Ultrahigh resolution C_n^2 Profiles Derived from an FM-CW Radar

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1. ABSTRACT

The US Army Atmospheric Science Laboratory operates a Frequency Modulated-Continuous Wave (FM-CW) radar at White Sands Missile Range, New Mexico. This 10-cm wavelength radar has the unique capability of measuring 2-m resolution C_n^2 profiles to 2-km above ground level. At this short wavelength, scattering from point targets, presumably insects, seriously contaminates the turbulence measurements. The ability of the FM-CW radar to resolve individual insects even at two km allows the insect signature to be removed from the turbulent backscatter. Radar calibration, data, and a technique for removing insect contamination are presented.

2. INTRODUCTION

The U.S. Army Atmospheric Science Laboratory operates a Frequency Modulated-Continuous Wave (FM-CW) Radar at White Sands Missile Range, New Mexico. This 10-cm wavelength radar has the unique capability of measuring 2-m resolution radio refractive index structure parameter (C_n^2) profiles to 2-km, and 1-m resolution profiles to 1-km above ground level. These profiles can be measured at 12-second intervals, producing high temporal resolution images. The radar equation, calibration technique, noise correction, and insect signal removal are discussed and demonstrated using 2-m resolution data.

3. RADAR EQUATION

The equation for calculating C_n^2 from an FM-CW radar was derived by Chadwick et. al. (1978)[1]. Although originally used for 160-m resolution, the equation is general and can be used on our 2-m data. This equation is given as

$$C_n^2 = \frac{8.43}{R_G(R)} \frac{A_R}{A_S} \frac{P_S}{P_T} \frac{R^2}{\Delta} ,$$

where

C_n^2 = radio refractive index structure parameter ($m^{-2/3}$);

$R_G(R)$ = antenna overlap weighting function as a function of range;

A_R = area under the clear air spectrum minus receiver noise;

A_S = area under the test signal spectrum;

P_S = equivalent test signal power (W);

P_T = transmitted power (W);

R = range (m);

Δ = range resolution (m).

The terms of the equation are described in more detail in the following sections.

3.1. Antenna Overlap Weighting Function

The FM-CW radar uses two antennas. It transmits continuously from one and receives continuously with the other. The received power must be corrected at low ranges for the overlap of the two antenna patterns. This correction is calculated from the autocorrelation function of the two identical antenna patterns. Figure 1 shows the weighting function for the measured antenna patterns of this radar. Below about 500 meters, C_n^2 strongly depends on accurate knowledge of the antenna overlap.

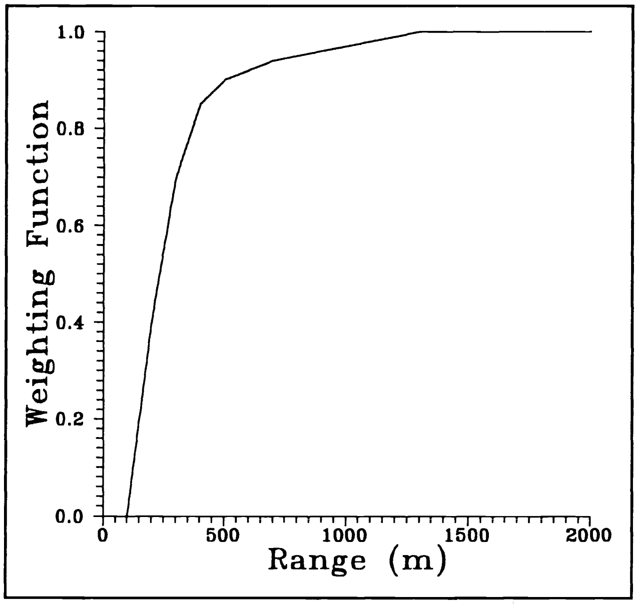

Figure 1 Range weighting function due to antenna pattern overlap.

Below 100 m, the weighting function goes to zero. The antennas may be aligned differently to increase overlap at low altitudes. However, the weighting function is only valid in the antenna far-field and should not be used in the near-field, below about 180-m. An empirical correction for low altitudes could be developed by comparisons with a calibrated sodar. Radars and sodars do not have the same scattering mechanism. Near the ground under dry conditions, however, it could be assumed that the radar and sodar were scattering off of the same turbulence.

3.2. Radar Calibration

The electronic calibration is determined by taking a known sample of the transmitted signal, attenuating it by a known amount, delaying it in a 10-μsec electro-acoustic delay line, and coupling it into the receiver. The response from the delay line represents a signal of known power and this calibrates the portion of the receiver after the point at which the delayed signal is coupled in. Since this coupling point is after the r-f preamplifier, the gain of this amplifier must be measured to complete the calibration. A block diagram of this circuit is shown in figure 2. The radar is calibrated periodically, and the area under the test signal spectrum (A_s) is then determined.

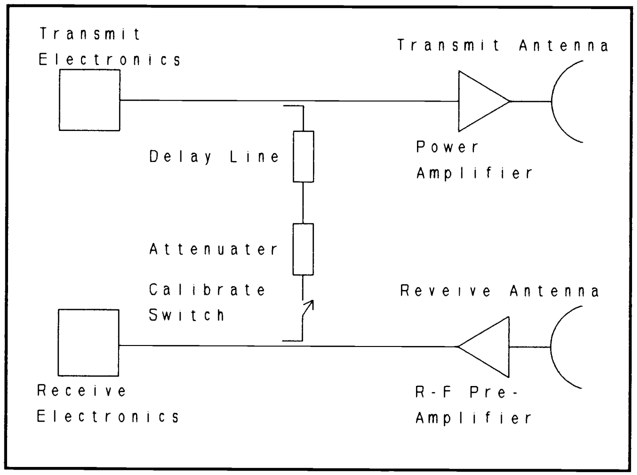

Figure 2 Block diagram of the electronic calibration circuit.

To determine the equivalent test signal power (P_S), first measure the amount of power coupled from the transmitter. Then add all the attenuation in the couplers, delay line, and attenuaters. Finally, adjust for the measured gain of the r-f preamplifier. The test signal power used for this data was -155 dBm referenced at the input of the receiver antenna.

3.3 Noise Correction

The area under the clear air spectrum is the sum of atmospheric return and receiver noise. For accurate C_n^2 values, the receiver noise must be removed. The noise is measured by terminating the output of the transmitter and recording the resulting spectra. Data collected by the radar have the recorded noise subtracted from each

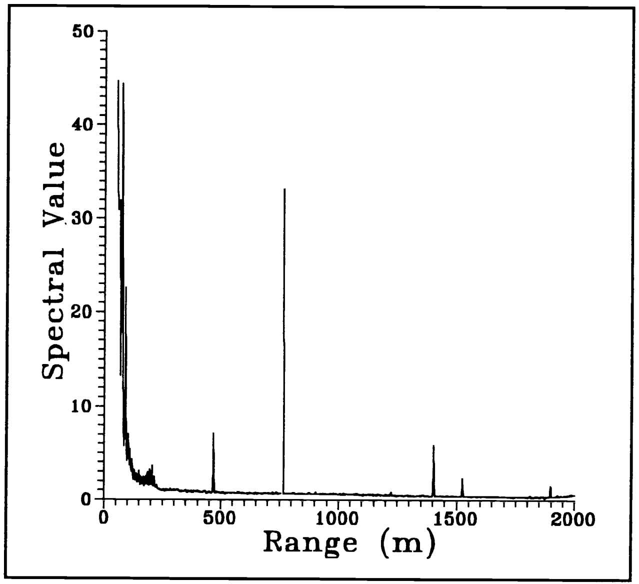

Figure 3 Typical noise spectrum.

spectral point, leaving only the desired atmospheric signal. Figure 3 show a typical noise spectrum. Low frequency noise below 100 m that is difficult to correct adds uncertainty to low altitude measurements. Also included in the noise spectrum are several spikes that result from transmitter power supply noise that cannot be completely removed.

4. Insect Removal

At this short wavelength (10-cm), scattering from point targets, presumably insects, seriously contaminates the turbulence measurements. The ability of the FM-CW radar to resolve individual insects even at 2-km allows the insect signature to be removed from the turbulent backscatter. In the past, C_n^2 data was only collected with 160-m resolution and the insect error was ignored, or data was collected only in the winter when there were no insects.

At White Sands Missile Range, the winters are seldom cold enough to discourage all the insects, so an insect removal algorithm was developed. Since individual insect return is a narrow spike 10 to 30 dB larger than the clear air return, the insects are easily removed. Figure 4 is an uncorrected C_n^2 profile from the FM-CW radar. The clear air return is evident as an increase in backscattered power with the boundary layer inversion clearly visible. Above the boundary layer, the clear air return falls below the radar noise floor. Sharp spikes from the insects are evident. Large valued data has also been clipped to make the clear air return more visible.

Insect removal is accomplished by passing a

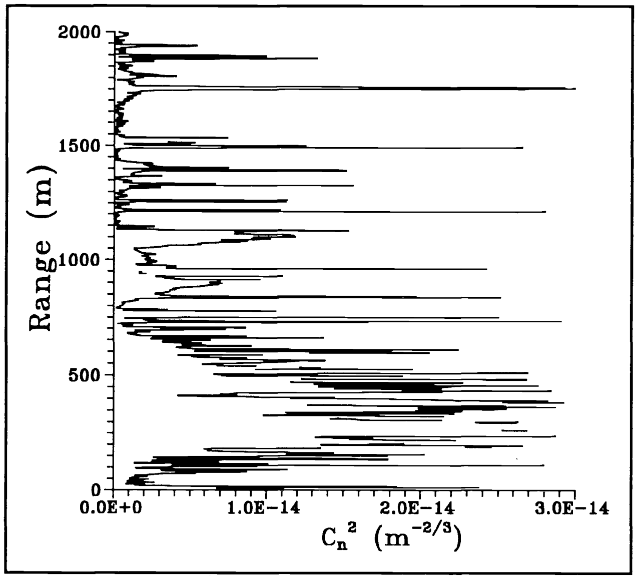

Figure 4 C_n^2 profile with insect return.

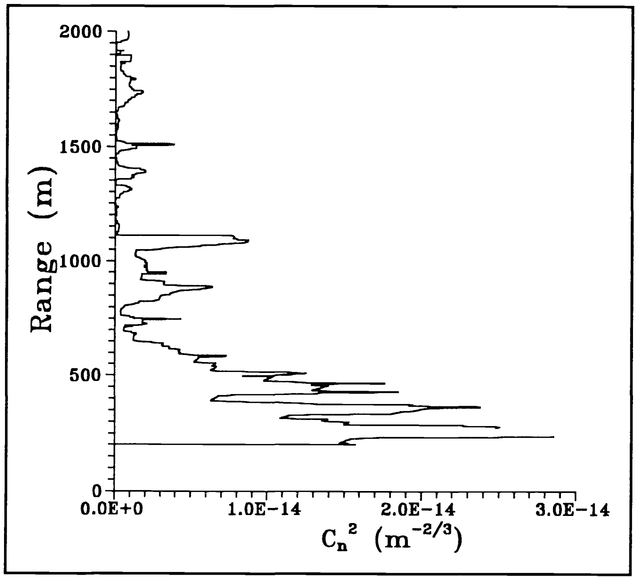

Figure 5 C_n^2 profile without insect return.

Figure 6a Time series of C_n^2 with insect return.

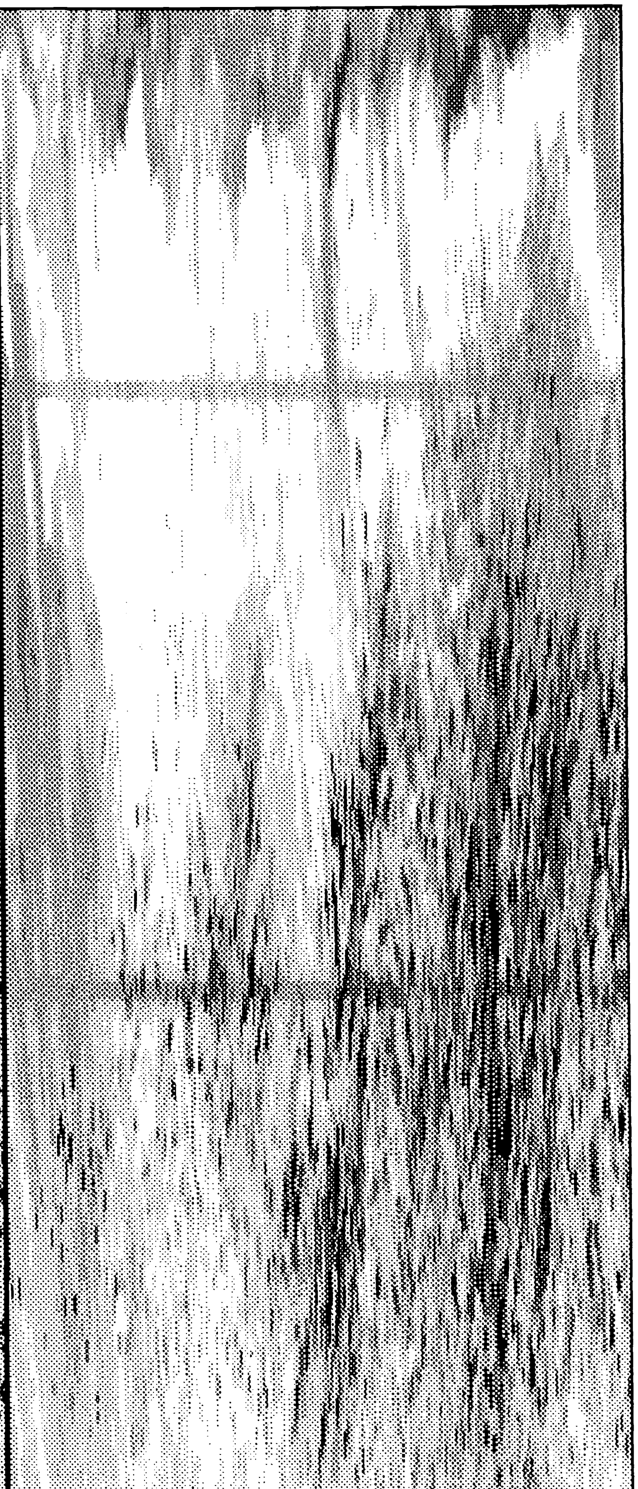

Figure 6b Time series of C_n^2 without insect return.

sliding median filter across the data. Each spectral point is replaced by the median of some number of points around it. The data for this paper uses a 17-point median which rejects spikes with a width of 8 points or less. The width of the median used depends upon how thin the inversion layers are in the atmosphere. Even a 27-point median seems to produce good results for the data seen so far. Figure 5 shows the profile from Figure 4 only with the insect signals removed. Insect signal removal has produced reasonable values for C_n^2 and retained the atmospheric structure. A 2-hour time series of C_n^2 profiles is displayed as images before and after insect signal removal in Figures 6a and 6b. The boundary layer inversion and thermal plumes are still evident after removal, but the spots from the insects are gone.

The use of an insect removal algorithm allows the FM-CW to measure C_n^2 profiles even in a warm climate like White Sands Missile Range. However, the algorithm only works when the density of insects is small enough that the radar can resolve individual insects or small regions of insects. If the density of insects is large, their spectral signature will be so broad that the algorithm will fail. Periods of time when the algorithm fails will only be detectable by unrealistically high values of C_n^2. Real-time data could be screened by setting a maximum threshold value. The threshold for Figures 6a and 6b is 5×10^{-13}, a value selected so that 98% of the clear air values will be less than the threshold (Fairall and Frisch, 1991)[2]. Black regions in the thermal plume in Figure 6b are regions where the insects were too dense to remove.

5. FUTURE PLANS

Calculations for a few test cases off line have shown the FM-CW radar capable of measuring calibrated C_n^2 profiles under most atmospheric conditions. The next step is to integrate these processing steps into the radar control software to be able to produce C_n^2 profiles in real time. Future plans also include comparing the FM-CW data with tower measurements and a calibrated sodar to verify the accuracy of the calculated values.

6. CONCLUSIONS

Ultrahigh resolution C_n^2 profiles can be obtained from an FM-CW radar. If the overlap of transmit and receive antennas and receiver noise are corrected for, reasonable value profiles to 2-km can be measured. An algorithm for the removal of insect return was developed allowing profiles to be measured under most atmospheric conditions. The ability for ultra-high resolution C_n^2 profiles in real time make the FM-CW radar a unique tool for boundary layer research.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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2. C. W. Fairall, A. S. Frisch, Diurnal and Annual Variations in Mean Profiles of C_n^2, 1991, NOAA Tech. Memorandum ERL WPL-195.