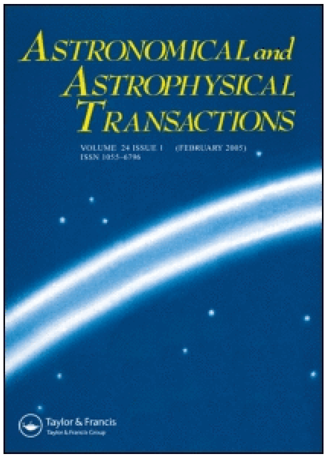

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COSMOLOGY

RECENT RESULTS OF THE TENERIFE CMB EXPERIMENTS

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We report some recent of the Tenerife experiments. On a strip at Dec = +40° we have identified structure in the microwave sky at several frequencies. Clear evidence is found for a feature centred at RA ~ 185° with a peak amplitude of 80 μK. A statistical analysis of the data at this declination reveals the presence of signal at an *rms* of 42 ± 9 μK. Assuming a model of a Harrison–Zeldovich spectrum of fluctuations, we infer an expected quadrupole term of 25^{+9}_{-7} μK. The radiometers are now observing adjacent bands of the sky separated 2.5 degrees in declination; some of the preliminary results obtained in these adjacent scans are discussed.

KEY WORDS Cosmology, large scale structure of the Universe, cosmic microwave background, observations

1 INTRODUCTION

The Tenerife experiments have the objective of detecting and mapping the primordial fluctuations in the Cosmic Microwave Background (CMB) on angular scales of several degrees. Such mapping from ground-based instruments requires long integration times, a careful choice of site, of frequencies and of observing technique. The Tenerife experiments have demonstrated that it is possible to achieve sensitivities of some tens of μK, the level of CMB fluctuations predicted by theoretical models. The experiments are a collaboration between the University of Manchester, the IAC Tenerife and MRAO Cambridge, and consist of three independent two-channel radiometers operating at frequencies of 10.4, 14.9 and 33 GHz, generically called the 10, 15 and 33 GHz experiments respectively. The instruments are installed at the Observatorio del Teide on the island of Tenerife (Spain), and have been collecting data continuously since 1984 (10 GHz), 1990 (15 GHz) and 1992 (33 GHz). Our objective is to make a survey in the region between declinations +30° and +45° covering in total about 5000 square degrees of the sky with sensitivities per beam-area of $\sim$ 60 μK for the 10 GHz, and $\sim$ 25 μK for the 15 and 33 GHz experiments. The strategy is to make observations in strips of the sky at constant declination separated by 2°5. This goal is very close for the 15 GHz experiment, while the 10 and the 33 GHz experiments have respectively reached about 70% and 30% of that objective. This paper presents a description of the observing technique and data processing (Section 2), an analysis of the results obtained at Dec = +40° (Section 3), and some preliminary results at adjacent declinations (Section 4).

2 OBSERVATION AND DATA REDUCTION

The instruments at each of the three frequencies have been scaled in order to have the same beam pattern on the sky, and use a double-switching technique (Davies *et al.*, 1992). The resultant configuration consists of three Gaussian beams (FWHM$\sim$ 5°); the central beam is positive and located on the meridian, and the other two are negative and are 8°1 to the West and East respectively, with half the amplitude and approximately at the same declination as the central beam. The range of multipoles over which the instruments are sensitive are between $\sim$ 10 and $\sim$ 40 (Watson *et al.*, 1992), and therefore they are sensitive to fluctuations larger than the size of the horizon in the last scattering surface.

Observations at well-spaced frequencies are necessary in order to distinguish between fluctuations in the GMB, descrete radio sources, and Galactic diffuse emission. In the spectral range covered by our experiments, the main Galactic contributors are the synchrotron and the free-free processes with temperature spectral indices $\sim$ 2.8 and 2.1 respectively (Lawson *et al.*, 1987). Both processes are likely to give negligible contributions at frequencies around 30 GHz. We have modeled the contribution of point-like radio sources using several catalogues (see Section 3). The contribution of unresolved extragalactic radio sources (Franceschini *et al.*, 1989; Aizu *et al.*, 1987) in our 5° beam is expected to be $\Delta T/T \leq 10^{-5}$ at 10 GHz. Assuming the conservative case of a flat spectrum for all unresolved

Table 1. Useful observing time (in hours)

	Declination						
ν(GHz)	30°0	32°5	35°0	37°5	40°0	42°5	45°0
10	–	1073	629	1410	2340	1003	358
15	1149	1515	1131	2448	3294	2028	2629
33	–	504	184	519	1978	–	–

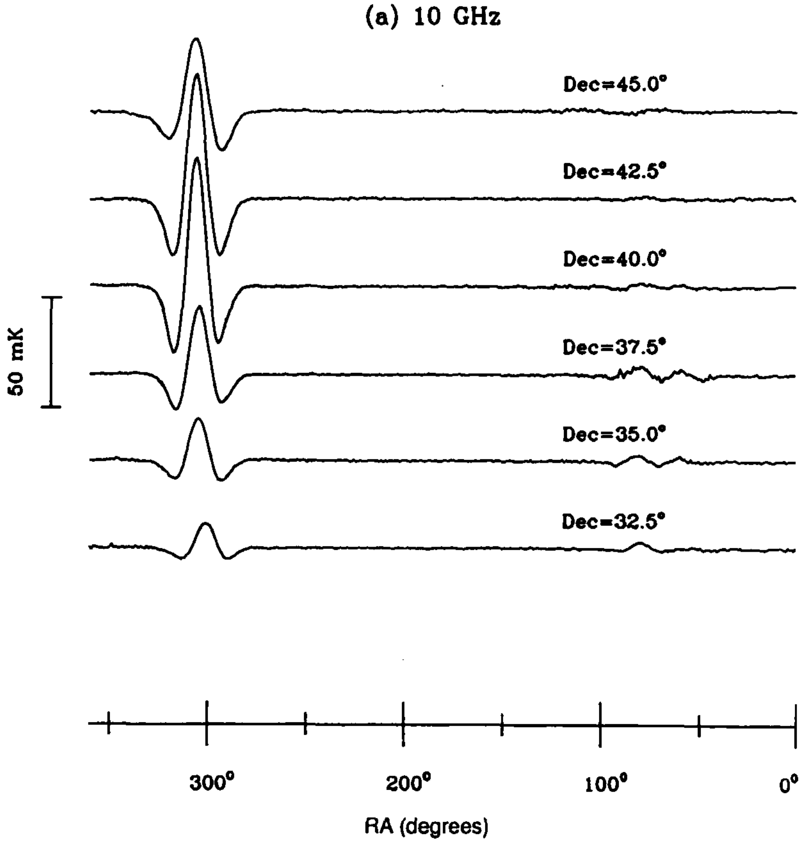


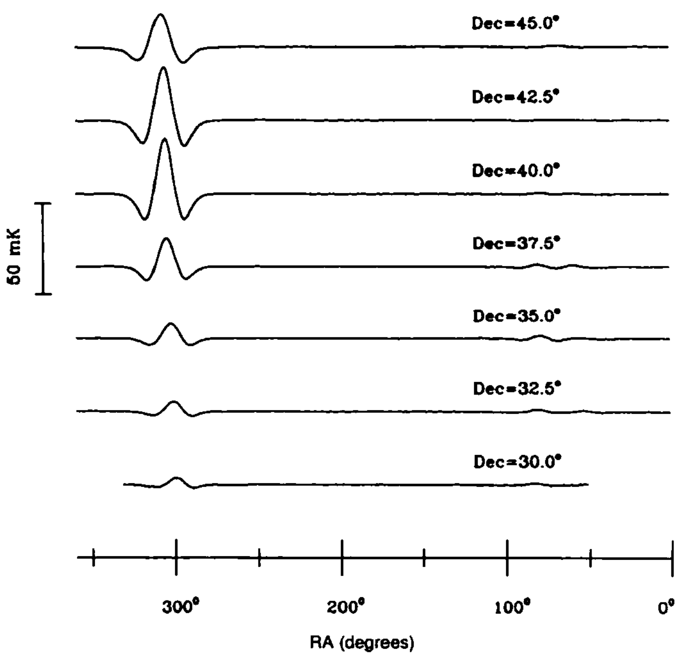
Figure 1 Stacked scans for each declination at (*a*), 10 GHz; (*b*), 15 GHz and (*c*), 33 GHz; showing the strong (RA ~ 300°) and the weak (RA~ 60°–90°) crossings of the Galactic plane.

sources, their contribution should be $\leq 5 \times 10^{-6}$ at 15 GHz, and a factor 10 smaller at 33 GHz.

The site, at an elevation of 2400 m, is usually above the inversion layer with a very stable atmosphere,very low humidity, and clear for three quarters of the year. The fraction of data lost due to atmospheric humidity effects throughout the year is about 30% at 10 and 15 GHz, and a greater proportion at 33 GHz. In addition we have discarded any data taken when the Sun or Moon are less than 50° and 30° respectively from the beam. We have also removed data when the standard error is larger than three times the average value for the day. The rest of the time is lost due to maintenance, calibration or system failure. Table 1 presents a summary of the useful data collected up to July 1994 at each frequency and declination.

When the data from N scans are stacked at each frequency and declination we obtain very sensitive scans with a reduction in noise by a factor $\sim 1/\sqrt{N}$ compared

(b) 15 GHz



(c) 33 GHz

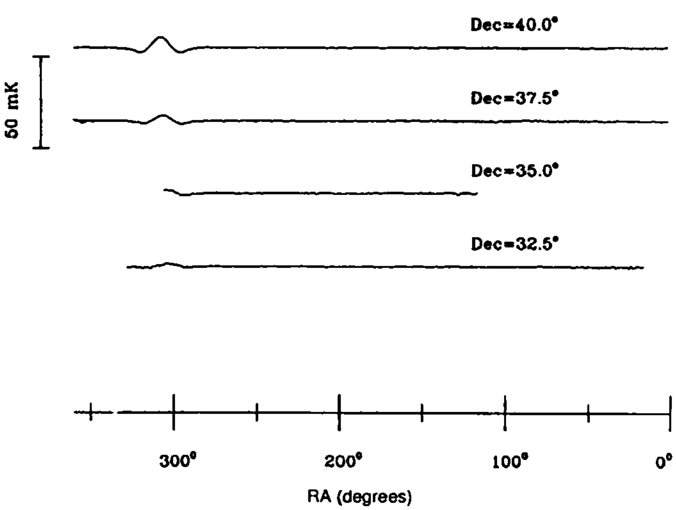


Figure 1 Continued.

Table 2. Standard error (in μK) per beam-sized area over the RA range 161°–250°

	Declination						
ν(GHz)	30°.0	32°.5	35°.0	37°.5	40°.0	42°.5	45°.0
10	–	69	97	62	57	75	77
15	22	27	30	19	30	25	24
33	–	38	54	47	21	–	–

with individual scans. Before stacking we removed any residual atmospheric drift in each daily scan by using a combination of sinusoidal functions of large period (at which the instruments are not sensitive to astronomical signals) using a Maximum Entropy Method approach (Lasenby *et al.*, in preparation). Figure 1 shows these stacked scans for each frequency. The intense structures in these plots are the strong Galactic plane crossings at RA $\sim 20^h$,which reproduce the triple beam response of the instruments. At some declinations it is also possible to observe several components of the weak crossing. There is clearly a good correlation between the crossings at different frequencies. From the amplitude in the peak at each frequency, we can work out the spectral index of the Galactic emission. The largest amplitudes of the strong Galactic crossings are at declinations +40° and +42°.5, and are due mainly to the emission from the extended Gygnus X HII complex. The spectral index of this Galactic emission is that expected from the free-free process (Gutierrez de la Cruz *et al.*, 1994).

Table 2 shows the sensitivity reached in the section at RA 161°–250° which is far from the Galactic plane and is used to study the cosmological fluctuations. The figures quoted are the *rms* sensitivity (μK) in a 5° beam which can be used as a measure of the intrinsic sensitivity of our instruments to a feature in the sky on this scale. This table shows a fairly uniform sky coverage at 10 and 15 GHz while at 33 GHz we have achieved the appropriate sensitivity only at Dec = +40°.

3 RESULTS AT DEC = +40°

To date we have obtained data of comparable high sensitivity at 15 and 33 GHz at only Dec = +40° (Hancock *et al.*, 1994). The lesser sensitivity reached at 10 GHz is probably not enough to detect cosmological fluctuations with good signal to noise but can be used to constrain any possible Galactic contaminant at two higher frequencies. Using several catalogues (Kühr *et al.*, 1981, VLA calibrators, and the Michigan bright radio source monitoring programme of M. and H. Aller, private communication) we have estimated the contribution of known discrete radio-sources in our data and subtracted them. Figure 2 represents the results (binned into 4° intervals in RA) at Dec = +40° in the region of RA 150°–240° (the section of our data at high galactic latitude).

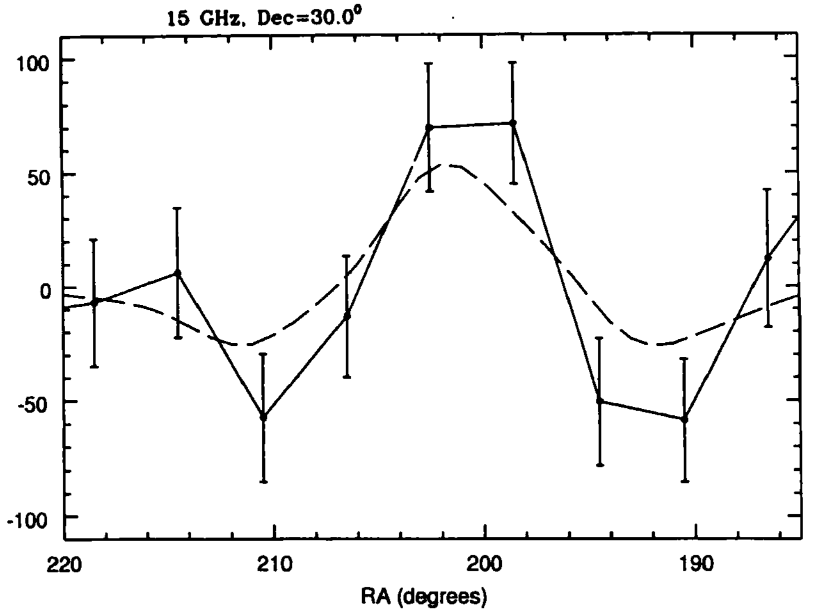


Figure 2 The stacked data scans at Dec= +40° and their one-sigma error-bars in a 4° bin in RA. A and B constitute splits of the data at 15 GHz and 33 GHz. The $(A+B)/2$ data contain the signal and the instrumental noise; the $(A-B)/2$ data contain only the noise.

Any real feature should appear in subsets of the data. We have split them into the two subsets A and B, each covering a similar number of observations. At 33 GHz, subsets A and B are from the two independent channels. In the case of 15 GHz one of the receiver channels failed for $\sim$ 30% of the observing cycle, so we have split the data in a different way: subset A comprises data taken during the observing season June to August,while subset B comprises data taken during the rest of the year. A real feature should appear at higher significance in the addition $(A+B)/2$; furthermore if the feature is cosmological,the amplitude at 15 GHz and 33 GHz should be similar. We believe that there is an obvious common structure at RA $\sim$ 185° with an amplitude at the peak of about 80 μK. There is also some evidence of a second feature at RA $\sim$ 225°. We believe that these features represent the first detection of individual primordial fluctuations in the GMB. It has been proposed that these structures be called COSMOSOMES (COSMOlogical Structures On MEdium Scales).

3.1 Statistical Analysis

We have quantified the statistical properties of the data at Dec = +40° (RA between 161° and 230°) in several ways, and in all cases we obtain clear evidence for the presence of a signal with similar strength at 15 and 33 GHz. A χ^2 test reveals that the probability that the results are a consequense of pure noise is

Table 3. Results of the likelihood analysis for a Harrison–Zel'dovich spectrum of fluctuations. The quoted errors are at 60% in the case of detections, and at 95% in the case of upper limits.

	$Q_{RMS-PS}(\mu K)$			
$\nu(GHz)$	A	B	$(A-B)/2$	$(A+B)/2$
15	27^{+16}_{-16}	17^{+9}_{-17}	≤ 26	22^{+12}_{-10}
33	24^{+15}_{-12}	28^{+12}_{-10}	≤ 24	26^{+12}_{-8}
15+33	25^{+13}_{-9}	27^{+11}_{-8}	7^{+4}_{-7}	25^{+9}_{-7}

less than 0.02, 1×10^{-4} and 3×10^{-6} for the 15, 33 GHz and their weighted addition respectively. It is possible to compute the mean level of the signal from the $(A+B)/2$ and $(A-B)/2$ results as $\sigma_s^2 = \sigma^2_{(A+B)/2} - \sigma^2_{(A-B)/2}$; for data binned at 1° intervals in RA, we obtain 41 ± 24, 49 ± 10 and 42 ± 9 μK at 15, 33 GHz and 15+33 respectively. A more sophisticated analysis can be made using a likelihood approach in the *bayesian* sense (Watson *et al.*, 1992; Gutierrez de la Cruz *et al.* 1994), this allows a determination of the parameters of the cosmological model assumed. In the case of a Gaussian field it is possible to describe entirely their statistical properties using the ACF (Auto-correlation Function) of the field $C_{\rm intr}(\theta) = \langle \delta T(\mathbf{n_1}) \delta T(\mathbf{n_2}) \rangle$, where δT are the fluctuations in temperature, and $\mathbf{n_1}$ and $\mathbf{n_2}$ two directions in the sky separated an angle θ. A useful model which allows a comparison of results obtained using different experimental configurations is given by the ACF $C_{\rm intr}(\theta) = C_0 \exp\{-\theta^2/2\theta_c^2\}$, where C_0 and θ_c are the amplitude and coherence angle of the fluctuations respectively. It is easy to demonstrate that the coherence angle at which our experiment is most sensitive is $\theta_c = 4°$. The results obtained for this model are $\sqrt{C_0} = 29^{+20}_{-20}$, 48^{+16}_{-16}, 60^{+16}_{-16} and 54^{+14}_{-10} μK at 10, 15, 33 and 15+33 respectively. The data at 10 GHz can be used to constrain the Galactic contribution to the signal detected at the two higher frequencies by considering the case in which all the signals at 10 GHz were Galactic. Assuming a model with a single component having the spectral indices given in Section 2, we obtain a maximum contribution at 33 GHz of 4 and 2 μK for the free-free and synchrotron processes respectively.

Another more interesting model from a cosmological point of view, is the prediction in the case of a power law spectrum of primordial fluctuations $P = Ak^n$, where n is the spectral index. A model with $n = 1$ corresponds to the prediction of most of the inflationary scenarios. We have applied a likelihood analysis to this model, and we obtain the results shown in Table 3 which presents the expected amplitude of the quadrupole (see Hancock *et al.*, 1994 for the notation used) deduced from each data set analyzed. The results are consistent, showing similar amplitudes for the A, B and $(A+B)/2$ data set, and a result compatible with null signal for the $(A-B)/2$ data set.

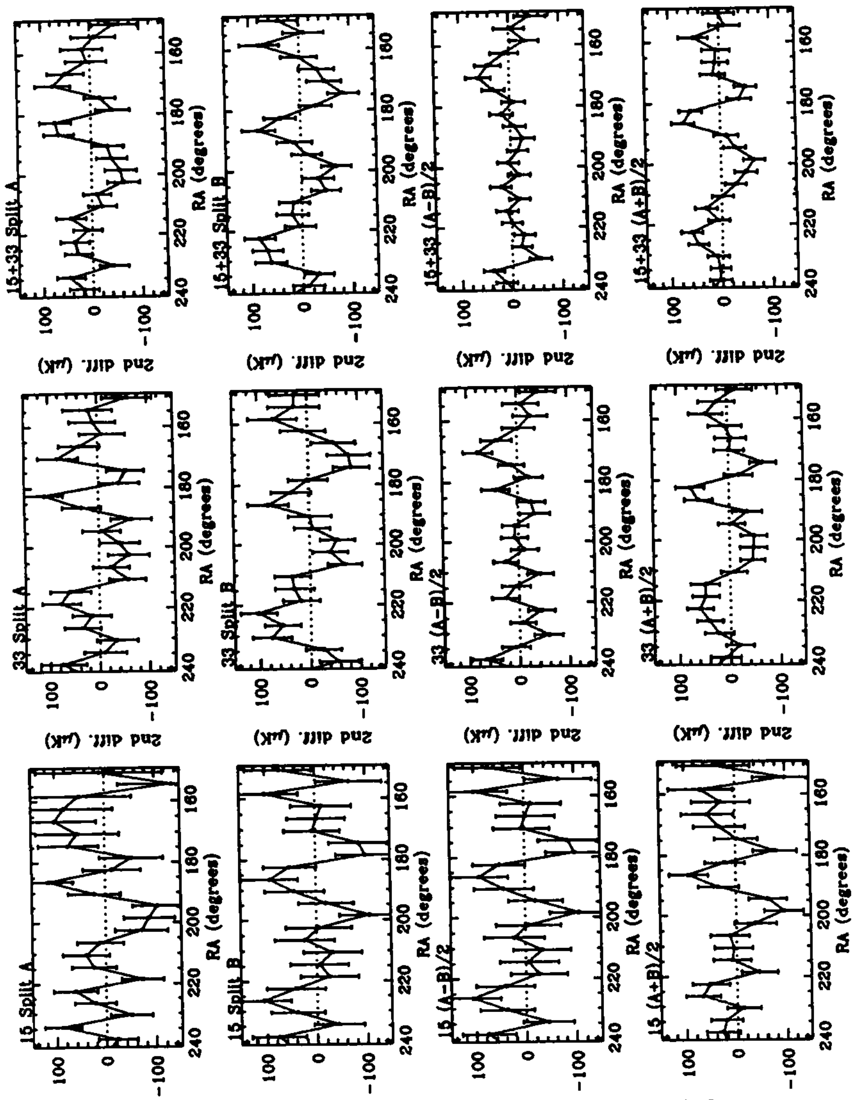


Figure 3 A comparison between the predicted contribution of the radio sources at 15 GHz (dashed line) and our measurements at Dec= +30° (solid lines).

4 ADJACENT DECLINATIONS

Apart from the data at Dec = +40°, we have data with similar or in some cases better sensitivities at adjacent declinations at 10 and 15 GHz. A full analysis is not possible until we have observed these declinations with the appropriate sensitivity at 33 GHz, but meanwhile some interesting preliminary results can be obtained. When comparing the data taken at 10 and 15 GHz in the region at high galactic latitude, we see a common structure at Dec = +45° RA = 225° with a reduced amplitude at 15 GHz; this structure also extends to the adjacent declinations, the relative amplitude at 10 and 15 GHz seems to be consequence of its Galactic origin, and is responsible for the detection of structure claimed by Davies *et al.*, 1987 using an early version of the 10 GHz radiometer with a beamwidth of 8°. At lower declinations we have observed a clear feature at Dec = +35° RA $\sim$ 215° which will require a detailed analysis when the data at 33 GHz will be obtained. At Dec = +30° in the data at 15 GHz there is a feature at RA $\sim$ 200° which corresponds to the amplitude expected from radio sources in this region (mainly due to 1328+30 3C 286 with a flux density $\sim$ 3.5 Jy at 15 GHz). In Figure 3 we show in an expanded scale our data at 15 GHz in this region and the modeled radio sources; the agreement between both in shape and amplitude confirms the consistency of our data and the fact that we are able to detect structures with amplitudes of $\sim$ 50 μK.

5 CONCLUSIONS

We have presented the Tenerife experiments on CMB fluctuations and have demonstrated the multifrequency detection of common features at Dec = +40° attributable to fluctuations in the CMB which represent the first detection of primordial cosmological features. Further observations at adjacent declinations are now in progress, and preliminary results have demostrated that we can detect radio sources with amplitudes $\sim$ 50 μK having the correct amplitude and shape; this amplitude is similar to that expected for fluctuations in the CMB. The sensitivity which is presently being reached in the band of declinations +30° to +45° allows us to be confident that a detailed two-dimensional map of cosmological fluctuations can be achieved in the near future.

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