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The Cosmic Background Radiation
Anisotropy Program at UCSB

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ABSTRACT: The Cosmic Background Radiation (CBR) is considered to be one of the best probes of structure in the universe on large scales and at early times. Most mechanisms for the production of structure have some effect on spatial temperature variations in the CBR. Models for galaxy and cluster formation, in particular the popular cold dark matter (CDM) models, suggest that the largest power in the anisotropy of the CBR occurs at angular scales of 10 arcminutes to a few degrees, with particular models making specific predictions for the shape and amplitude of the CBR temperature autocorrelation function.(Bond *et al.*1987)

During the past two and a half years we have undertaken several experiments to measure the structure of the CBR on scales from 10 arcminutes to 10 degrees, from both balloon borne and ground based (South Pole and mountain top) sites. We will briefly summarize these measurements and discuss possible future directions. Our current sensitivity is at the 10^{-5} level at 30 arc minutes and below 10^{-5} at 90 arc minutes. The goal is to achieve part per million sensitivity in the next few years.

Introduction

In the past two and a half years we have made CBR anisotropy measurements with two different optical systems and four separate cryogenic detectors. One system is a 1 meter diameter off-axis Gregorian telescope which has been configured with a 90 GHz SIS mixer, a four channel (3, 1.6, 1.1, 0.8 mm) Helium-3 bolometric detector, and a broad band direct amplification HEMT receiver from 25 to 35 GHz. The second system consists of two pairs of corrugated scalar feeds with fixed angular separation, operating at 15 and 23 GHz, also with direct amplification HEMT detector systems. In what follows, we discuss measurements from the 90 GHz system, the two frequency direct amplification system, and the broad band direct amplification system. The bolometer system and results are discussed in Alsop *et al.*1991 (this volume).

Gregorian telescope system

Since 1985 we have designed, built and flown a millimeter wave telescope system for making measurements of anisotropy in the CBR at angular scales from 0.5 to a few degrees. To date, this system has made three balloon flights and two expeditions to the South Pole for ground-based observations, making anisotropy measurements of the CBR as well as galactic emission, at wavelengths from 1 mm to 1 cm, and with Gaussian beamwidths of 0.5 and 1.6 degrees full width at half maximum (FWHM).

The instrument discussed here has operated in several different configurations. The original goal was to fly the telescope at balloon altitudes (from 30 to 42 km) to avoid most of the contributions from the atmosphere, particularly water vapor and oxygen. Figure 1 shows a calculated plot of atmospheric emission at sea level, South Pole (or mountaintop) elevation, and balloon altitude. In particular, at 90 GHz, the atmospheric emission at 30 km is roughly 4 orders of magnitude smaller than at sea level. This required development of a stabilized pointing platform for operation in the balloon environment, with rms tracking stability better than 1/10 of the beamsize for both elevation and azimuth controls. Well into the development of the pointing platform, we decided the same system could be easily adapted to do measurements from the ground at the South Pole, and constructed a servoed rotation stage for azimuth tracking from the ground.

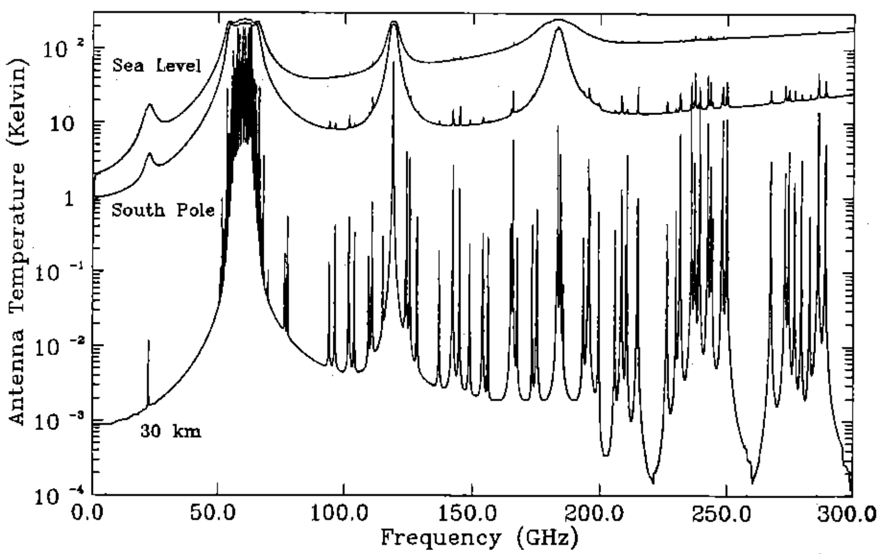

Figure 1: Atmospheric Emission Calculated From JPL Line Catalog and US Standard Atmosphere, for 30 km, 3.6 km (South Pole Barometric Altitude) and Sea Level.

The original detector for the experiment was a Niobium junction SIS (Superconductor-Insulator-Superconductor) mixer based receiver. In addition, we have recently built a wide band direct amplification receiver, using a High Electron Mobility Transistor (HEMT) amplifier operating from 25 to 35 GHz which has also made measurements using this telescope. Following is a brief description of the system and results from some of the detectors. As part of the Center for Particle Astrophysics we are also flying multi-frequency bolometric detectors in this same system in collaboration with Paul Richards and Andrew Lange at UC Berkeley (see Alsop *et al.*in this volume for further details).

Telescope

Our system is based on an off axis Gregorian telescope with a movable ellipsoidal secondary. The primary mirror is a 1 meter focal length, 1 meter diameter aluminum dish, machined from a single piece of material on a numerically controlled mill. The secondary mirror is placed so that one focus is in the feed horn of the detector system, while the other is in the focal plane of the primary mirror. Rotation of the secondary about the axis of the feed horn moves the second focus in the focal plane of the primary, which moves the beam on the sky. We generally throw the beam by roughly 2 x FWHM to measure temperature differences between patches of sky. For a full description of the system see Meinhold, 1990, Lubin, Meinhold and Chingcuanco, 1990.

The main reason for choosing this particular configuration is the extremely low sidelobe response. The central lobe is well approximated by a Gaussian with 0.5° FWHM. In addition we have made measurements of the sidelobe response to about -85 dB, limited by the antenna test range. We also include a large reflective groundshield during flight, and an even more extensive ground and sun shield for our ground based work, since the sun was continually up during our measurements at the South Pole.

Pointing platform

A schematic drawing of the pointing system is shown in figure 2. The platform is suspended from a 3 million ft^3 Helium filled balloon by a parachute and a 20 meter steel cable "ladder". The system is a basic az-el mount, the azimuth motion accomplished by moving the entire frame, and elevation by moving the inner frame, to which the telescope is mounted. Our requirement is to remove motions associated with the balloon, point to target positions in right ascension and declination, and track these positions over time, compensating for latitude and longitude changes, and obtaining arcminute rms stability.

Attitude sensing is accomplished with a 3 axis gyro and navigation processor, with absolute pointing verification from a real time CCD star tracking camera aligned with the telescope beam. For backup sensors, we have a 3 axis magnetometer for the azimuth and a 16 bit resolver for the elevation. The gondola azimuth is controlled by an active triple race bearing/torque motor combination and a flywheel, incorporated into a PID (proportional, integral, differential) control algorithm. Elevation tracking is done with a ball screw linear actuator driven by a stepper motor. All sensors and servo systems are controlled by an onboard computer, which also does data acquisition. Science and housekeeping data are telemetered down in real time as well as recorded on board.

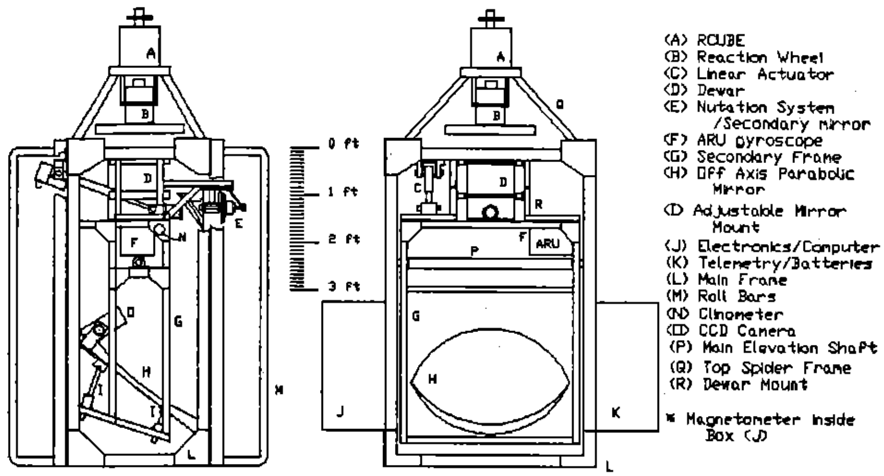

Figure 2: Scale drawing of gondola showing all major telescope and servo elements

Expedition summaries

The first flight occurred in August, 1988, from the National Scientific Balloon Facility in Palestine Texas. The detector system was the 90 GHz SIS (Superconductor-Insulator-Superconductor) mixer. The pointing system worked well during the flight, and useful calibration scans of Jupiter and a measurement of emission from the galaxy were obtained, though telemetry problems prevented long CBR integrations.

The same system which was flown in August was taken to the South Pole in November, 1988 and obtained over two hundred hours of data on the CBR. Scanning efficiency and weather reduced this to about 50 hours of effective integration time at a nominal noise level including sky of about 6 mK$\cdot$sec$^{1/2}$ (Rayleigh-Jeans). In addition interesting results concerning atmospheric fluctuation levels and sky opacity were obtained for this site.

There have also been two flights of the system as part of our Center for Particle Astrophysics collaboration. This experiment (called "MAX" for Millimeter Anisotropy eXperiment) first flew in November, 1989 and for a second time in July, 1990. The system used a different secondary mirror and a multi-frequency bolometric detector system (for spectral discrimination of spurious and foreground sources, primarily galactic and atmospheric). These flights are discussed in detail in another paper in this volume (Alsop *et al.*).

Our group has just completed another South Pole expedition from November 1990 to January 1991, again using the SIS superheterodyne receiver, as well as a new direct amplification HEMT system at 25-35 GHz with extremely low noise (about 1/10 of the noise of the 1988 SIS system), and a slightly larger (1.6° FWHM) beam. Data analysis of this expedition is underway, and some preliminary results are discussed below.

CBR anisotropy study at 0.5° FWHM

Data taken with the SIS detector during December, 1988, have been used to place an upper limit on fluctuations in the CBR of $\delta T/T < 3.5 \cdot 10^{-5}$, for fluctuations with a Gaussian autocorrelation function of σ=20 to 30 arcminutes (Meinhold and Lubin 1991). This result places stringent limits on cold dark matter (CDM) theories of structure formation. For theoretical interpretations of this data see Bond *et al.*1991, Vittorio *et al.*1991.

Our measurement strategy consists of throwing the beam sinusoidally on the sky with an amplitude of 0.7° and at a frequency of 8 Hz, giving an effective throw similar to a square wave chop of 0.5°. Using a lockin amplifier, we then integrate the radiometric difference between the two chop positions for one second at a time. The telescope thus makes a single difference measurement of temperature for two points separated by about 1 degree on the sky, with a characteristic size of 0.5° FWHM. We then integrate for approximately 1 minute and slew the entire telescope by one degree and integrate again. We measure 9 differences, spaced so that one beam from each point coincides with a beam from an adjacent point. During the entire measurement, the telescope tracks the earth's rotation, and the final result is a linear scan of points about some fiducial center in celestial coordinates.

The data obtained this way are edited to remove bad weather, then fit to remove long term offsets due to drifts in the detector, optics, electronics and atmosphere. We found it necessary to remove a gradient in right ascension from the data, which appears to be due to atmospheric structure. This changes our sensitivity to CBR anisotropies and is taken into account in calculating the upper limits. Figure 3 is the result of binning the edited and fit data in right ascension. The error bars are

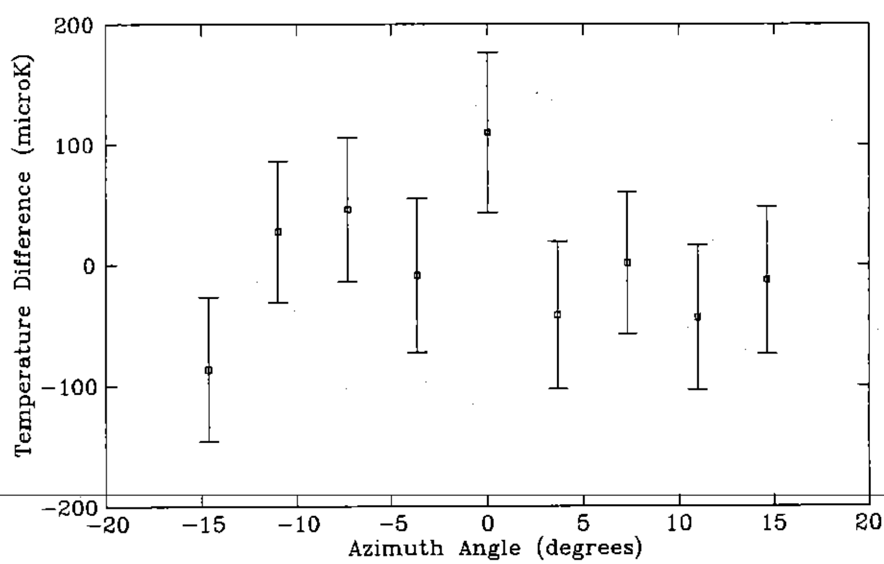

Figure 3: Final South Pole 1988–89 SIS Data Set Gradient Removed. Errors are 60 microK per point.

"measured", that is they reflect the total scatter of the points in a bin. Our upper limits are calculated by Monte Carlo simulations of Gaussian correlated sky maps, which are then "measured" with the experimental response. By varying the signal to noise, and comparing statistical measures of the simulated data sets to the actual one, we can estimate 95% confidence level upper limits. These limits are at 55% power and are shown in figure 4. In addition to simple Gaussian correlation function models, more realistic CDM models have been calculated, leading to constraints on CDM parameters (Vittorio *et al.*1991; Bond *et al.*1991).

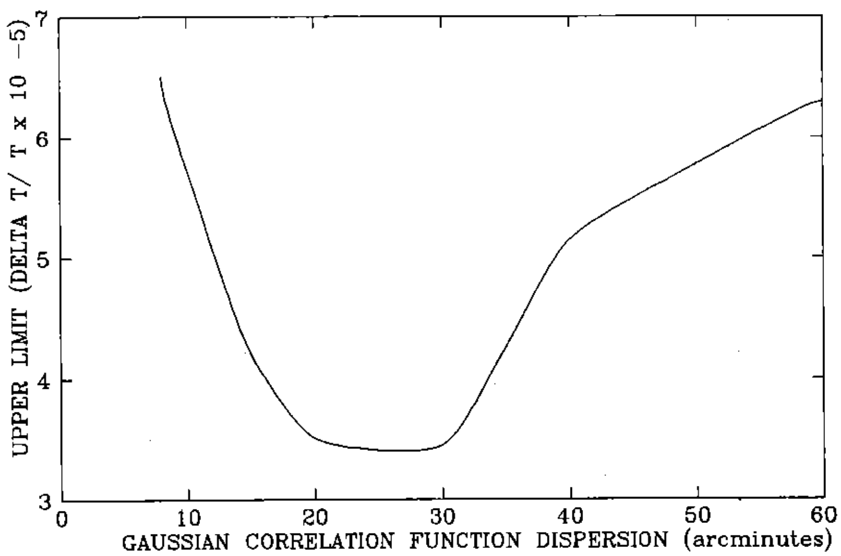

Figure 4: Upper limits on Gaussian fluctuation in the CBR from SIS data taken during 1988–1989 polar summer.

Galaxy data

In addition to CBR anisotropy data, we have made measurements of galactic emission. Galactic emission is a foreground source for CBR measurements, to be minimized and subtracted. At 90 GHz, we have made two separate measurements of galactic emission near the galactic center. The first was a highly undersampled 3 point single difference scan near the galactic center, performed during the August, 1988 balloon flight, yielding a full scale signal of 20 mK. In December 1990, a set of single difference scans with 0.25° spacing in RA and 0.5° spacing in Dec were made from the South Pole. These scans show significant signal levels, the largest being about 12 mK peak to peak. We match these two measurements to the 100 micron IRAS maps, in order to get an estimate of the brightness ratio from 90 GHz to 100 microns. We do this by taking the high resolution (2 arcminute bins) IRAS map at 100 microns, convolving with our beam and chop strategy, then sampling the measured region. Figure 5 shows the results of this for one of the measured declinations, with the 90 GHz measured points and the calculated response on the IRAS map, scaled by a constant. For this measurement, we find 200 MJy/sr at 100 microns corresponds to 1 mK Rayleigh-Jeans at 90 GHz. This is useful in attempting to locate regions of low galactic contamination, and in subtraction of whatever contamination exists. The scaling described is very naive, and says nothing about the difficult problem of extrapolating numbers measured in the galactic plane and near the galactic center to regions far from the plane, where we do our CBR measurements. Specifically, contributions from galactic components such as HII regions are highly localized, and can seriously complicate both the estimates of dust emissivity scaling and the understanding of spectra found off the plane. In fact, there is at least one potentially confusing HII region close to the position where we measure the galactic center emission. To help discriminate galactic contamination from CBR fluctuations, we also need to perform multi-frequency measurements such as our MAX flights.

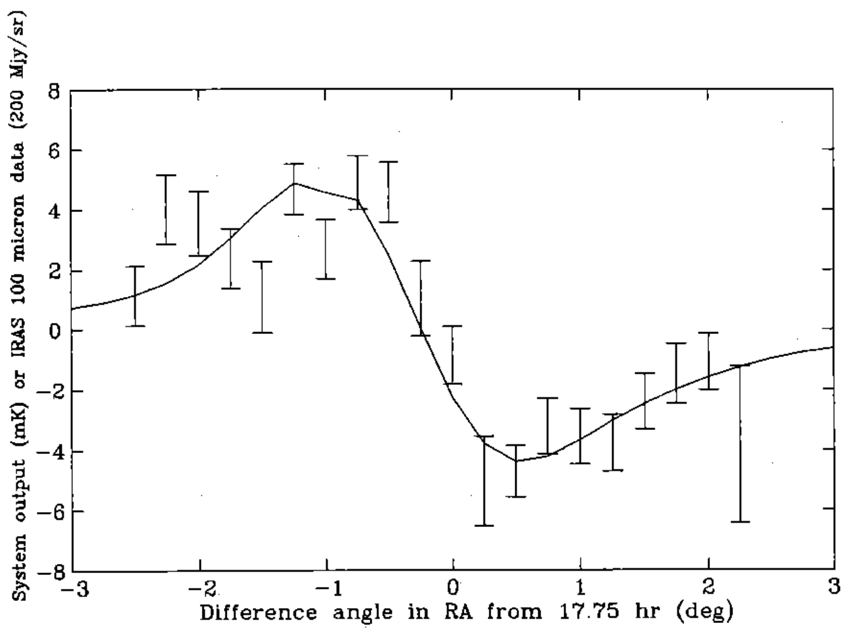

Figure 5: SIS data from South Pole, Dec, 1990. Scan of Galactic center (RA 17.75 hr, Dec −29 deg). Error bars are +/− 1 sigma, and smooth curve is smoothed, differenced IRAS 100 micron map in units of 200 Mjy/sr.

7° HEMT Radiometer

In 1987-1988, we built a HEMT (High Electron Mobility Transistor) radiometer to study the anisotropy of the CBR at larger angular scales. Angular scales between 5 and 15 offer a good test of inflationary models and large-scale structure via the Sachs-Wolfe effect. This is also the scale where a possible anisotropy detection was reported a few years ago (Davies *et al.*1987).

The instrument operates at 15 and 23 GHz. By making a measurement at two frequencies we hoped to remove possible signals from galactic emission which is expected at these frequencies at a level of 0.1 mK. The optics consist of pair of scalar feed horns with a beam width of 7 deg FWHM and a separation of 10 deg. By keeping the optics simple we achieve high sidelobe rejection. A cryogenic circulating switch modulates the signal between a pair of horns at each frequency. The signal is then amplified by a cryogenic HEMT amplifier. Further amplification is achieved by ambient RF amplifiers. The signal can then be passed through a bandpass filter and converted to a voltage in a detector diode. The signal is then demodulated electronically and stored on a computer. The target field of the instrument can be varied by placing the entire apparatus on a rotation table or by placing a flat movable reflector in front of the antennae.

The noise in both systems is about 3.5mK·sec$^{1/2}$ including sky. Noise during runs could be higher depending upon location and seeing conditions. Some excess noise could be removed by wagging the beams periodically on the sky and subtracting signals from adjacent sky positions. This system is shown in figure 6.

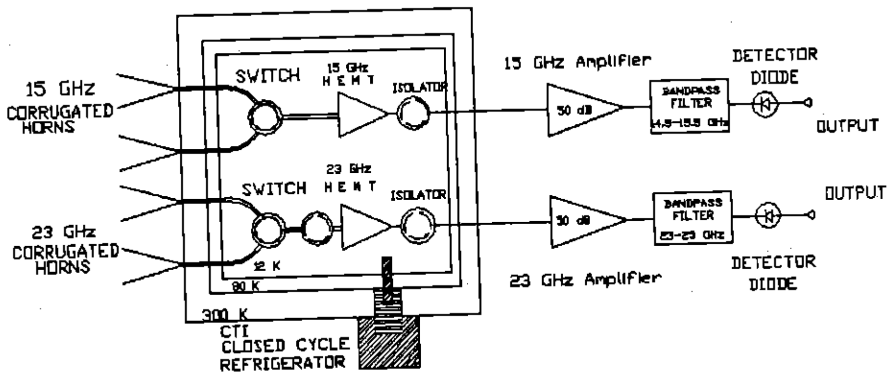

Figure 6: Dual Frequency HEMT Radiometer Schematic

Data acquisition strategy

The instrument was used on three separate occasions to obtain data. In all three cases high, dry sites were chosen to reduce the effects of atmospheric emissions. The instrument was operated at the South Pole during the austral summers of 1988-89 and 1990-91. A northern hemispheric measurement was made from the White Mountain Research Station fall of 1989. Data from the two earlier results will be discussed here. The data from the most recent South Pole expedition have not yet been analyzed.

Our first South Pole strategy was similar to that described by Davies *et al.*. Our instrument, with an output proportional to temperature differences on the sky, is slewed between two azimuth positions, and the field of view changes with the rotation of the earth. Signals from the two positions are subtracted resulting in the familiar three-beam response, sensitive to the second derivative in sky fluctuations. After this second subtraction a small offset of about 1 mK remained. A slight linear trend was also evident across a 9 hour RA stretch of data. Removal of this line has a negligible effect on our sensitivity at our most sensitive angular scale, about 8 deg for Gaussian fluctuations. This is the only fitting that was necessary on this data set. The sky at the South Pole is very stable for long periods of time.

This data set is shown in figure 7, and represents about 24 hours of useful data, which was all we were able to use after editing data from poor weather periods and large systematics. Still we are able to set a good upper limit with this data, and compare it to the result of Davies et. al.. Figure 8 shows such a comparison of relative likelihoods of both our data set and that of Davies et. al. While both upper limits are about the same for the same experimental geometry, we do not detect any significant fluctuations. Their result has a 40 percent probability of being consistent with this data set.

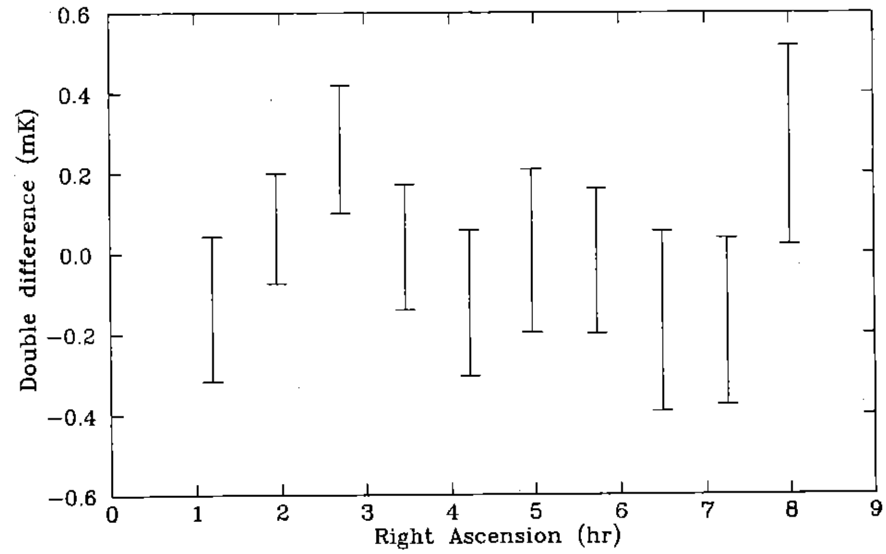

Figure 7: 23 GHz HEMT system. South Pole 1988–89 data set. Binned in 0.5 FWHM bins, linear fit removed.

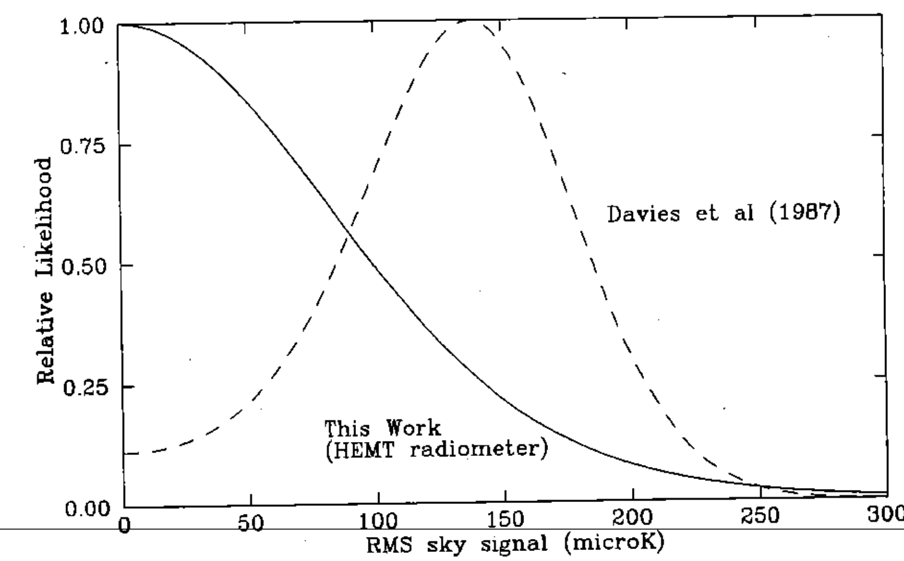

Figure 8: Comparison of relative likelihoods for Davies et al, 1987 data and HEMT radiometer 1988–89 South Pole data.

The expedition to White Mountain was staged to allow us to look directly at the anisotropy of Davies et. al. The experimental configuration was not as clean as for our previous expedition. Due to the geometry of the mid-latitude observation, a flat movable mirror was used to provide a slow second chop. The unfortunate effect of such a chop through large elevation differences is a large second chop offset proportional to the DC atmospheric temperature. This offset was about 30 mK in the 15 GHz channel and 70 mK in the 23 GHz channel. Because the DC level of atmospheric emissions varies on time scales of several hours, a linear fit is insufficient for removal of excess atmospheric noise. A bandpass filtering scheme was devised which again preserves sensitivity at our most sensitive scale. A section of data from Dec=40 is shown in figure 9. This is precisely the region where Davies *et al.*saw excess signal. While we see no evidence for this signal in our respective data set, we do not have the sensitivity to fully rule out their detection. The 23 GHz channel could not be used to obtain useful data due to the large atmospheric effect.

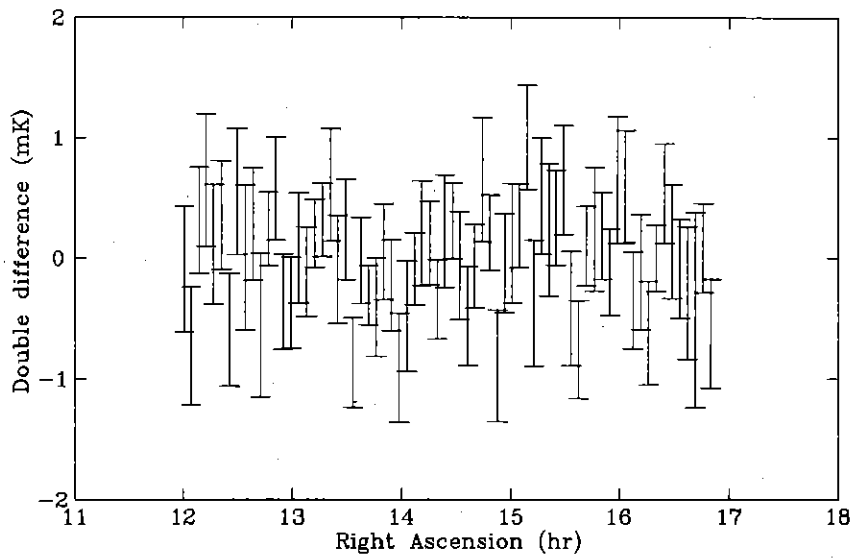

Figure 9: 15 GHz HEMT radiometer White Mountain, 1989 data. Dec 40 degrees. Data binned as in Davies et al (1987).,

25–35 GHz HEMT experiment

For the 1990-1991 South Pole expedition, we built a new HEMT based detector with very low noise from 25 to 35 GHz. By installing a detector with one of these amplifiers in the Gregorian telescope discussed above, we could make a measurement at $1 - 3°$ scales with little modification of the platform or optics.

We multiplexed the output into 4 channels of 2.5 GHz in order to obtain spectral information on any fluctuations detected. This technique also helped us to evaluate systematics. The beamsize is 1.6° FWHM and is chopped sinusoidally resulting in an effective beam separation of 2.1° on the sky (3° p-p). The instrument operated without incident for 3 weeks. During times of good weather our best channel exhibited noise of $1.4\text{mK}\cdot\text{sec}^{1/2}$. The combined channels show sensitivity around 700 to 800 $\mu\text{K}\cdot\text{sec}^{1/2}$, including sky noise. A sample of ten hours of this data is displayed in raw form (with no fitting) in figure 10. A total of about 200 hours of useful data were obtained after editing. This time is divided into six independent measurements. Each measurement is similar to the SIS measurement strategy described above, consisting of 9 overlapping single difference measurements. During preliminary analysis, scans of this data have exhibited single point errors of less than 10 μK. Further evidence of the instrument sensitivity is shown in figure 11a and b, which show one hour of data taken around the Large Magellanic Cloud. The complete data analysis is still in progress, these results are preliminary.

Conclusion

We have described measurements of CBR anisotropy made over the past few years. Published upper limits on $\delta T/T$ from these experiments are at the $3.5x10^{-5}$ level. New data which is still being analyzed should push the sensitivity below 10^{-5}. Experiments currently underway or being contemplated both in collaboration and within the UCSB group are expected to make measurements with precision of a few $x10^{-6}$ within a few years, either detecting anisotropy or putting even stricter limits on the parameters of current cosmological models. If no anisotropy is found at the 10^{-6} level very few of the current theories appear viable.

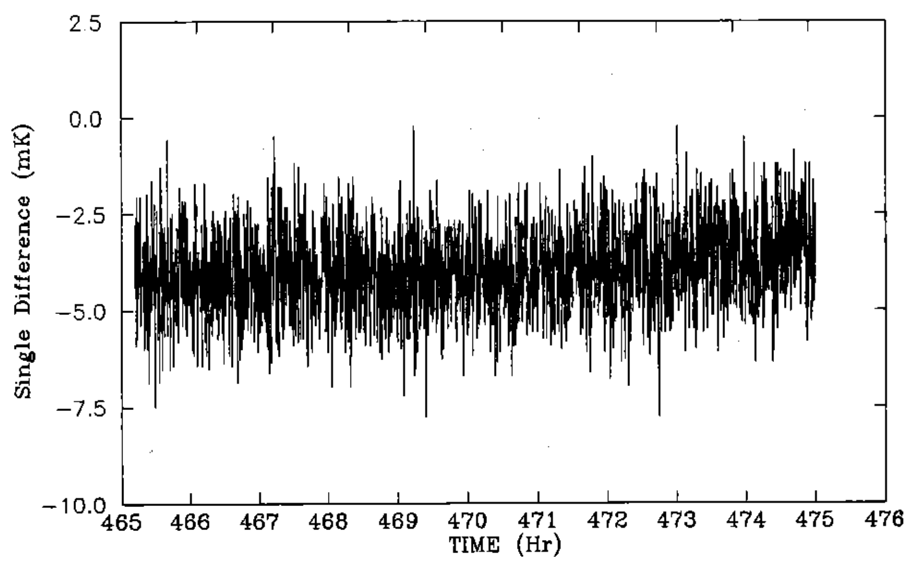

Figure 10: PHEMT Channel 2 raw data, South Pole 1990–91.

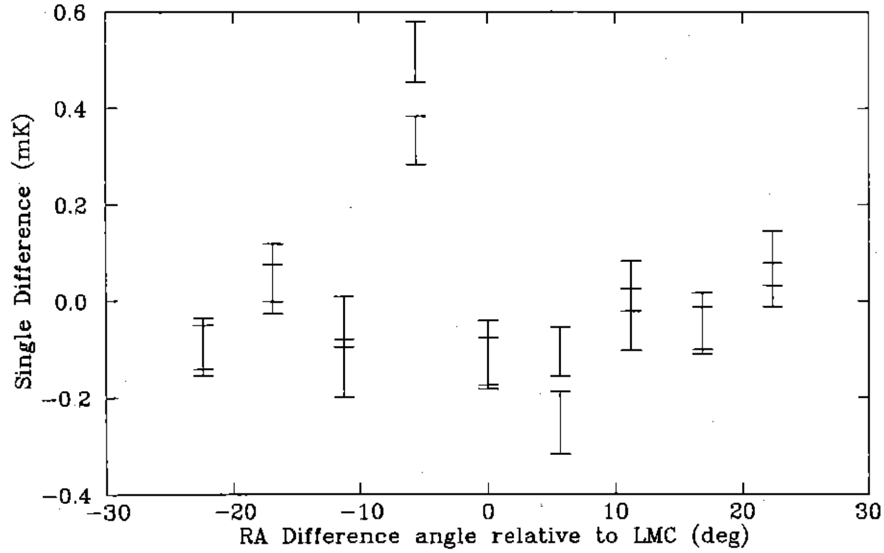

Figure 11a: PHEMT channels 1 and 2. Scan of Large Magellai
(centered at RA 5.6 hr, Dec −68 deg).

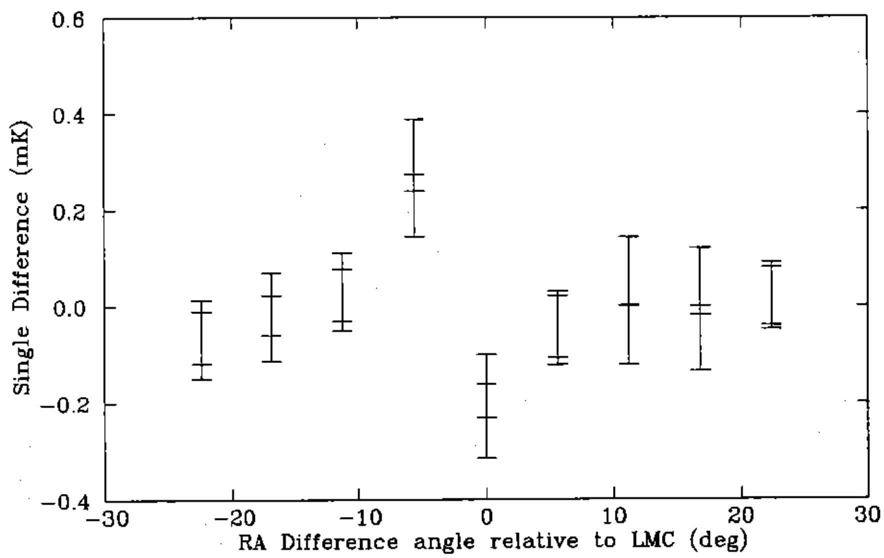

Figure 11b: PHEMT channels 3 and 4. Scan of Large Magellanic Cloud
(centered at RA 5.6 hr, Dec −68 deg).

Acknowledgements

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