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Final Report for NASA Grant NAGW-2801

A proposal entitled:

**A NOVEL APPLICATION OF FOURIER TRANSFORM SPECTROSCOPY
WITH HEMT AMPLIFIERS AT MICROWAVE FREQUENCIES**

**Award dates Feb 1, 1992 to Jan 31, 1995
with an additional "no-cost" extension to July 31, 1995**

by

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FINAL TECHNICAL REPORT

Summary of project.

The purpose of the project was to develop cryogenic high-electron-mobility transistor (HEMT) based radiometers and use them to measure the anisotropy in the cosmic microwave background (CMB). In particular, we would develop a novel Fourier transform spectrometer built entirely of waveguide components.

Summary of results.

Over the three and one half years of funding there were a number of successes that were funded, in whole or in part, by NAGW-2801.

- 1) Ed Wollack built a dual-polarization K_a band HEMT radiometer and Barth Netterfield built a similar Q-band radiometer. In a series of measurements spanning three years made from our ground-based site in Saskatoon, SK, the amplitude, frequency spectrum, and spatial frequency spectrum of the anisotropy were measured.
- 2) Bill Tompkins, John Keatley and Lyman Page built and tested a prototype K_a -band FTS. A simplified version of the FTS is proposed for the MAP satellite mission.
- 3) Norm Jarosik made a series of measurements with Wollack's radiometer and quantified the $1/f$ characteristics of HEMT amplifiers using correlation techniques.

The budget was spent almost as outlined. NRAO has only recently developed the 90 GHz amplifiers that we proposed to purchase and so the money in the final year of the grant was spent on more Q-band amplifiers.

Observing the CMB anisotropy from Saskatoon, SK, CA.

The primary reason for investigating HEMT amplifiers was to identify promising technologies for measuring the anisotropy in the CMB. Over the last three years, we have modeled, built, and taken data with both K_a -band and Q-band HEMT radiometers developed under this grant. Each radiometer views the sky with two polarizations in each of three frequency bands. This allows us to measure both the amplitude and spectrum of the fluctuations.

In 1993, we detected a sky signal with the K_a -band system that matched the amplitude and spectrum expected for the CMB. The results are reported in Wollack *et al.* (Ap. J. L 419, L49, 1993). In 1994, we returned to our Saskatoon site with the Q-band radiometer. The previous year's results were confirmed and, with the increased frequency baseline, the limit on potential contamination by galactic foregrounds was tightened. These results were reported in Netterfield *et al.* (Ap J. L., 445, L69, 1995). In 1995 (working in part on a no-cost extension), we returned for a third time to confirm the previous two year's results, observe the same part of the sky as the MSAM experiment, and to observe the sky with a smaller beam. The combined results of the three years are shown in Figure 1.

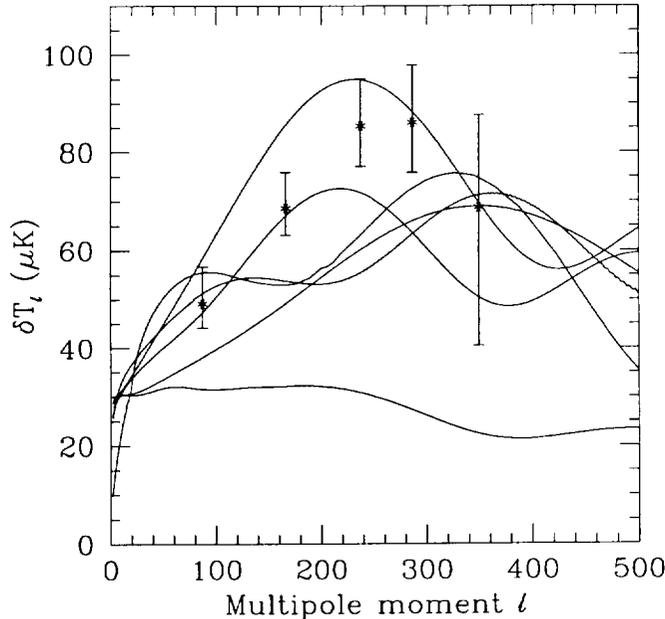


Figure 1. The angular power spectrum of the anisotropy averaged into five spectral bands. The predicted power spectra from six representative theories are also shown.

The HEMT FTS.

Two versions of a HEMT-based waveguide FTS were built in waveguide. The first was done by Bill Tompkins '93 for his senior thesis. Bill is now a graduate student in physics at Stanford University. The second was built by John Keatley '95, also for a senior thesis. John is now an Engineering Consultant in Los Angeles. As far as we know, these are the first waveguide FTS's built.

The waveguide FTS concept works; results have been shown in previous reports. Ultimately, the limiting factor in the current design is the port-to-port isolation in the circulators which are the microwave analog of optical beam-splitters. When used in the classic FTS mode, the lack of isolation produces sub-harmonics in the output signal. These can be filtered with the result that the FTS bandwidth is limited to one octave.

The HEMT FTS can be used to characterize the phase-matching between amplifiers. Part of John Keatley's thesis was devoted to determining the phase difference between two similar commercial amplifiers. He was able to show that they were matched to better than 20° over most of the band even though this was not a production specification. This was important to know for the *MAP* differential radiometers.

Characterizing HEMT Amplifier Noise.

In the data analysis for Wollack *et al.* 1993, we discovered that fluctuations between channels of a single HEMT amplifier were correlated. After observing, the Saskatoon radiometer was transformed into a correlation receiver to measure the noise fluctuations produced by a single amplifier. We found that gain fluctuations of a part in 10^5 were responsible for the correlated noise. The results are reported in Jarosik *et al.* 1993 and

Jarosik 1996.

Until our measurements, it was widely believed that HEMTs had little or no $1/f$ noise. These new results have had a strong impact on the proposed observing strategies for HEMT-based satellite experiments. In particular, the radiometer design in *MAP* was in part dictated by the need to operate at audio frequencies much higher than $1/f$ knee.

Education.

Both Barth Netterfield and Ed Wollack were supported by this grant (though not at the same time) as graduate students. Ed Wollack is a post-doc at NRAO and Barth Netterfield is a post-doc at Princeton. The grant also supported graduate students Sanje Ram and Bill Vinje for shorter periods.

The following undergraduates were supported by this grant both during the summer and school year in 1992, 1993, & 1994: Bill Tompkins, Peter Kalmus, Naser Qureshi, Stephen Vandermark, Peter Wolanin, John Kulvicki, and Young Lee.

Publications that refer to NAGW-2801.

- Wollack, E. J., Jarosik, N. C., Netterfield C. B., Page, L. A., and David Wilkinson. "A Measurement of the Anisotropy in the Cosmic Microwave Background Radiation at Degree Angular Scales," *Ap. J. Letters* **419**, L49, 1993.
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- Page, L. A., et al. "Observations of the Anisotropy in the Cosmic Microwave Background by the FIRS, SK93, and MSAM-I Experiments" in "CMB Anisotropies Two Years After COBE." World Scientific, Ed. L. Krauss.
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- Netterfield C. B., Devlin, M., Jarosik, N. C., Page, L. A., and Wollack, E. J. "A measurement of the Angular Power Spectrum of the Anisotropy in the Cosmic Microwave Background." In preparation, planned submission is Jan, 1996.
- Jarosik, N., "Measurements of the Low Frequency Gain Fluctuations of a 30 GHz High-Electron-Mobility Transistor Cryogenic Amplifier" *IEEE Trans. MTT*, Vol 44, Issue 2. Accepted for publication in Feb 1996.
- Wollack, E. J., Devlin M., Jarosik, N. C., Netterfield C. B., Page, L. A., and David Wilkinson. "An Instrument for Investigation of the Cosmic Microwave Background Radiation at Intermediate Angular Scales" In preparation, planned submission is Jan, 1996.