0.05$, $\Omega_{\rm CDM} = 0.40$, $\Omega_\lambda = 0.55$ and $H_0 = 70\,{\rm km\,s^{-1}}$ Mpc^{-1}, this is shown for illustrative purposes and does not represent a fit to the data.

on a value of $\Delta T = 60 - 70\,\mu$K. However, over the wider ℓ range of 50 - 300 discrepancies appear in the data sets significantly greater than the quoted errors. There appears to be evidence for 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 $\ell = 106$ and $\ell = 208$. This is intrinsic to the CMB since the parameters of the interferometer system, including calibration, remain the same except for the spacing. The data in Fig. 1, 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 ($\ell = 106$), observing 5 declinations spaced by 1°.2 from Dec +37°.4 to +43°.4; these data will reduce the sample variance of the result at $\ell = 106$ to the order of 5%.

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