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Observations of atmospheric noise fluctuations with a metre–baseline interferometer in the 13–17 GHz band

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Abstract. This paper describes the atmospheric noise fluctuations that we have observed with the Cosmic Anisotropy Telescope (CAT) at Cambridge. The CAT is a short baseline radio interferometer designed to make observations of primordial anisotropies in the Cosmic Microwave Background Radiation at angular scales between 20 arcminutes and 1 degree. During clear weather the observations are limited by receiver noise, whereas emission and scattering from clouds limits the sensitivity of the instrument during rain and cloudy weather on the very shortest baselines. Fluctuations in the correlated antenna temperature up to 100 mK have been seen, with a typical coherence time of 10 seconds.

Key words: atmospheric effects – instrumentation: interferometers – techniques: interferometric

1. Introduction

The operation of a ground–based radio telescope is always affected to some degree by the atmosphere. Incoming astronomical signals suffer absorption and scattering, and their phases are disturbed. Atmospheric structures such as clouds can also act both as emitters and as reflectors of ground radiation, which can cause fluctuating coherent signals in the instrument's response (see Thompson et al. 1986, for a review). Water in the troposphere causes the most problems in the 13–17 GHz band, both when it is in its vapour and liquid forms, because it is poorly mixed in the atmosphere. The scattering and absorption coefficients of ice, on the other hand, are several orders of magnitude lower than those for water liquid and vapour (Gasiewski 1993) and hence is less likely to be seen in our data. Water vapour has a pressure broadened resonant absorption line at 22.235 GHz, whose main effect in the CAT observing band is to cause an overall increase in the mean brightness temperature of the sky which increases steeply with frequency. In Cambridge we see about 5 K of atmospheric emission in the zenith at 17 GHz of which about 10% is due to water vapour and 90% is due to oxygen. The latter is well mixed in the atmosphere, but poor mixing of the water vapour can result in up to 0.5 K changes in sky temperature. A much greater problem is caused by water in the form of liquid droplets, or 'hydrometeors'. A typical cumulo–nimbus cloud might have a peak brightness temperature of 20 K at 17 GHz, and the brightness temperature of the sky in a particular direction can change by this amount in a matter of minutes in windy conditions with non–uniform cloud cover.

Structures such as clouds in the atmosphere cause correlated signals in the output of an interferometer whenever they lie within the region of overlap of the two antenna beams. Large instruments are immune from this effect when their regions of overlap lie beyond the top of the atmosphere. However, microwave interferometers with baselines of the order of one meter do not share the same immunity because the beams overlap significantly in the lower troposphere where most of the water resides. Although the signals vary in a random fashion, their time–scales are of order 10 seconds and hence average towards zero more slowly than the band–limited receiver noise, ultimately limiting the sensitivity of the instrument.

This paper describes the atmospheric noise fluctuations observed with the Cosmic Anisotropy Telescope (CAT), at the sea–level Cambridge site. The CAT is a three–element radio interferometer designed to observe temperature fluctuations in the Cosmic Microwave Background Radiation (CMBR) at angular scales between 20 arcminutes and 1 degree. The instrument has three antennas with circular apertures of 0.7 m which can be set on baselines between 1 and 5 m, and it observes within a 500 MHz bandwidth which can be centred anywhere between 13 and 17 GHz (see Robson et al. 1993). The system temperature is about 50 K. Significant overlap of the antenna beams begins at a distance of about 200 m above the antennas. CAT observations are therefore greatly perturbed by water droplet emission and scattering in the lower troposphere. The CAT design includes the ability to switch rapidly between frequencies so that the atmospheric emission may be distinguished by its spectral signature. The baselines can also be set to produce identical fringe patterns on the sky at different frequencies to aid in this process.

We present observations of a region of sky which are limited only by receiver noise (clear cold nights), together with observa-

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tions limited by atmospheric emission more typical of autumnal days at Cambridge. We also present a map made with data collected during December of 1993 and the first week of January 1994, which was a period of cloudy and rainy weather. Even so, there were long periods of time during which data were limited only by receiver noise. Those periods when severe atmospheric contamination occurred stood out from the rest quite clearly, and could be edited manually. By selecting only the good data, we found that the sensitivity of the final map was limited by receiver noise with no obvious atmospheric artefacts visible.

2. Observations

The observations described in this paper were made either at 13.5 or 16.5 GHz. Each second of integration was split into two sections, one for each frequency, so that observations at the two frequencies were almost simultaneous. This enabled the spectral properties of the emission to be investigated. The interferometer was calibrated using the signals from the bright radio sources Cassiopeia A, Cygnus A, and the Crab Nebula. Noise injection was used to monitor variations in system temperature. Random fluctuations due to receiver noise in the integration period of 0.25 s used were at a level of ΔT_{rms} = 3.5 mK.

Average atmospheric noise fluctuations can be examined by monitoring the correlated antenna temperature over a long period of time and in a range of weather conditions. Figure 1a contains several plots which show the percentage of time for which the interferometer output power fell within a given range. During clear weather the power was rarely above the 3 σ level (10.5 mK), as expected for random instrument noise. For cloudy and rainy weather, the correlated power displayed a varying level of atmospheric contamination. Fig. 1b shows the values obtained for 300 hours of data obtained over a period of several months, between August and October 1993 and in a wide variety of weather conditions. The percentages in the bins suggest contamination for only about 25% of the time, but in practice we cut out long chunks of data in bad weather, perhaps losing as much as 40% in total. Very little of the rise in correlated antenna temperature is thought to have been caused by man–made interference; only short bursts have ever been seen, and these were clearly associated with aircraft flying over the telescope. In addition, none of the rise could have been due to astronomical sources, as none were present in the fields which were bright enough to have been detected.

A region centred on the North Celestial Pole (NCP) was observed with the CAT from the 12th to the 30th of September 1993, specifically to observe atmospheric emission and scattering. The three antennas were placed in a straight line with projected spacings of 0.89, 1.10 and 1.99 m, chosen so that the two smallest spacings produced identical fringe patterns on the sky apart from differences in the primary beams of the antennas (0.89m at 16.5 GHz and 1.10m at 13.5 GHz). It was already known that the NCP region contained no radio sources bright enough to be detectable within each quarter–second integration period used. Figure 2 displays plots of system temperature (as measured by noise injection) and correlated antenna temperature (as measured by the interferometer output) versus time, for showery, cloudy, and clear weather conditions. During showery weather, the system temperature varied by about 15 K. At the same time there were large fluctuations in the correlated antenna temperature. The response is that expected for extended blobs of emission passing through the antenna beam in about 20 s. The emission was resolved out by the largest spacing, whereas the shorter two spacings displayed the intrinsic spectral variation of the emission, which is seen to rise steeply with frequency. A cloud at height L, moving with velocity V, spends a time within the antenna beam of

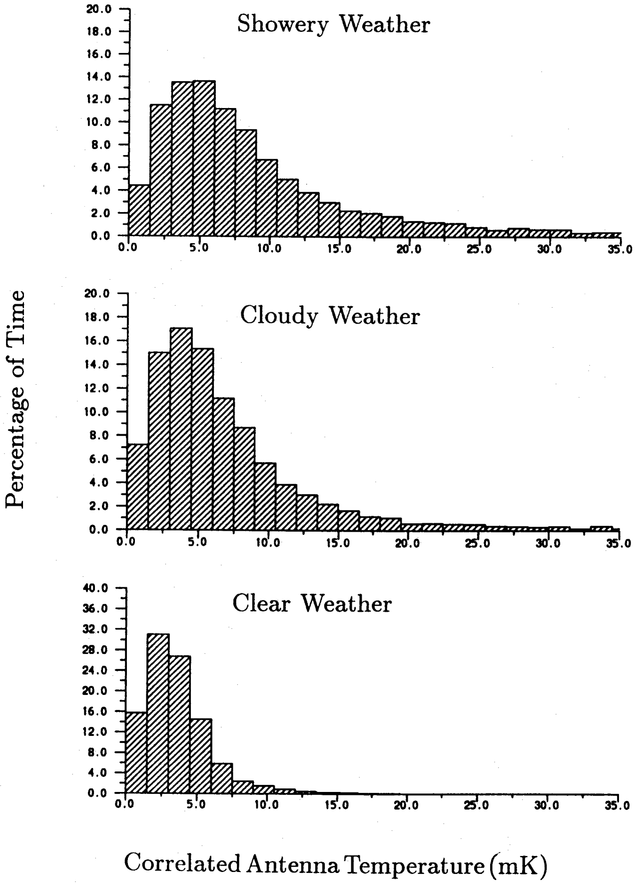

Fig. 1. **a** The percentage of time for which the correlated antenna temperature fell within given ranges, during observations in three types of weather conditions: showery, cloudy and clear

$$t_0 \approx \phi L/V, \quad (1)$$

where ϕ is the primary beamwidth of the antennas. The instrument's response is therefore consistent with that caused by clouds at heights of about 1 km being blown by a 1.75 m s^{-1} wind through the 2° CAT primary beam. The data recorded during cloudy weather (Fig. 2b) indicate that the system temperature was quite stable and yet the correlated antenna temperature displayed features as high as 30 mK on the shortest baseline. During clear weather (Fig. 2c) we saw nothing but instrument noise.

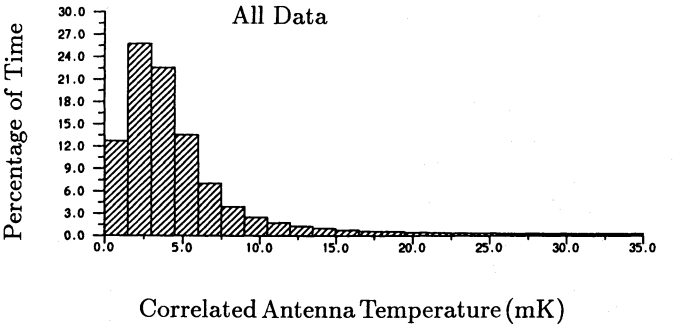

Fig. 1. b The percentage of time for which the correlated antenna temperature fell within given ranges, averaged over 300 hours of observations in a wide variety of weather conditions

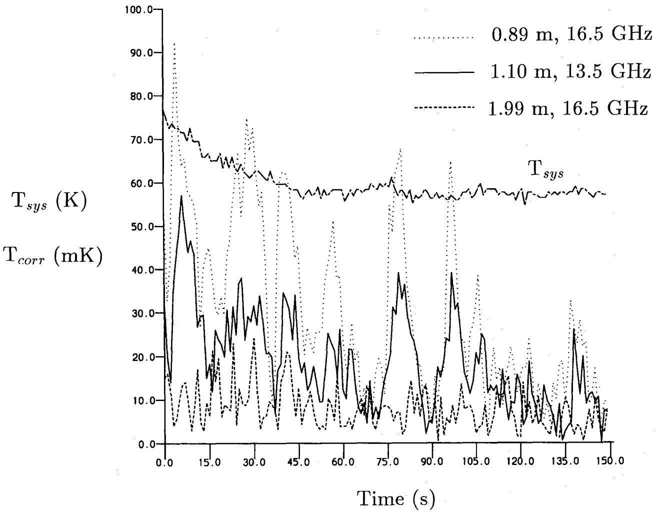

Fig. 2. a Plots of system temperature and correlated antenna temperature versus time for a 150 second dataset recorded during showery weather

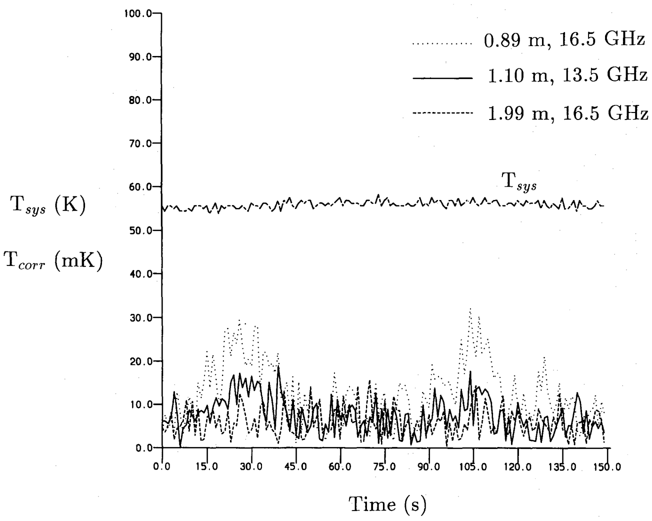

Fig. 2. b Plots of system temperature and correlated antenna temperature versus time for a 150 second dataset recorded during cloudy weather

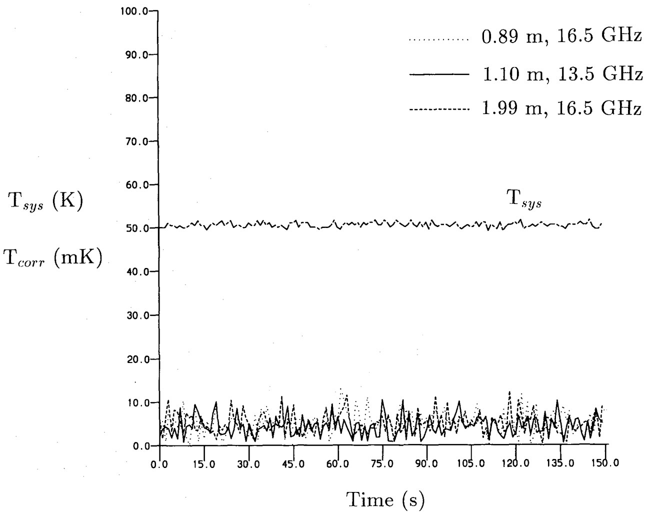

Fig. 2. c Plots of system temperature and correlated antenna temperature versus time for a 150 second dataset recorded during clear weather

Figure 3 shows the phase variations measured on the two scaled baselines for the showery–weather data of Fig. 2a. The phase was ramping almost linearly with time with the same frequency of about 0.15 Hz on each baseline, as expected for signals from moving atmospheric structures. A cloud at a height L, moving with velocity V parallel to the baseline of length D, would produce a phase ramp with a frequency of

$$f_0 \approx (DV)/(\lambda L), \tag{2}$$

where λ is the wavelength. A cloud at a height of 1 km and moving with a speed of 1.75 m s^{-1} would give f_0=0.1 Hz. The phase difference measured between the two scaled array spacings should be constant if the two spacings are observing the same emission or scattering: this is so, apart from deviations which are due to instrument noise and differences in the primary beam at the two frequencies.

The spectral index of the emission, α, was calculated from the data obtained using the two scaled baselines with

$$f_{v_i}/f_{v_j} = \left(v_i/v_j\right)^{\alpha}, \tag{3}$$

where f_{v_i} is the observed flux density at frequency v_i. The results for 2.5 hours of observations during showery weather are shown in Fig. 4. We rejected all points with deflections below 6 σ in order to select only data showing strong emission. The plot shows a wide dispersion about a spectral index of about three. Note that purely thermal emission would result in a spectral index of two on this plot.

The measured spread of spectral index shown in Fig. 4 can be explained in terms of the particle sizes of the liquid water which caused the emission or scattering. For liquid water droplets much smaller than $\lambda/4\pi$, the attenuation, α_c, follows an empirical law (Staelin 1966),

$$\alpha_c = (\rho_l/\lambda^2)\times 10^{0.0122(291-T)-8}, \tag{4}$$

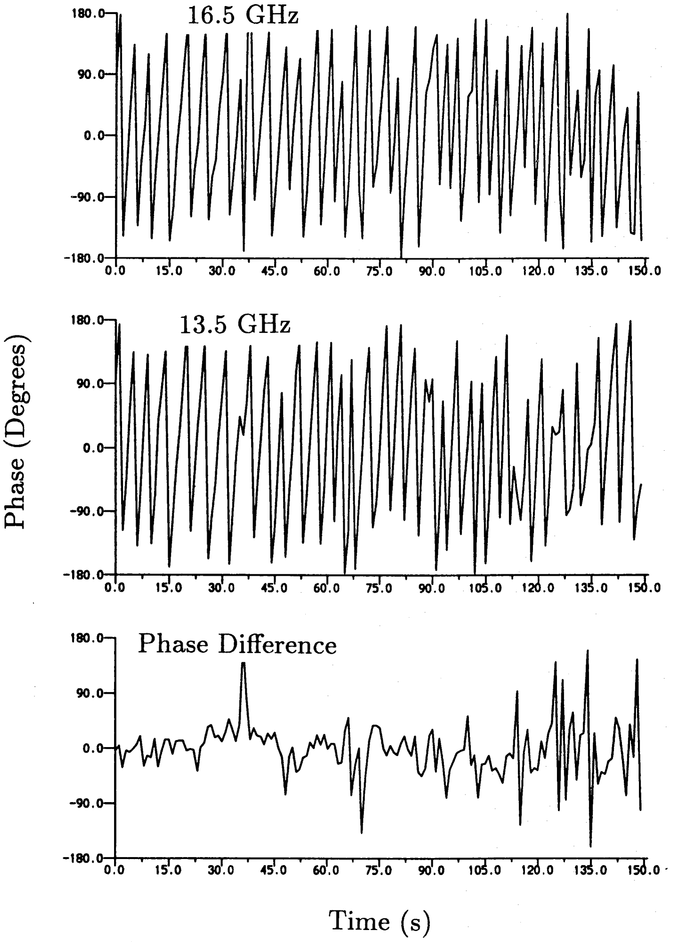

Fig. 3. The phase variation for the scaled spacings as a function of time for the same dataset as used in Fig. 2a. The top two plots illustrate the phase variations observed over the two shortest baselines, and the third shows their phase difference

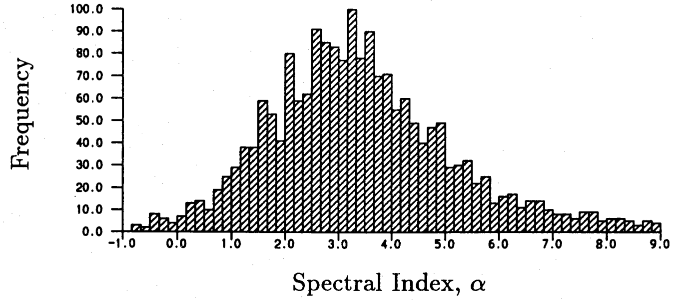

Fig. 4. The spectral index between the flux densities measured by the scaled baselines at 13.5 and 16.5 GHz during showery weather

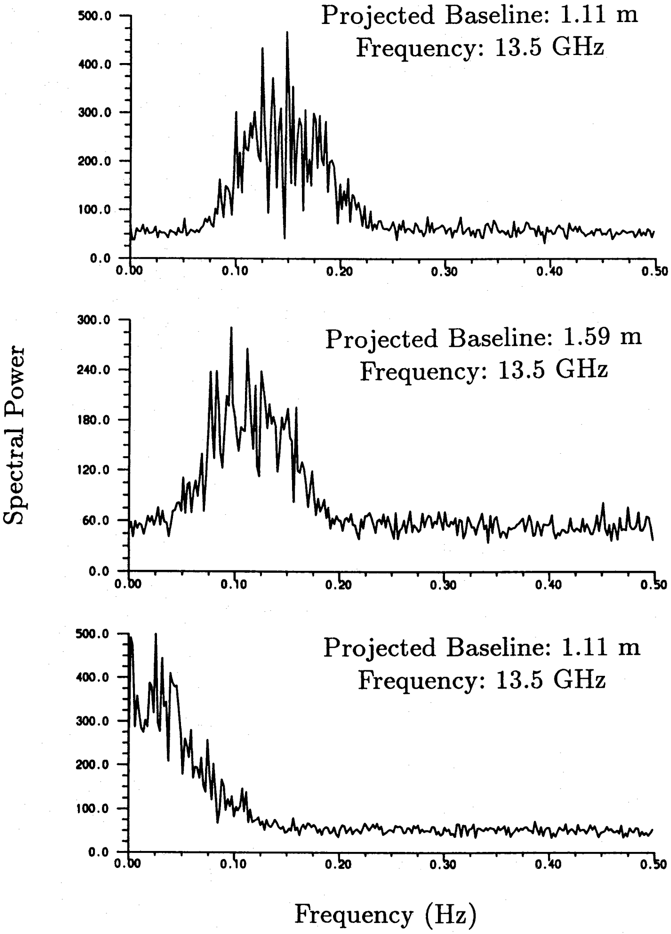

Fig. 5. Power spectra measured at 13.5 GHz on three spacings in triangular configuration, averaged over 2.5 hours

and the scattering has the same spectral dependance. Here, T is the cloud temperature in K and ρ_l is the liquid water density within the cloud in grams m^{-3}. Hence the spectral index expected for the emission and scattering from clouds in the Rayleigh–Jeans region is 4. The primary beam differences at the two frequencies cause part of the spread in apparent spectral index, as do instrument noise fluctuations. The major contribution to the spread arises from water droplet sizes greater than 1 mm where the attenuation and scattering coefficients become independent of frequency (in our band) and α is then 2 (Gasiewski 1993).

We next investigated the effect of relative wind direction by changing the configuration of the instrument to that of a triangular array with projected baselines of 1.11, 1.11, and 1.59 m when observing the North Celestial Pole. Figure 5 shows the mean power spectra measured at 13.5 GHz during showery weather. The central frequency of the power spectra was found to be roughly proportional to the wind speed measured at ground level in the direction of the baseline, with the constant of proportionality also being a linear function of the baseline length. This was again consistent with the model of blobs being blown by the wind in a particular direction relative to the baseline.

Despite observing large fluctuations in the interferometer output during cloudy or rainy conditions, it is possible to make very sensitive maps with the CAT. Figure 6 shows a map made with data recorded during December 1993 and the first week of January 1994, which was a period of rainy and cloudy weather. The map was made from a total of 283 hours of data, selected as showing no obvious atmospheric effects; 179 hours of data were

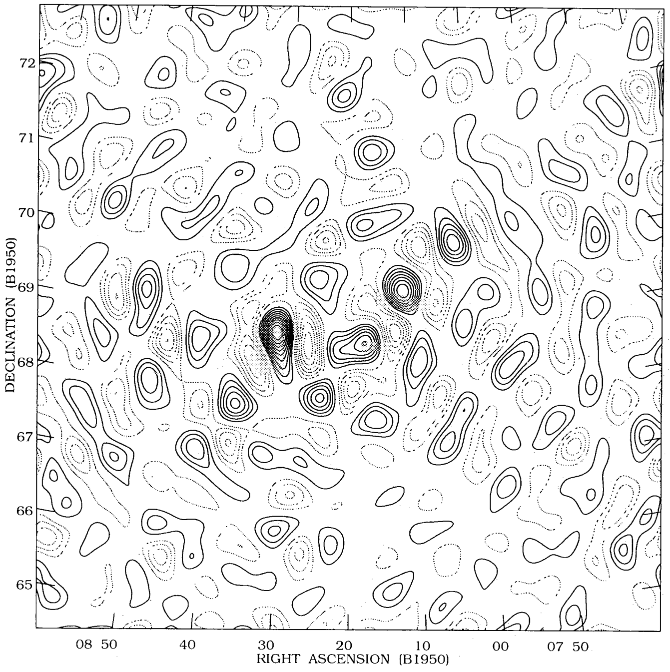

Fig. 6. A map made from a CAT observation at 16.5 GHz of the field at 69 degrees declination and 8 hours 20 minutes right ascension. The map was made from a total of 283 hours of data, recorded on 32 consecutive days. The contour levels run from -60 to 100 mJy in intervals of 10 mJy, with positive levels drawn in solid line and negative levels drawn in dashed line

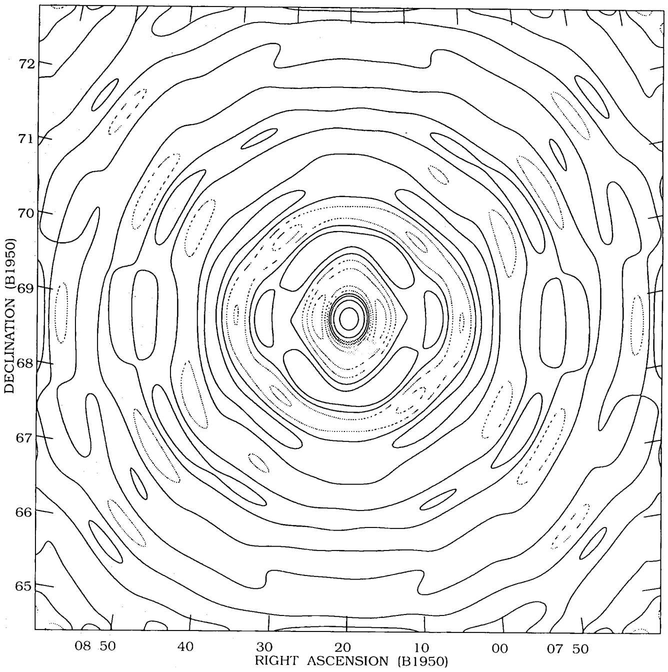

Fig. 7. The synthesized beam for the map shown in Fig. 6. The contour levels are at -30, -20, -10, 0, 10, 30 and 70% of the beam's peak

rejected over this period. The data were rejected in half hour blocks if the data within the block showed noise inconsistent with that from the receivers alone. The 2° primary beam of the instrument covered only the centre part of the map, and this is the only region where any features are seen. The outer parts of the map display a noise level of about 10 mJy, consistent with the expected instrument noise. The synthesized beam is shown in Figure 7. A 1 μK source which fills the synthesized beam would have a flux density of about 1 mJy. Note that atmospheric effects would show up anywhere in the map, and not just in the central region. Astronomical interpretation of this map will be considered in a later paper.

An important point to make is that for a data set which has had no editing performed on it, the atmospheric emission averages down quite quickly. The clouds reside in the beam of the telescope for periods much shorter than the effective integration time (for each map pixel) of about 1000 seconds. The total area under the fringe pattern produced by a cloud being blown by the wind in a direction parallel to the baseline is exactly zero. It is for this reason that, if atmospheric emission is not apparent above the instrument noise in each quarter second sample, then its effect on the final map should be negligible.

3. Conclusions

Atmospheric emission affects observations made by the CAT during cloudy or rainy weather. The emission produces correlated antenna temperatures at levels up to 100 mK, and has a typical coherence time of 10 seconds. The spectral properties of the emission are consistent with that predicted for liquid water droplets, behaving like thermal emitters when larger than 1 mm but exhibiting a more steeply raising spectrum when much smaller. The emission is highly extended and is almost entirely resolved out by a 2 m baseline at 16.5 GHz.

We conclude that sensitive observations of the CMBR using the CAT from Cambridge are likely to be limited for about 40% of the time by atmospheric emission. It will be difficult to correct the data recorded during such periods to remove the effects of the atmosphere without affecting the astronomy because (a) the spectral signature of emission from clouds is not sufficiently different from the thermal CMBR and, (b), the primary beam differences at different frequencies make exact corrections difficult. However, during clear cold conditions the observations made with the CAT are limited only by receiver noise. The CAT is sensitive enough to make detections of CMBR fluctuations within just weeks of observing in such conditions.

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