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# SOME OBSERVATIONS OF METEOROLOGICAL EFFECTS ON OPTICAL WAVE PROPAGATION

By

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April 1972

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### ABSTRACT

Values for the refractive index structure coefficient,  $C_n^2$ , were determined from spaced temperature probe measurements and from measurements of the log-amplitude variations in a laser beam. The values of  $C_n^2$  obtained from the optical measurements were smaller than the values obtained from the temperature measurements. Variations in  $C_n^2$  derived by the two methods were in good agreement even though the values obtained optically are over a 440-meter path while the temperature-derived values are essentially point measurements. The variations in the measured horizontal winds along the leeward side of the optical path showed a structure closely related to the optically derived  $C_n^2$  variations.

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## INTRODUCTION

Inhomogeneities in the clear atmosphere affect the propagation of optical beams. In particular, atmospheric turbulence will induce amplitude and phase variations in optical signals. Thus, the optical signals contain information on the turbulence characteristics. The atmospheric-induced signal variations also result in limitations in the use of laser signals for communications or remote sensing. The validity of theoretical predictions and assumptions concerning the interaction between atmospheric turbulence and the optical signal can be investigated by making simultaneous measurements of laser propagation characteristics and direct measurements of atmospheric turbulence.

The refractive index field measured by the variance of the optical beam amplitude is an integral measurement providing a result which is a weighted average over all turbulent scales within the propagation path. The direct meteorological measurements are generally point measurements that involve determination of temperature variations or temperature difference variations at one or more points along the path [1]. One point of interest is how the general meteorological conditions affect the turbulence values obtained from the two different measurements. The characteristics of the wind field near the surface will determine, because of the mixing, the intensity of the temperature variations along the optical path, and this will influence the refractivity field. Also, as the surface wind characteristics depend on the surface roughness, it is believed that both wind and surface effects will be factors in determining the characteristics of the temperature fluctuations or turbulence. Observations for this study were taken over a rough desert surface.

## THEORY

The random characteristics of the atmosphere can be described in terms of structure functions [2]. A temperature structure function can be determined from a measurement of temperature difference between two points separated by a distance  $r$  with  $\ell_0 \ll r \ll L_0$  where  $\ell_0$  and  $L_0$  define the inner and outer scales of the inertial subrange, respectively. The structure function takes the form

$$D_T = C_T^2 r^{2/3} = \langle (T_2 - T_1)^2 \rangle. \quad (1)$$

Here  $D_T$  is the structure function,  $C_T^2$  is the structure coefficient which relates the observed temperature difference,  $T_2 - T_1$ , between the two points to their separation,  $r$ . According to the Kolmogorov theory,  $C_T^2$  does not depend on  $r$  within the inertial subrange. In the same way, a refractivity structure function,  $D_n$ , can be written as

$$D_n = C_n^2 r^{2/3} \quad (2)$$

Since the refractivity field for optical wavelengths is primarily dependent on the temperature fluctuations,  $C_n^2$  can be related to  $C_T^2$  by [3]

$$C_n^2 = \left[ \frac{77.6 p}{T^2} \right]^2 \left[ 1 + \frac{.00753}{\lambda} \right]^2 \times 10^{-12} C_T^2 \quad (3)$$

where  $p$  is the pressure in millibars,  $T$  is the temperature in degrees Kelvin and  $\lambda$  is the signal wavelength in micrometers.

The amplitude variations of an optical signal can be expressed as the log-amplitude variance,  $C_\ell(0)$ . Fried [4] has shown that for a spherical optical wave subject to atmospheric turbulence,  $C_\ell(0)$  can be expressed by

$$C_\ell(0) = .124 \left[ \frac{2\pi}{\lambda} \right]^{-7/6} L^{11/6} C_n^2 \quad (4)$$

where  $L$  is the propagation path length in meters, and  $\lambda$  is the signal wavelength in meters.

Thus, for a given wavelength, the refractive index structure coefficient,  $C_n^2$ , can be determined through Equations (1) and (3) from the appropriate meteorological measurements, or optically through Equation (4) from a measurement of the log-amplitude variance observed in a laser beam.

#### EXPERIMENT

The basic experimental configuration employed is shown in Figure 1. A Spectra Physics model 132 helium-neon laser provided a 1 mw, single mode, .6328 micrometer, optical signal with a beam divergence of 1 milliradian. This provided sufficient beam diameter at the detector to minimize any effects due to beam wander. The signal detector consisted of a 10 Å interference filter followed by a 1 mm aperture in front of a photomultiplier tube, RCA type 6199. A horizontal path 440 meters in length, about 3 meters above the base of a roughened desert surface at White Sands Missile Range, New Mexico, served as the propagation path. Surface roughness was the result of wind erosion and consisted of hills about 1 to 2 meters high and about 10 meters in diameter. A detailed description of the site is given by Hansen [5] where he computed a roughness length,  $z_0$ , of 20 cm.

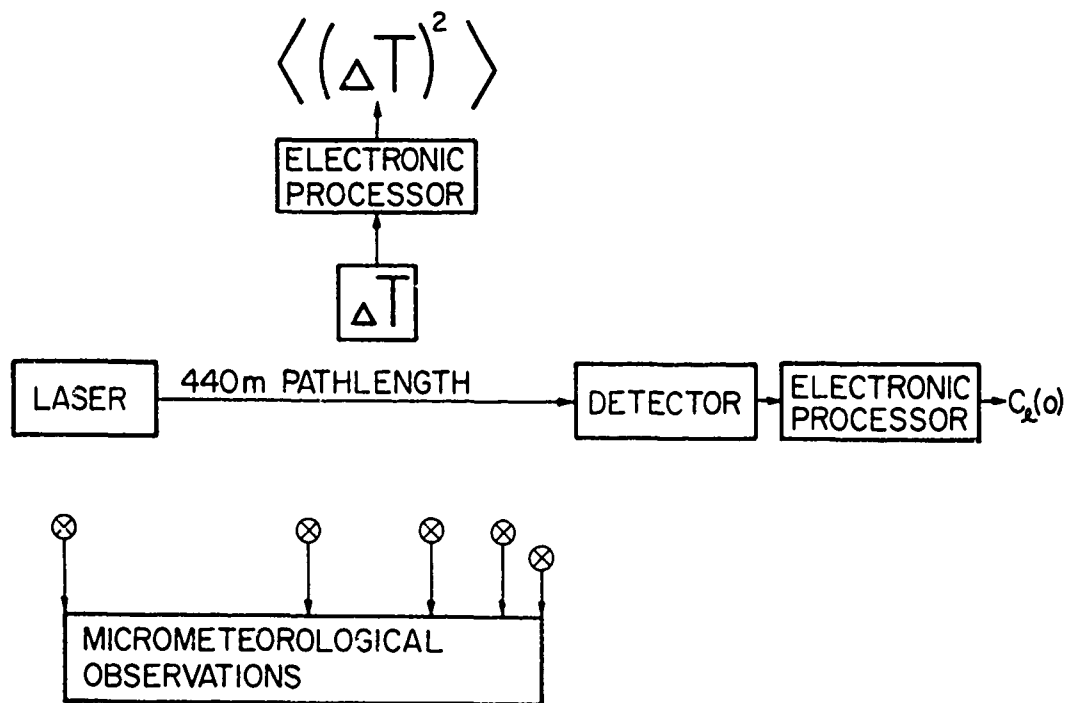


Figure 1. Block diagram showing the basic experimental configuration.

The propagation path was to the windward of and parallel to a line of five poles which are part of a meteorological instrumentation array described by Armendariz, et al. [6]. Temperature and vector wind measurements were available at various levels to 32 meters. Measurements of  $T_2 - T_1 = \Delta T$  near the center of the optical path, 3 meters above the surface, were obtained from two fine wire (.001 in.) copper-constantan thermocouples separated vertically by 20 cm.

The output of the photomultiplier, which is proportional to the incident irradiance, was fed to an electronic processor which computed the log-amplitude variance of the optical signal. The output of the processor is

$$C_{\ell}(0) = \langle (\ln A - \langle \ln A \rangle)^2 \rangle \quad (5)$$

where  $A$  is the amplitude of the detected beam. After  $C_{\ell}(0)$  was obtained, Equation (4) was used to compute the refractive index structure coefficient  $C_n^2$ . The time constant associated with the averaging of the  $\ln A$  and of the squared difference between the logarithms was 25 seconds. This instrument was calibrated by applying a biased square wave as a substitute for the photomultiplier signal and comparing the output of its processor to the calculated log-amplitude variance of the square wave.

The input to the electronic processor associated with the temperature differential measurement was proportional to the differential potential between two series-connected thermocouples. This difference was squared and averaged, again using a time constant of 25 seconds. Thus, the output of the electronic processor for temperature measurements is proportional to  $\langle (\Delta T)^2 \rangle$ . Calibration was accomplished by providing fixed voltage inputs which correspond to the thermocouple outputs over the ranges of  $\Delta T$  expected.

Observations were made continuously from 1000 MDT July 28, to 1400 MDT July 29, 1971 over the path previously described, with the mean wind direction nearly perpendicular to the laser path. Analog recordings were obtained showing the data from the  $C_{\ell}(0)$  and  $\langle \Delta T^2 \rangle$  processors along with data from an Eppley Model 50 pyranometer that measured the solar intensity. These data were also fed to a digital processor, which provided 15-minute averages and time information. The wind and temperature sensors on the meteorological array were sampled at  $4 \text{ sec}^{-1}$ , and these data were also averaged over 15-minute intervals.

#### DISCUSSION

Figure 2 shows a typical 60-minute interval representing  $C_{\ell}(0)$ ,  $\langle \Delta T^2 \rangle$  and solar intensity for a seven-hour period of analog data taken on

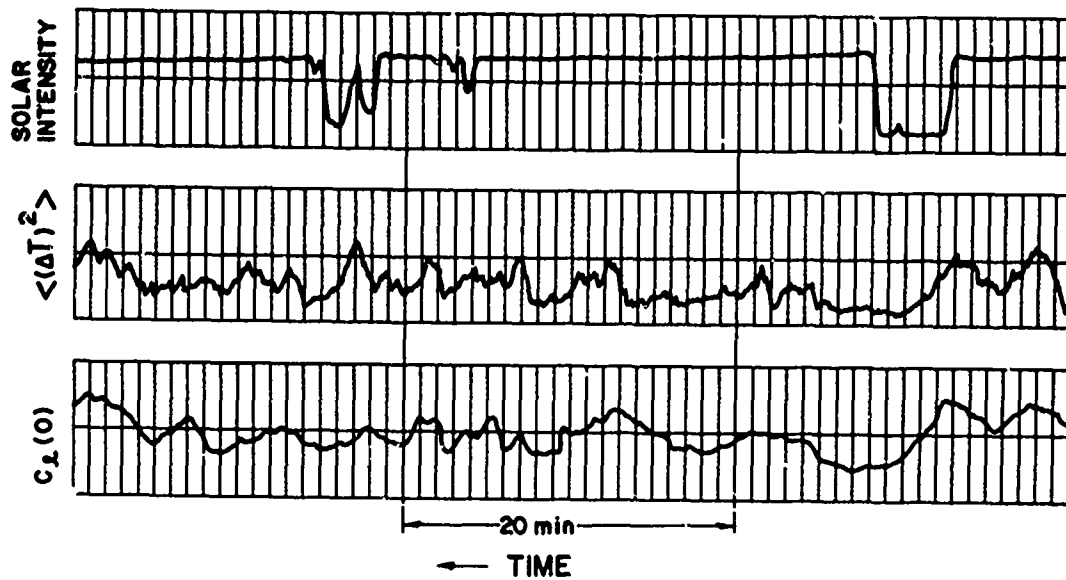


Figure 2. Analog recording of the log-amplitude variance ( $C_L(0)$ ), differential temperature ( $\langle (\Delta T)^2 \rangle$ ), and solar intensity (S.I.). ( $C_L(0)$  bottom,  $\langle (\Delta T)^2 \rangle$  middle, S.I. top) July 28, 1971, White Sands Missile Range, New Mexico.

July 28, 1971. Each point of Figure 3 is a 15-minute average of the above data. As expected, the analog record shows that the refractivity coefficient as obtainable from  $C_\ell(0)$  does not display the fine structure evident in the refractivity obtainable from  $\langle \Delta T^2 \rangle$ , but the low-frequency characteristics of the two curves are nearly identical. This latter point is demonstrated by the similarity exhibited by the averaged values of  $C_\ell(0)$  and  $\langle \Delta T^2 \rangle$ .

The refractive index structure coefficients,  $C_n^2$ , were calculated from the  $C_\ell(0)$  and  $\langle \Delta T^2 \rangle$  data by using Equation (4) and Equations (1) and (3), respectively, including the calibrations for the electronic processors. In general, the extent of the variations in  $C_n^2$  as determined from  $C_\ell(0)$  was smaller than those for  $C_n^2$  obtained from the temperature measurements. This has been observed by Kerr [7]. To obtain the same range of variation in the  $C_n^2$  measured by the two methods, the  $C_\ell(0)$ -derived values of  $C_n^2$  were multiplied by 1.7. The resultant values for the 15-minute averages are compared in Figure 4. There is a reasonably good agreement in the general shapes of the curves.

Figures 5 and 6 compare the turbulence measurements with the average winds measured near the path. Figure 5 compares the variations in the 15-minute averages of  $C_\ell(0)$  and in the averaged magnitude of the horizontal wind measured near the center of the optical path. Figure 6 shows the variations of averaged  $C_\ell(0)$  compared to the average magnitude of the horizontal wind along the entire path. Between 1000 and 1400 hours, the magnitude variations for the path-averaged and the midpath winds were almost identical. After 1400 hours, the log-amplitude variance changes were more like the path-averaged wind variations. Under the wind conditions which prevailed, the variation in  $C_\ell(0)$  is inversely related to the variations of average wind speed along the path, and there is almost a one-to-one correspondence over a two-hour period about noon. Although the  $\langle \Delta T^2 \rangle$  and  $C_\ell(0)$  variations were similar, as shown in Figure 3, the variations in  $C_\ell(0)$  follow more closely the variations in the average wind speed along the path. Thus, under light wind conditions, the log-amplitude variance changes appear related to the average wind speed changes along the path.

The inverse relationship between  $C_\ell(0)$  and average wind speed can be explained by the character of the mixing. For low wind speeds, bubbles of warm air are moved up intact thus causing large temperature differences [8]. With increased wind, the bubbles are broken up and the temperature differences become smaller. Since the winds near the surface are affected by the terrain, it is likely that the correlation between  $C_\ell(0)$  and wind will depend on the surface characteristics.

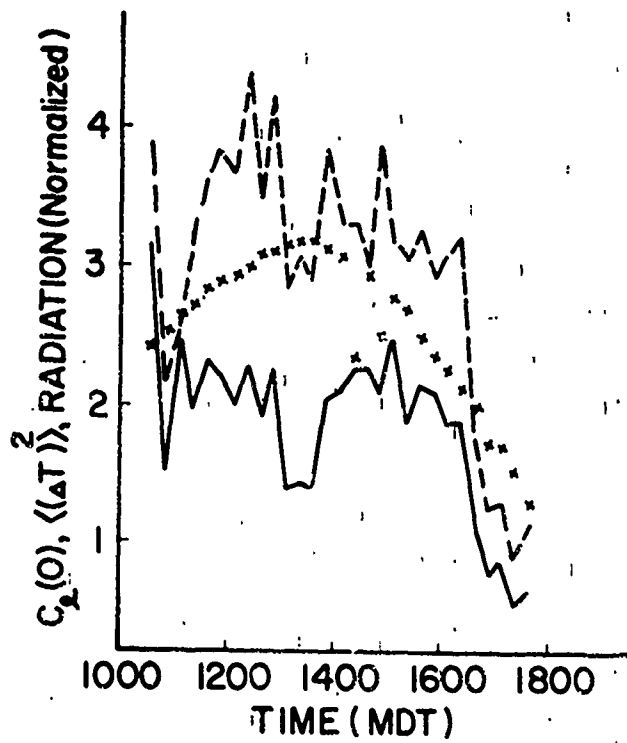


Figure 3. Fifteen-minute averages of the log-amplitude variance ( $C_2(0)$ ), differential temperature ( $\langle(\Delta T)^2\rangle$ ), and solar intensity (S.I.).  $C_2(0)$  solid line,  $\langle(\Delta T)^2\rangle$  dashed line, S.I. x.

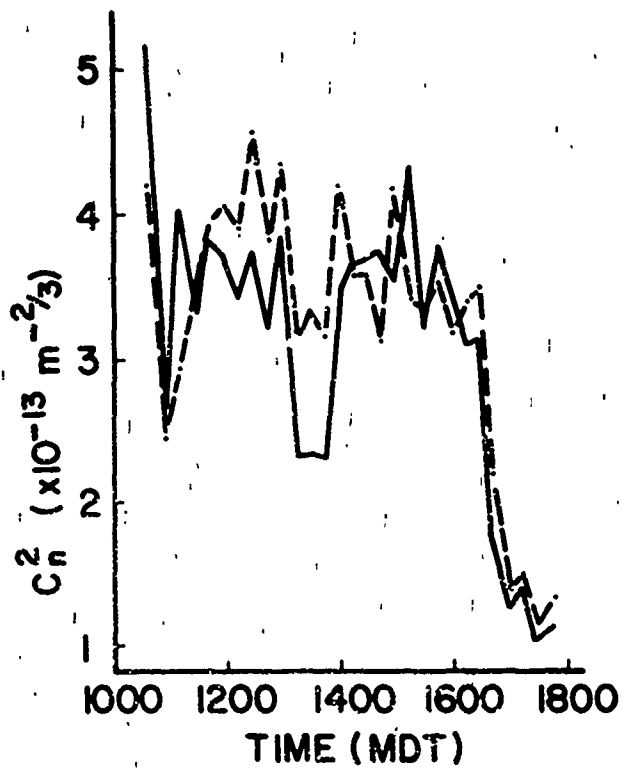


Figure 4. Comparison of refractivity structure coefficient ( $C_n^2$ ) derived from optical (solid line) and temperature (dashed line) measurements. (Optical values have been multiplied by 1.7.)



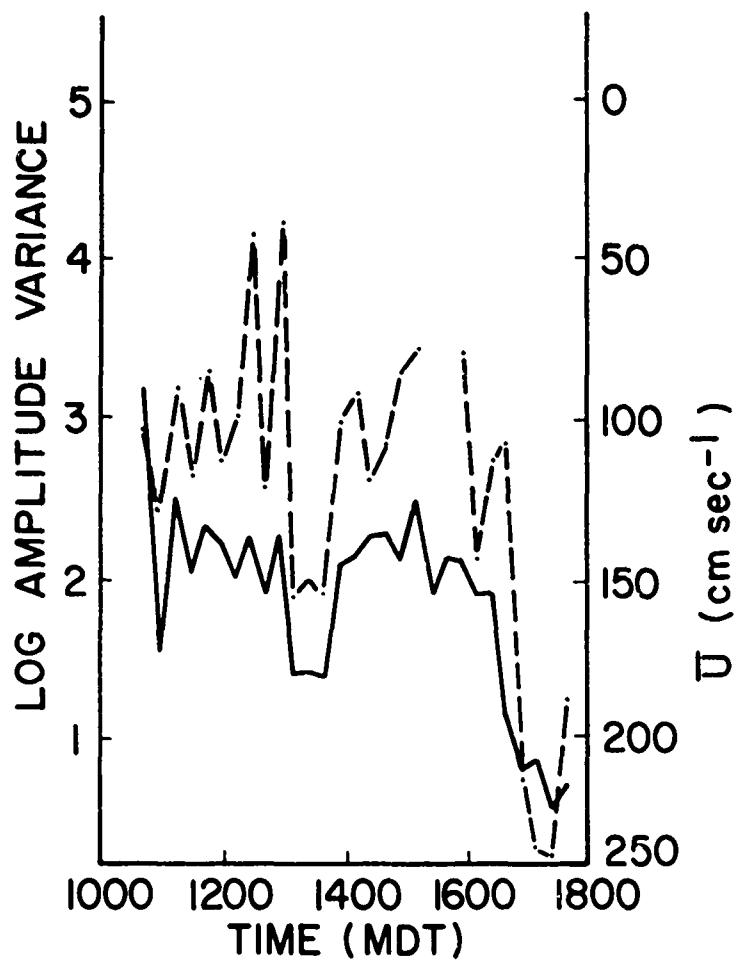


Figure 5. Comparison of the log-amplitude variance (solid line) to the wind (dashed line) measured near the center of the optical path (15-minute averages).

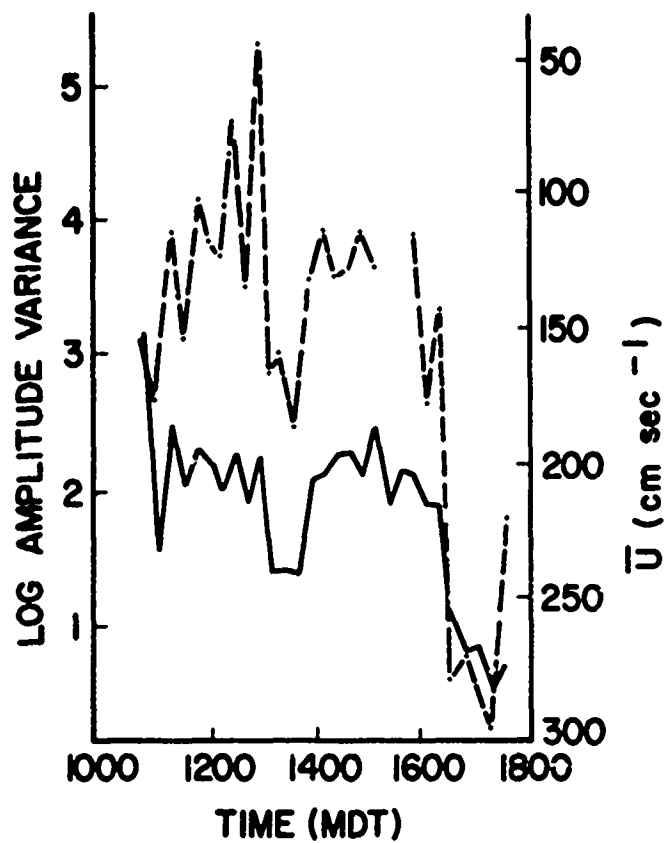


Figure 6. Comparison of the log-amplitude variance (solid line) to the averaged wind magnitude obtained from five positions along the optical path (dashed line). (15-minute averages)

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