NOAA Technical Memorandum ERL WPL-106

A STUDY OF FACTORS INFLUENCING THE CALIBRATION OF OPTICAL C_n^2 METERS

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ABSTRACT

We report the results of a study to identify factors affecting the calibration of optical C_n^2 meters of the modulated LED design. Design modifications to the 5 cm units have been made as a result of this study. The results indicate that a system working over 500 to 1000-meter paths, employing a 15-cm diameter transmitter and a single 15-cm diameter receiver, has advantages over the dual 5 cm systems in certain applications.

1. INTRODUCTION

An optical technique has been developed for measuring the refractive-index structure parameter C_n^2, that largely avoids the effects of the inner scale of turbulence and the saturation of scintillation by using relatively large incoherent transmitting and receiving optics.[1] Several kinds of optical systems have been designed that measure C_n^2 by this technique. The first system used an incandescent quartz-halogen light for the incoherent source.[2] The second system employed a modulated LED as the light source.[3] The irradiance at the receiver is much less when the LED light source is used. The signal-to-noise ratio (S/N) is about the same, however, since filtering can be employed. The quartz-halogen system has to be calibrated at night to clearly differentiate the transmitter signal from the background light. The assumption is then made that background light within the receiver bandwidth and field of view does not fluctuate enough to affect the measurement. Generally this is the case even in the daytime if bright reflections from the sun can be avoided. Background light effects are almost entirely eliminated from the modulated LED system, however. The LED has a half-power bandwidth of about 400 Å, so that the receiver can filter out much more of the background light. Also by using a carrier, 1/f noise is minimized, and C_n^2 can be derived from the log-intensity variance of the irradiance, so that the calibration is not dependent upon the brightness of the transmitter.

After some experience with the modulated systems, however, differences in calibration were observed between the quartz-halogen and LED systems, with the LED systems generally reading somewhat higher. These observations prompted the additional studies reported here.

2. DISCUSSION OF FACTORS INFLUENCING THE CALIBRATION

Most of the differences in calibration between the quartz-halogen and LED systems were eventually traced to an effective receiver aperture that was smaller than the objective lens diameter, and to a nonuniform distribution of light across the transmitting and receiving apertures. It is easier to obtain a uniform distribution of light across the transmitting aperture when the large and bright quartz-halogen source is used. Much less light is available from the LED however, and it is difficult to conserve light and obtain a uniform distribution at the same time. The resulting optical design turned out to be too difficult to focus and point. An example of the light intensity distribution across the aperture of one of these compound optical systems is shown in Fig. 1.

In addition, not all points on the transmitting aperture were radiating over the same angular spread, so that the calibration was somewhat sensitive to transmitter angle. This resulted in higher readings because the transmitting aperture appeared like one or more smaller apertures. An example of angular sensitivity that occurs with an LED active surface at the focus of an objective lens is shown in Fig. 2. When the transmitter pointing is sufficiently off axis, the aperture appears only partially illuminated from

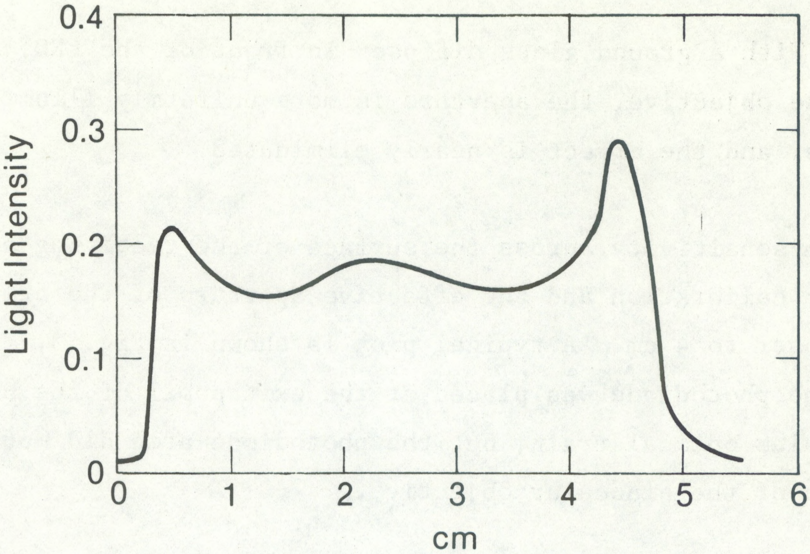

Fig. 1. Light intensity distribution across the transmitter that employed a compound optical system.

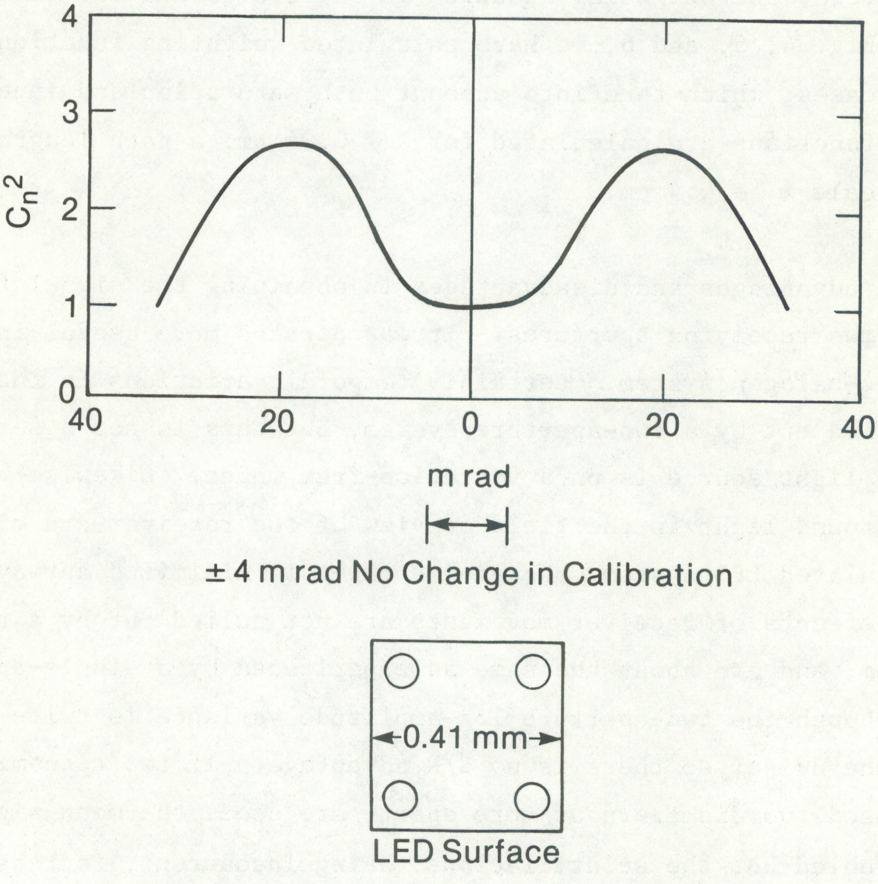

Fig. 2. Effect of off-axis transmitter pointing on the C_n^2 measurement. The transmitter has an LED at the focus of an objective lens, so that a sharp-edged cone of light is projected.

the receiver. With a ground glass diffuser in front of the LED, and inside the focus of the objective, the aperture is more uniformly illuminated when viewed off axis, and the effect is nearly eliminated.

Nonuniform sensitivity across the surface of the receiving aperture can also affect the calibration and the effective aperture of the original receiver was in fact closer to 4 cm. A typical plot is shown in Fig. 3. In this optical system the photodiode was placed at the exit pupil of the nominally 20 power binocular optical train, but the photodiode area did not completely cover the image of the binocular objective.

If either the transmitter or receiver diameter D_s is slightly smaller than the diameter D used in the calibration equation, then the C_n^2 reading will be too high by the factor $k = (D/D_s)^{7/6}$. With unequal transmitter and receiver diameters, the weighting function is shifted toward the smaller aperture. In Fig. 4, 5, and 6, we have calculated weighting functions for some specific cases, which take into account both saturation and inner scale effects. The functions are calculated for $\lambda = 0.94$ μm, a path length L = 200 m, and an inner scale $\ell_o = 0.4$ cm.

There are advantages and disadvantages in obtaining the signal from the difference of two receiving apertures. It was perhaps more useful in the original quartz-halogen system. Certainly temporal variations in the light source are nulled out by a two-aperture system, but this is not a serious problem if the light source is on a vibration-free mount. Likewise variations in background light in the field of view of the receiver are minimized, but in the modulated LED system, background light is minimized anyway. In practice, the effects of receiver movements are not nulled out by a two-aperture system, and are about the same as experienced by a single-aperture receiver. Although the two-aperture log-amplitude variance is twice as large, so is the noise, so there is no S/N advantage. If two transmitting apertures, spaced two diameters or more apart, are used, the mean signal strength is doubled but the scintillations, being incoherent, increase only as the square root of 2. In this case the log-amplitude variance is one-half

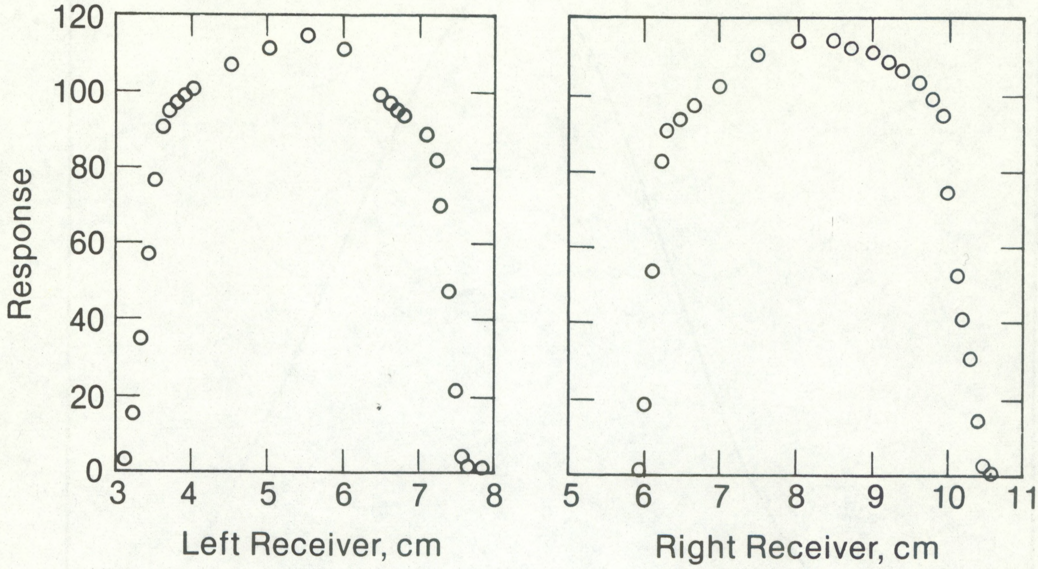

Fig . 3. Receiver aperture sensitivity of original 5 cm system.

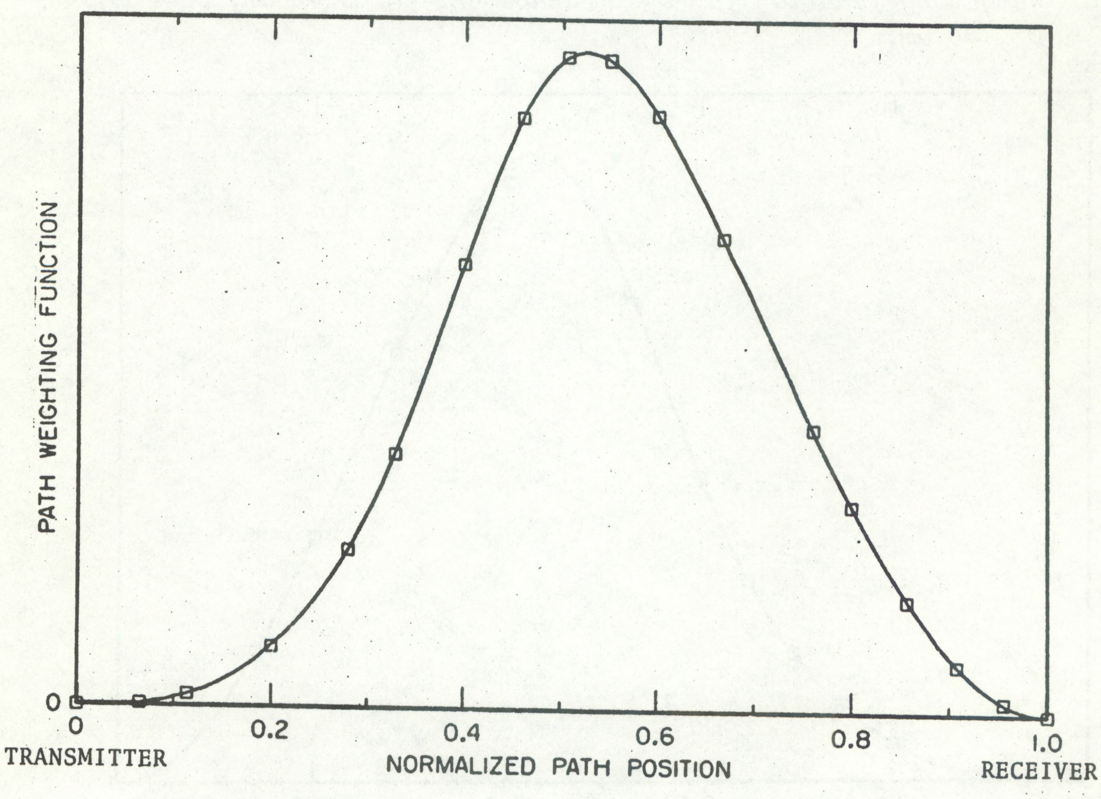

Fig. 4. Weighting function for C_n^2 measurement for transmitter diameter D_t=5 cm, receiver diameter D_r=5 cm, and receiver aperture center separation D_{sep}=5 cm.

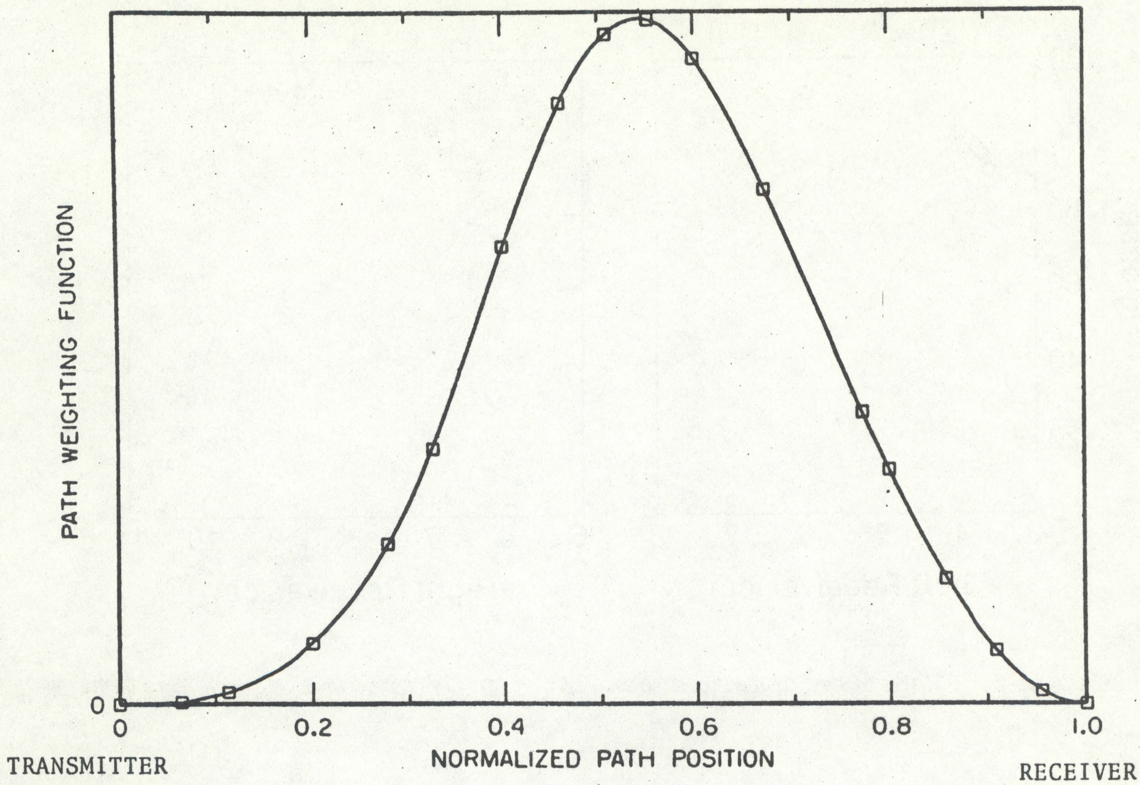

Fig. 5. Weighting function for C_n^2 measurement for D_t=5 cm, D_r=4 cm, D_{sep}=6 cm.

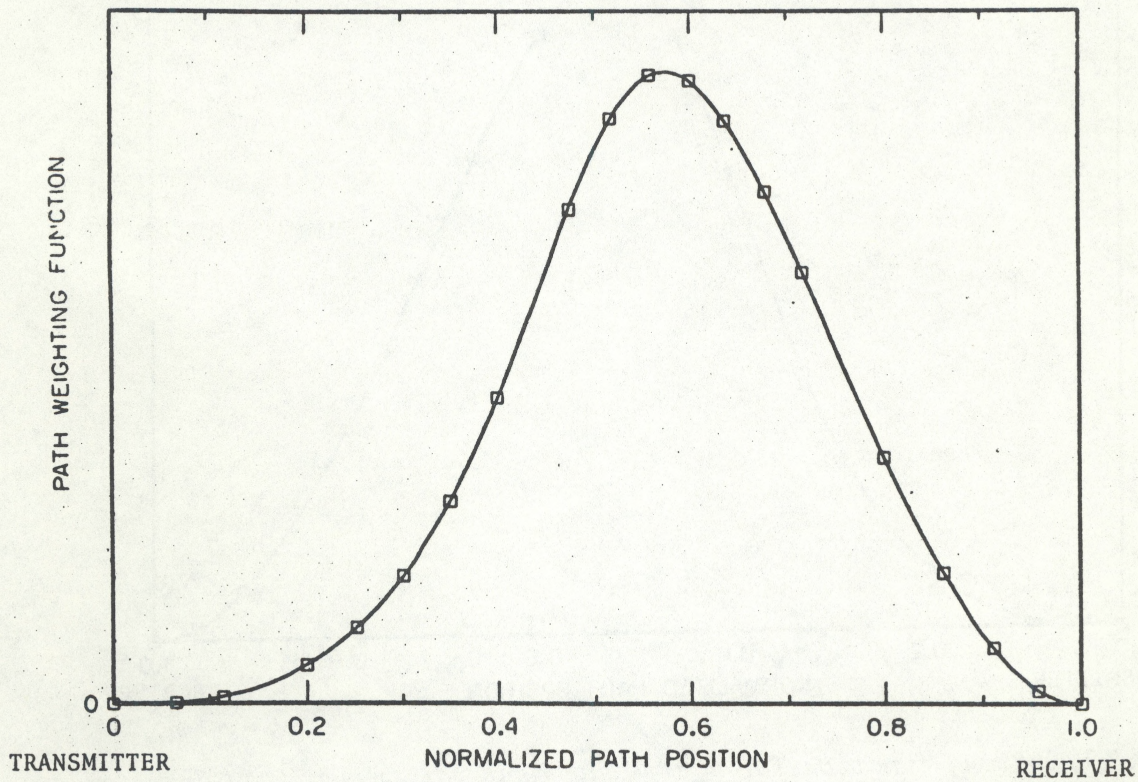

Fig. 6. Weighting function for C_n^2 measurement for D_t=5 cm, D_r=4 cm, D_{sep}= 4 cm.

the single-transmitter value, but there is a net S/N advantage, especially for longer optical paths. It should be noted that similar improvements in S/N can be obtained by using a larger transmitter. In this case, of course, the weighting function is altered. In Fig. 7 we show the weighting function for a 15-cm diameter transmitter, and two-aperture 5-cm receivers. The signal is 9 times larger and the log-amplitude variance .208 that of the same system using a 5-cm transmitter. Larger irregularity sizes are observed and there is greater resistance to saturation, although an exact calculation has not been made.

Figure 8, reproduced from ref. 1, shows that the single-aperture system observes both larger sizes and a greater range of sizes of irregularities, as compared to a two-aperture system with the same diameter optics. Again there are advantages and disadvantages. In many applications, the observation of larger irregularities relative to aperture size is desirable; however the large-scale "tail" of the response can extend to outer scale sizes, outside the inertial subrange.

3. INSTRUMENT CIRCUIT DESIGN CONSIDERATIONS

Reference 3 contains a detailed description of the C_n^2 instrument and the principle of operation. The following discussion concerns design considerations and changes that have been made to the original circuit.

We wish to precisely observe the small amplitude fluctuations imposed by the atmosphere upon a distant light source. If the light source is modulated, it is easier to distinguish it from noise. This modulation or carrier frequency must be far enough from the atmospheric amplitude fluctuation frequencies so that it can be completely removed in the detection process. A 30 kHz carrier frequency was chosen for the original system. Even with this relatively low frequency, it is not easy to build a high-gain amplifier with automatic gain control that is sufficiently linear.

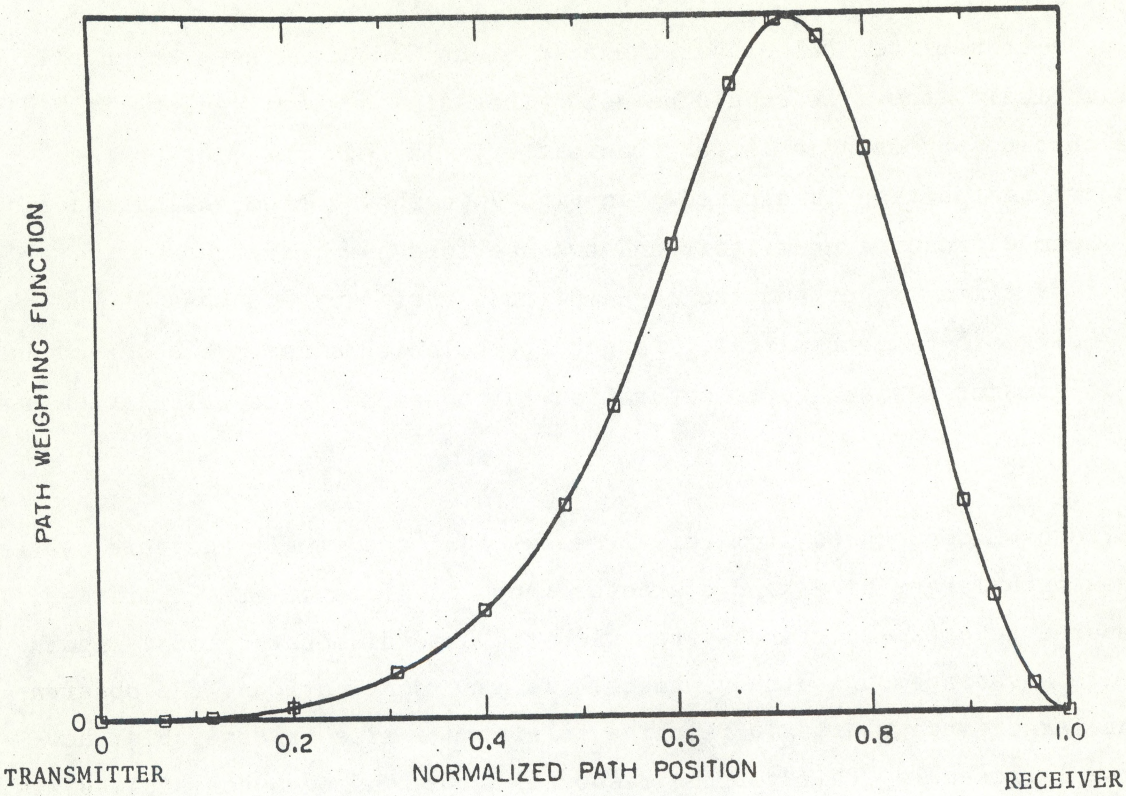

Fig. 7. Weighting function for C_n^2 measurement for D_t=15 cm, D_r=5 cm, D_{sep}=6.7 cm, and L=500 m.

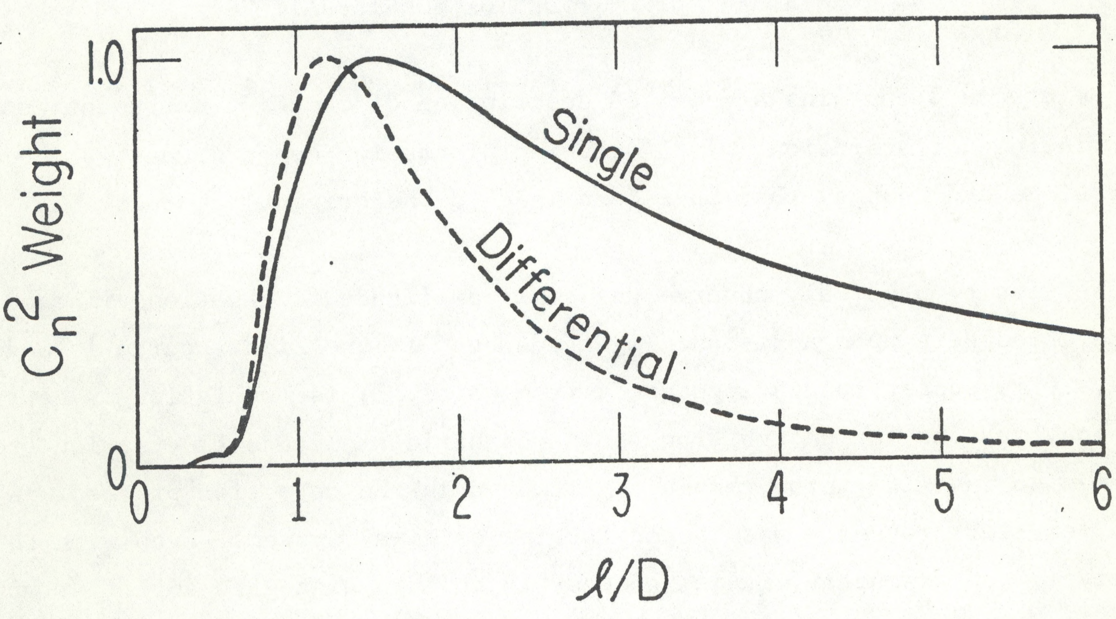

Fig. 8. The C_n^2 weighting versus the eddy size normalized to the receiver aperture size. Solid-line: for single detector. Dashed-line: for two equal-aperture tangent detectors.

For the best S/N, the bandwidth of the instrument should be no larger than absolutely necessary. The noise background is not important at high C_n^2 levels, but it determines the lowest C_n^2 levels that can be read. From Fig. 8, it can be seen that for the two-aperture system, the frequency range for a given wind speed v and aperture diameter D, the frequency range should be about v/.6D to v/6D for the two aperture systems; and to about v/10D for the single aperture systems. For a wind speed range of 0.5 to 10 m/s, the bandwidths required are listed in Table 1.

Table 1.

System	Required Bandwidth
5 cm single aperture	1 - 330 Hz
5 cm two aperture	1.7 - 330 Hz
15 cm single aperture	0.3 - 110 Hz
15 cm two aperture	0.5 - 110 Hz

The smaller bandwidth required for the 15 cm system is an advantage, although it would not seem to be, since a longer time would be required by the 15 cm system to obtain the same measurement accuracy, due to the lower scintillation frequency. However, because of the intermittancy of atmospheric turbulence, both systems require about the same averaging time, much longer than the signal frequency requirement alone.

In the systems, the bandwidth of the signal is limited by predetection filtering on the carrier, averaging of the square of the signal in the detector, and post-detection filtering. Some changes have been made to enlarge the passbands. A wider pre-detection filter reduces errors caused by a transmitter frequency not exactly tuned to the receiver passband and/or a distorted receiver passband. Some signal reduction occurred in the original systems at wind speeds above 5 m/s; there is less reduction in the modified systems, but some reduction is still present as a reasonable compromise with the minimum readable C_n^2 value.

The precision, that is, the repeatability of the C_n^2 measurement can be determined easily by operating a number of units side by side. The absolute accuracy of the C_n^2 measurement is another matter. In this report the optical C_n^2 meter measurements are compared to C_n^2 values derived from fine-wire thermometer measurements of C_T^2, the temperature structure parameter. A uniform optical path is required so that the space average of the optical measurement can be compared to a time-averaged point measurement. The time average of C_n^2 determined by the two methods is then compared. The time average should be at least as long as the time taken for the wind to blow the length of the optical path. In most cases we have used 15-min averages for comparison.

Most of the comparisons were made using the tungsten filaments from 3 watt 120 volt pilot light bulbs as the temperature sensing element, with a frequency response correction made according to ref. 4. Shorter runs were made using platinum filaments 2.5 μm in diameter, and reasonable agreement was obtained with the corrected tungsten filament readings. No corrections were applied to the platinum filament readings. It is possible that filament support wire effects make the derived C_n^2 reading 5 to 10% low, however.[5] The calibration of the optical C_n^2 meter is based upon the existence in the atmosphere of a Kolmogorov spectrum of turbulence within the inertial subrange. Perturbations from this spectrum can be significant, however, especially in the region just above inner scale sizes.[6,7] Ideally, the fine wire measurement should observe the same spectrum of spatial sizes as the optical C_n^2 meter. This is most closely satisfied with a differential thermometer separation of .7 to 1 times the C_n^2 meter aperture diameter. The required spacings for the 5 cm units are not practical using the 3 watt filament probes, however.

Calculations[6] and the experiments agree that the saturation criteria given in reference 1 is not restrictive enough. For example the maximum path lengths should only be about one-half those specified earlier. These changes are included in the instruction book revisions.

Values of C_n^2 vary over orders of magnitude so an output voltage proportional to C_n^2 is not provided. Instead two outputs are available, one in which the output voltage is proportional to the square root of C_n^2, and the other having a voltage output proportional to the logarithm of C_n^2. Both outputs are averaged over approximately one second. If either of these outputs are digitally recorded then the recommended technique is to compute C_n^2 from one-second samples and average these values. One obtains different values of C_n^2 depending on whether one averages the square-root-C_n^2 output or the logarithmic-C_n^2 output. There is little difference between the two methods of averaging if the averaging time is not too long. In Fig. 9 the ratio of logarithmic to linear averaging is shown for real data taken on a 500-m path. There is little difference, as long as the averaging time is only a few minutes.

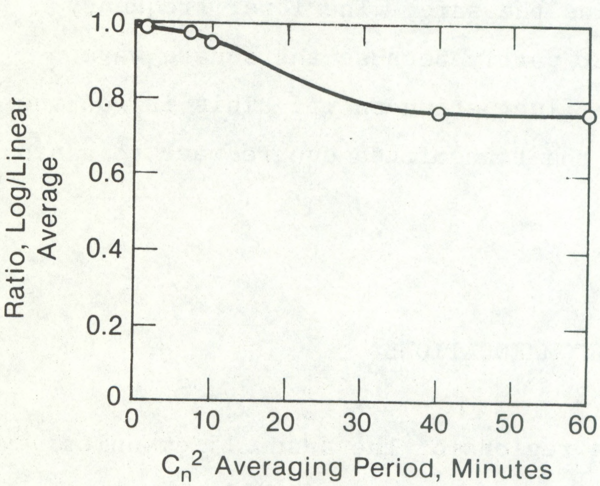

Fig. 9. Linear and logarithmic averaging of C_n^2.

4. DISCUSSION OF INSTRUMENT MODIFICATIONS

Some changes in the original 5 cm instrument have been made as a result of this study, but the basic circuit principle remains the same. The original optical system left the binocular intact and placed the photodiode at the exit pupil focus. Some vignetting of the objective occurred with this arrangement. In the new system, the eyepiece is removed and the photodiode is placed about 2 mm back of an aperture in the focal plane. The new system has a somewhat smaller field of view with a resulting S/N improvement but in fact the effective aperture diameter is still about the same. With the smaller field of view, a rifle scope has been added for convenience in pointing. The preamplifier circuitry has also been changed, with the first stage having much higher gain (2 megohm feedback resistor). A servo loop removes the DC offset current from background light that would otherwise saturate the amplifier.

A decision was also made to change the modulation frequency from 30 kHz to 7 kHz and do very little predetection filtering. Several observations prompted this change. It was discovered that differences in tuning had an effect on the calibration because of changes in the amplitude of the signal sidebands, as noted in the preceeding section. A second problem concerned nonlinear feedback, that was more easily eliminated with a lower frequency carrier. Also more signal power is received from the square-wave carrier with a wider predetection bandwidth. The noise is increased very little as the post-detection signal bandwidth remains the same. The lower frequency carrier is no more difficult to filter out partly because the square wave signal after detection has little carrier fluctuation on it. This is not the case when predetection filtering changes the transmitted square wave to a sine wave.

5. RESULTS AND RECOMMENDATIONS

Figures 10 and 11 show the operating regions of the 5 and 15 cm units. The lowest C_n^2 value that can be read is limited by low scintillation at the shorter path lengths; past the optimum path length, signal attenuation limits the reading. The broad line is due to differences in background light levels. The combined effects of the various circuit changes have lowered the low signal limit by about a factor of 5. It should be remembered, however, that shorter path lengths require vibration free mounts to realize the lower limits, as the scintillation is very small. On long path lengths, the maximum C_n^2 values are limited by saturation.

One can obtain greater dynamic range with the 15 cm unit, if longer path lengths are useful. As discussed earlier, the 5 cm units have their peak response for spatial wavelengths around 6 cm. This is an advantage if one

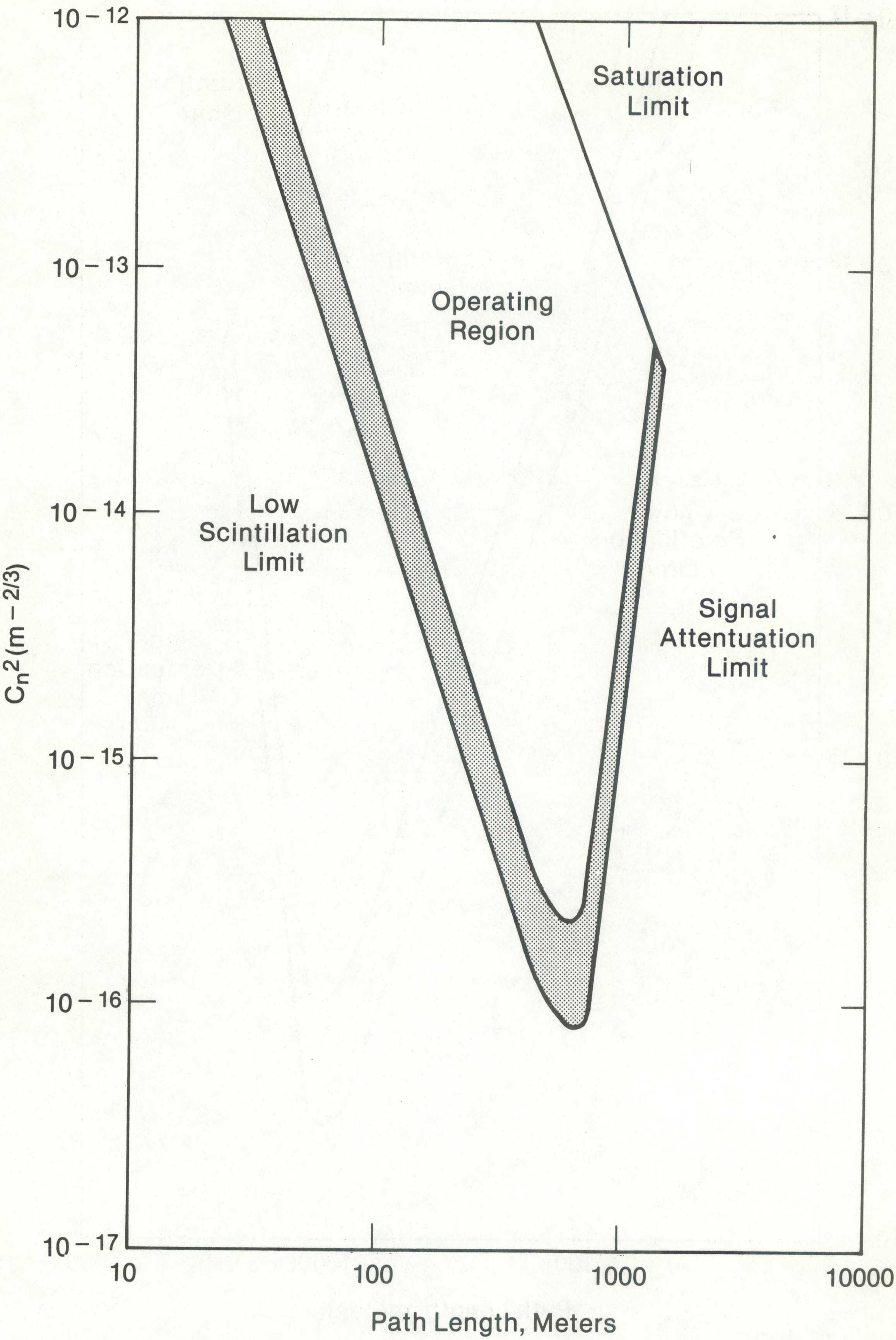

Fig. 10. Operating region of the 5 cm unit as a function of C_n^2 and path length.

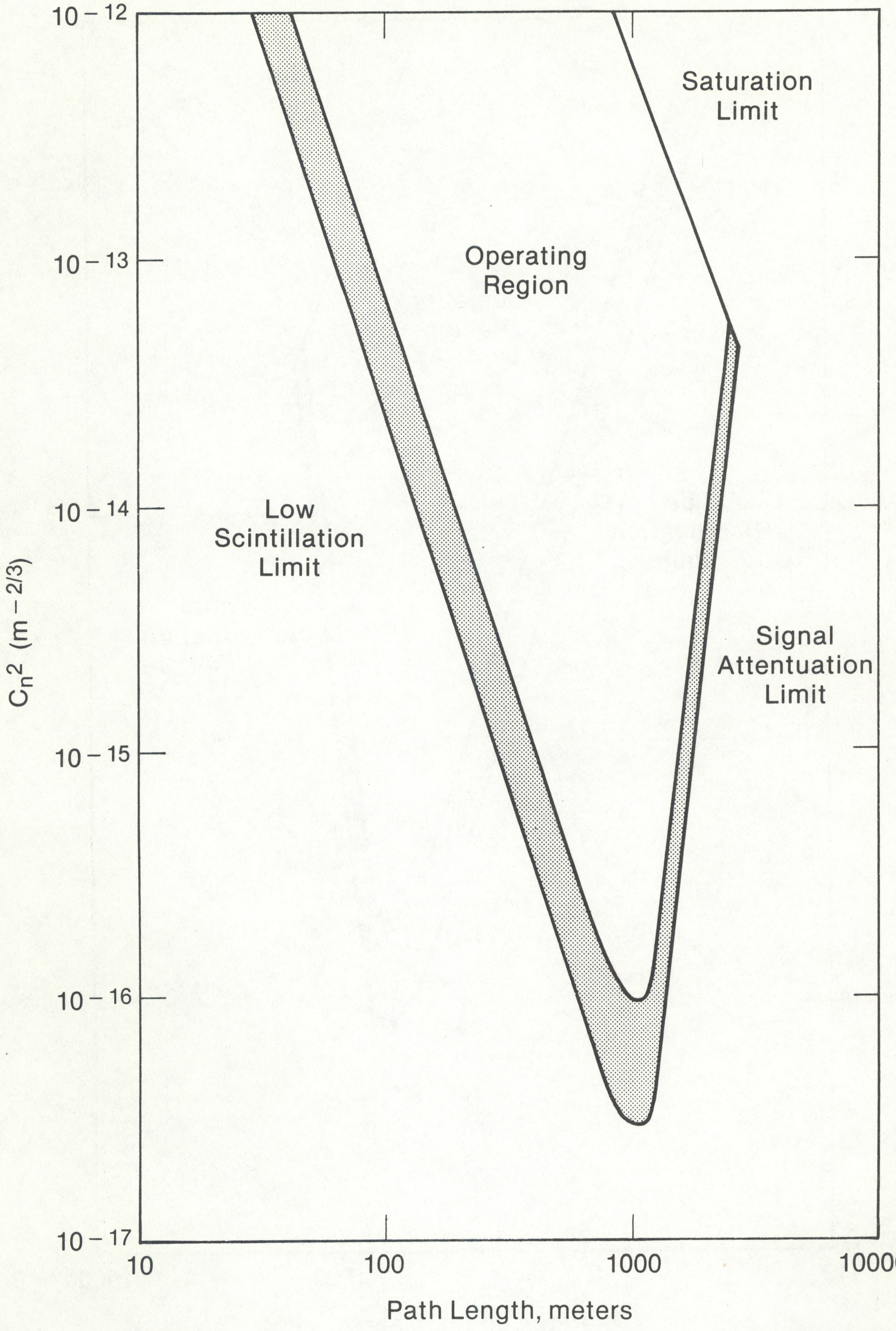

Fig. 11. Operating region of the 15 cm unit as a function of C_n^2 and path length.

wishes to relate the C_n^2 measurement to the performance of optical systems sensitive to this atmospheric spatial wavelength region. This region has sizeable departures from the Kolmogorov spectrum of turbulence, however, and it varies with inner scale size.[6] Also, the inner scale size increases with height above ground. Thus if the larger scale sizes are of interest, it is better to measure using larger apertures. If only one aperture is used, the spectral sensitivity moves toward larger spatial sizes, as shown in Fig. 8. A better solution is to use one or two 15 cm apertures, however, as these extend to much larger spatial sizes, and the signal strength increases as D^4.

The accuracy with which the instruments measure C_n^2 is of primary interest. We use C_n^2 derived from a fine-wire temperature measurement as the standard. Most of the measurements have been made using tungsten 3 watt light bulb filaments as the temperature sensing element, and frequency response corrections have been made according to ref. 4 for a 20-cm spacing. Some measurements have also been made using platinum wires 2.5 μm in diameter and about 2 mm long. Comparisons between the two systems verify the corrections used for the tungsten elements. The 2.5 μm wires are supported by the unetched Wollaston wire and no correction has been applied for end effects or effects of support wires, both of which would decrease the reading. We use .00385 for the temperature coefficient of resistance for platinum which is readily verified. Of less certainty is how well a point measurement represents C_n^2 over the weighting function of the optical measurement.

Since the calibration depends on the effective diameter of the optics, several methods were devised to determine the intensity distribution of light across the transmitting aperture, and the sensitivity across the receiving aperture of the revised system. Long light paths were used so that if the angular spread of each point on the transmitter aperture or the angular cone of acceptance of each point on the receiver aperture was not sufficiently large, it would be detected in the measurement. A 24-m path was used for the 5 cm system and the transmitter intensity and receiver sensitivity as a function of aperture diameter were determined by passing a 3-mm diameter aperture across the diameter of the transmitter while observing the irradiance of the unobstructed receiver. Similarly, the 3-mm aperture was passed across the receiver to determine the sensitivity pattern. The results are shown in Fig. 12. From these plots we determine an effective diameter for the receiver and transmitter of 4.1 and 4.7 cm, respectively.

The 15-cm measurement was made in a slightly different manner over a 500-m path. For this long a path, there was not sufficient light available through a small aperture, so masks of various diameters were placed in front of the transmitter and receiver, and the square root of the received light

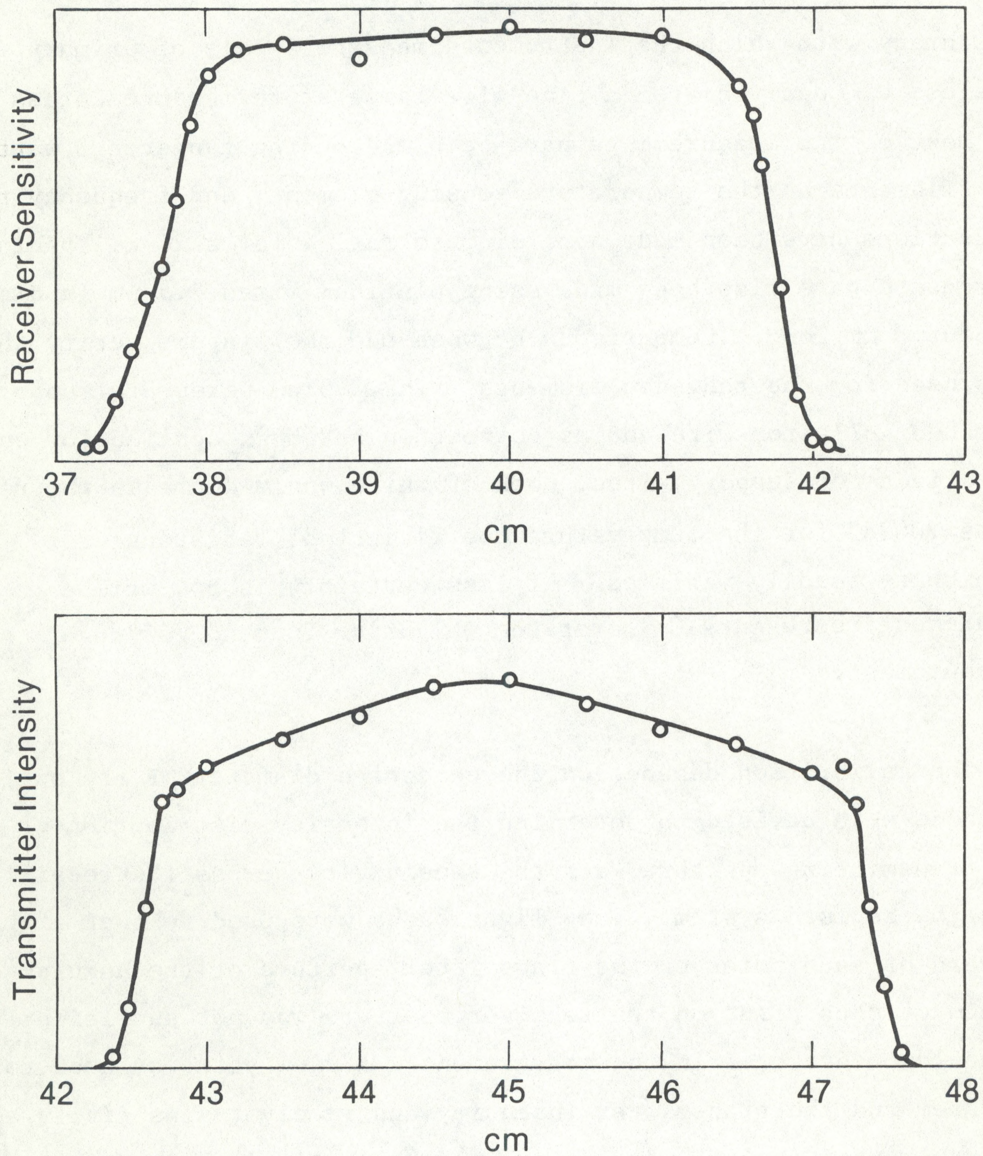

Fig. 12. Crossection of transmitter intensity and receiver sensitivity as a function of diameter for the 5-cm system.

intensity was plotted versus diameter. In these coordinates, a straight line represents uniform light intensity. The results are shown in Fig. 13. Here the effective diameters of the receiver and transmitter, as determined from the break points on the curves, are 14.4 and 14.8 cm, respectively. As a result of these measurements, the effective diameters which are used to compare optical and thermal measurements of C_n^2 using the 5 and 15 cm systems are 4.4 and 14.6 cm, respectively.

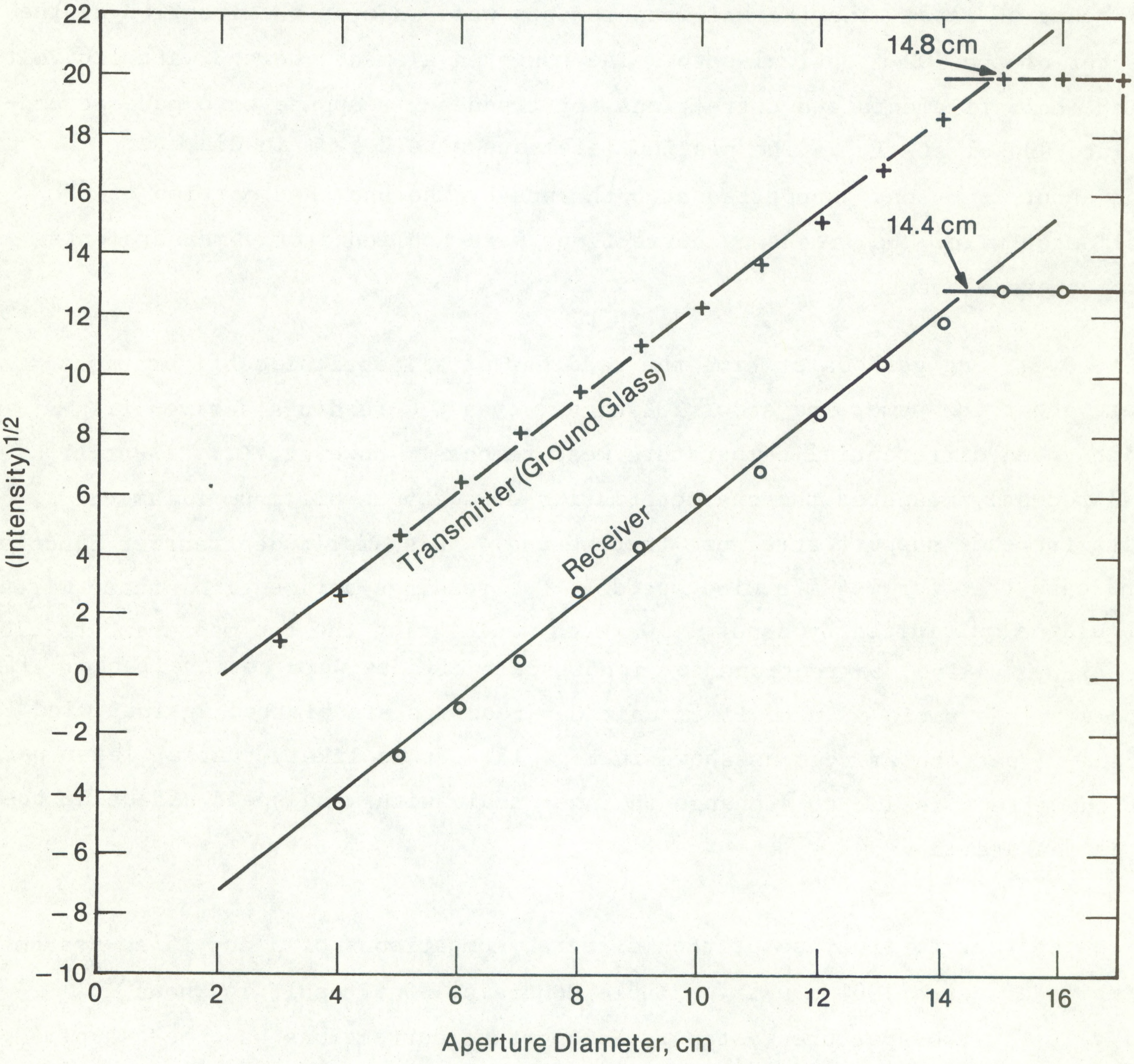

Fig. 13. Transmitter intensity and receiver sensitivity as a function of diameter for the 15-cm system.

A typical comparison on a 500-m path is shown in Fig. 14. The aperture corrections have not been applied to this data. Number 1 denotes the 2-aperture 5 cm system, 2, the 2-aperture 15 cm system, and 6 is the C_n^2 value derived from 3 watt tungsten filaments spaced 20 cm vertically, with frequency corrections applied.

A summary of thermal and optical measurements of C_n^2 at Table Mountain is tabulated in Table II. Except as noted, each entry is an average of about 24 hours of data. The thermal measurements were made at one location at the center of the 500-m optical path. The tungsten elements were 3 watt 120 volt light bulb filaments and corrections for frequency response were made according to Kunkel et al.[4] The platinum elements were 2.5 μm in diameter and about 2 mm long, supported at both ends by the unetched portion of the Wollaston wire. No frequency corrections were applied at the measurements from these elements.

Over long periods of time the readings of all optical configurations were about the same, and about 20% higher than C_n^2 readings derived from high-speed differential temperature measurements. However, Dr. C. Petit has recently measured the characteristics of a 2.5 μm platinum filament with the same support structure that we use.[9] His amplitude transfer functions indicate that for 1-4 m/s wind speeds, C_n^2 readings derived from these wires should be multiplied by about 1.10 which would bring the two measurements closer together. Also, corrections for inner scale effects were not available. If, however, the ratio of 5 to 15 cm unit C_n^2 readings are plotted against wind speed, a pattern emerges as shown in Fig. 15. It is likely that at least part of the effect is due to a change in inner scale with wind speed affecting the 5 cm measurement.

In order to study saturation effects, comparisons of 5 and 15 cm systems were made over a 1000-m path on Table Mountain. One result is shown in Fig. 16 for two-aperture systems. No aperture corrections have been applied. Some effect on the 5 cm readings is seen above $C_n^2 = 1 \times 10^{-13}$, and complete saturation occurs at 2×10^{-13}. By the criterion of ref. 1, the 5 cm C_n^2

measurement should be good to $C_n^2 = 5 \times 10^{-13}$, which is obviously too optimistic. If $C_n^2 = 1 \times 10^{-13}$ is taken as the maximum value that is read accurately, then Eq. (21) of ref. 1 becomes

$$\alpha_r + \alpha_t > 5.4 \, (\sigma_T^2)^{3/5}$$

which is in reasonable agreement with the predictions of ref. 6.

Except for the more stringent saturation criteria, the experiments verify the calibration as well as can be expected. It should be noted, however, that new instrument calibrations are required, based upon the measured effective diameters of the 5 and 15 cm units (actually 4.4 and 14.6 cm, respectively). These same calibrations are applicable to the original instruments, i.e., data taken using the original calibrations should be multiplied by $(\frac{4.4}{5})^{7/3} = 0.74$ for the 5 cm system and $(\frac{14.6}{15})^{7/3} = 0.94$ for the 15 cm system.

This study indicates that for most applications, a system utilizing 15-cm diameter optics and a single-aperture receiver is the best choice. The largest dynamic range (C_n^2 values from 10^{-12} to 10^{-16}) is obtained for path lengths of about 800 m.

Table II

Date 1982	Path Length m	Ratio $C_{n\,OPT}^2/C_{n\,TEMP}^2$ 5 cm 1-AP	5 cm 2-AP	15 cm 1-AP	15 cm 2-AP	Wind m/s	Remarks
2/17-2/18	1000					0.8	Saturation study
4/13-4/24	500		1.10		1.18	1-3	W, 20 cm
5/ 6-5/ 7	500		1.19		1.07	0-3	W, 20 cm
5/18-(42 min)	500		1.29	1.16		1.3	Pt, 20 cm
6/ 4-6/ 5	500		1.20			1.5	W, 20 cm
6/ 5-6/ 6	500		1.08			3.9	W, 20 cm
6/ 8-6/ 9	500		1.11			1.6	W, 20 cm
6/10-6/11	500		1.40			1.3	W, 20 cm
6/19-6/20	500		1.36		1.43	1.4	W, 20 cm
6/20-6/21	500			1.26		1.4	W, 20 cm
6/22-(3 hr)	500	1.17		1.14		1.3	Pt, 10 cm
6/27-6/28	500		1.04			0.9	W, 20 cm
Average		1.17	1.20 ± .13	1.19 ± .06	1.23 ± .18		

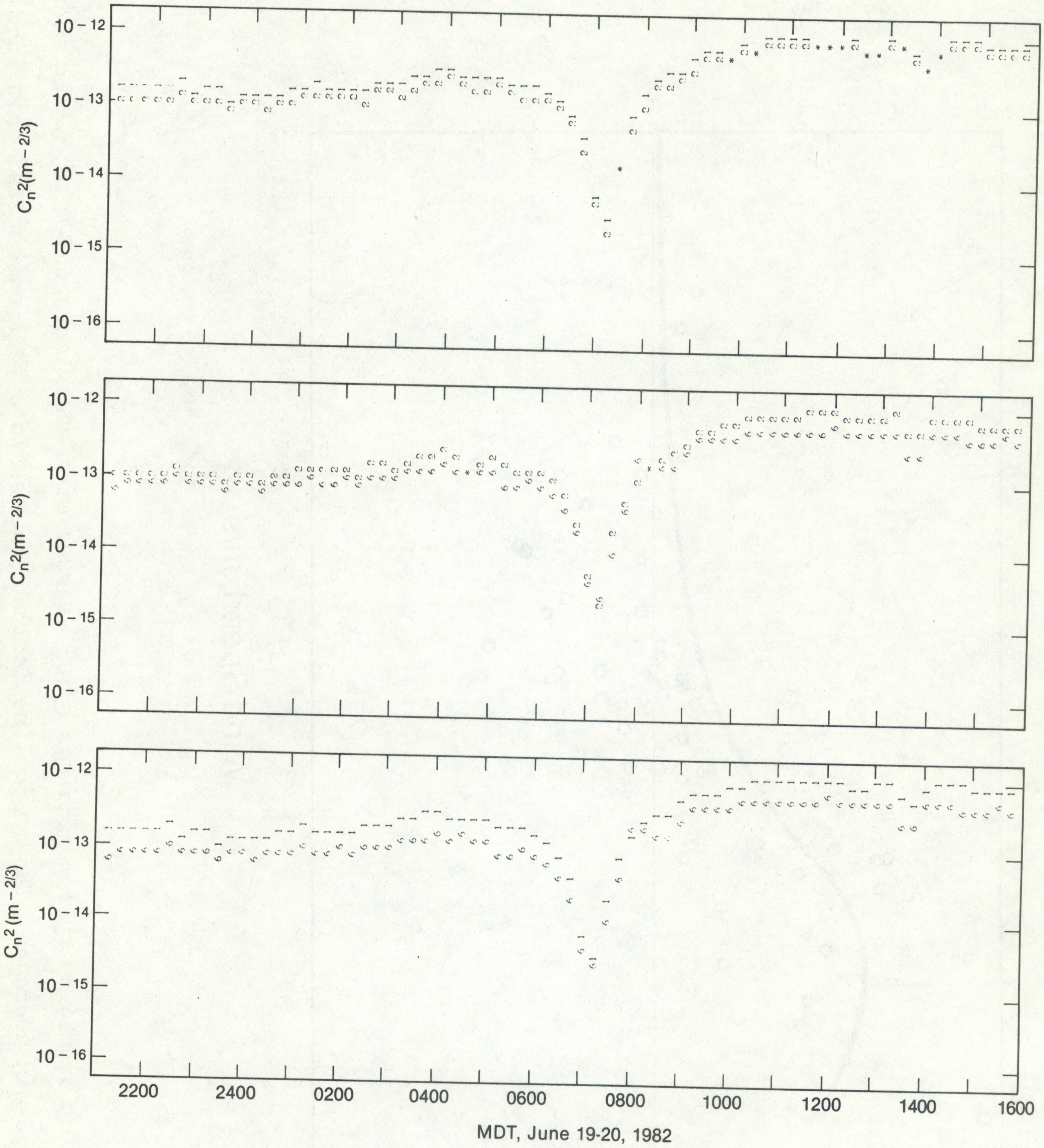

Fig. 14. Comparison of C_n^2 measurements derived from optical and fast thermometer techniques. Aperture corrections have not been applied to this data. Number 1 denotes the 2-aperture 5 cm system, 2 is the 2-aperture 15 cm system, and 6 is the C_n^2 value derived from 3 watt tungsten filaments spaced 20 cm vertically, with frequency corrections applied.

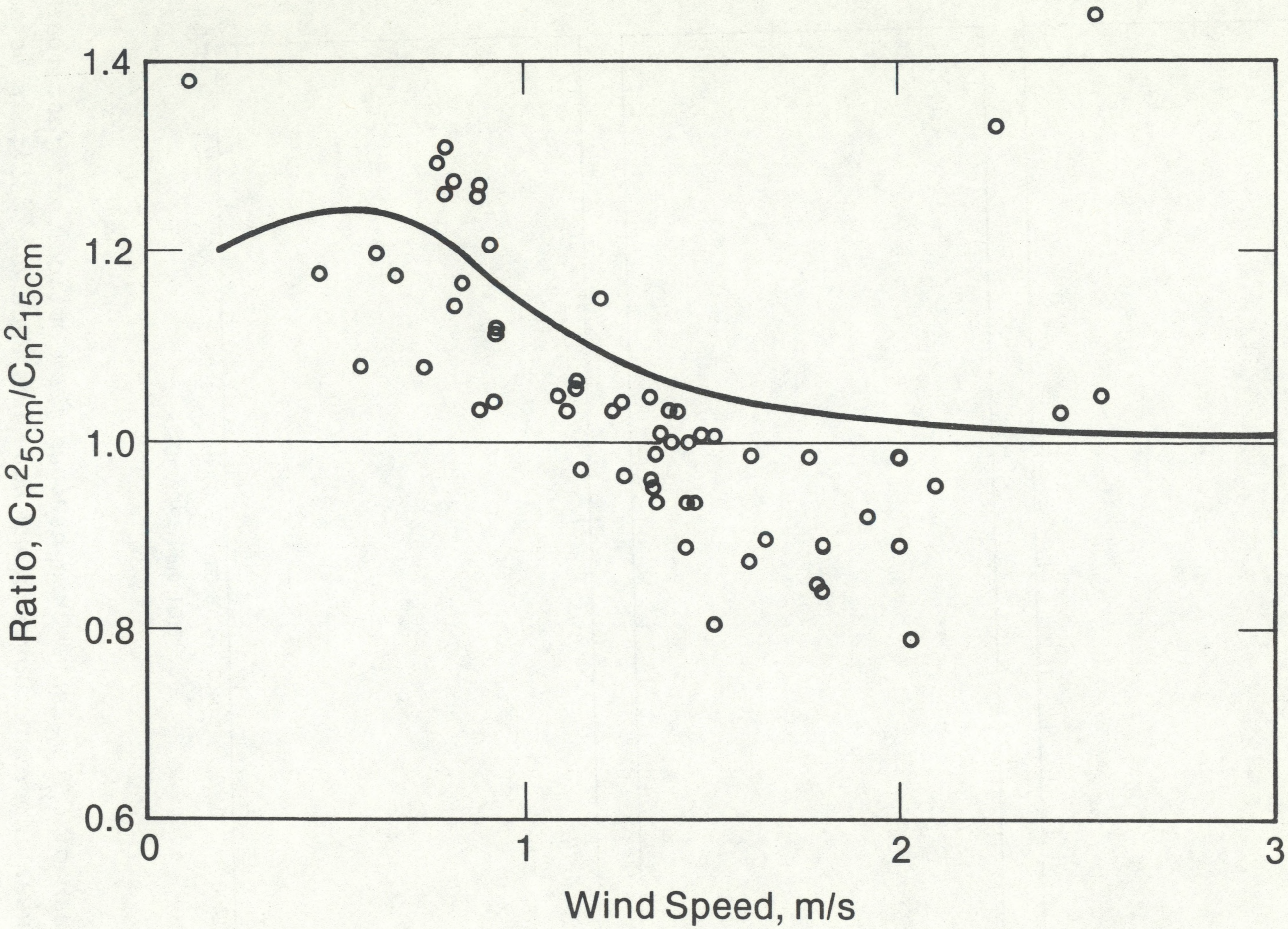

Fig. 15. Ratio of 5 cm and 15-cm system readings of C_n^2 versus wind speed on a 500-m path. Each data point is a 5-min average. The solid line is the inner scale effect calculated from Fig. 3 of reference 7, using an estimate of inner scale from Table I of reference 8.

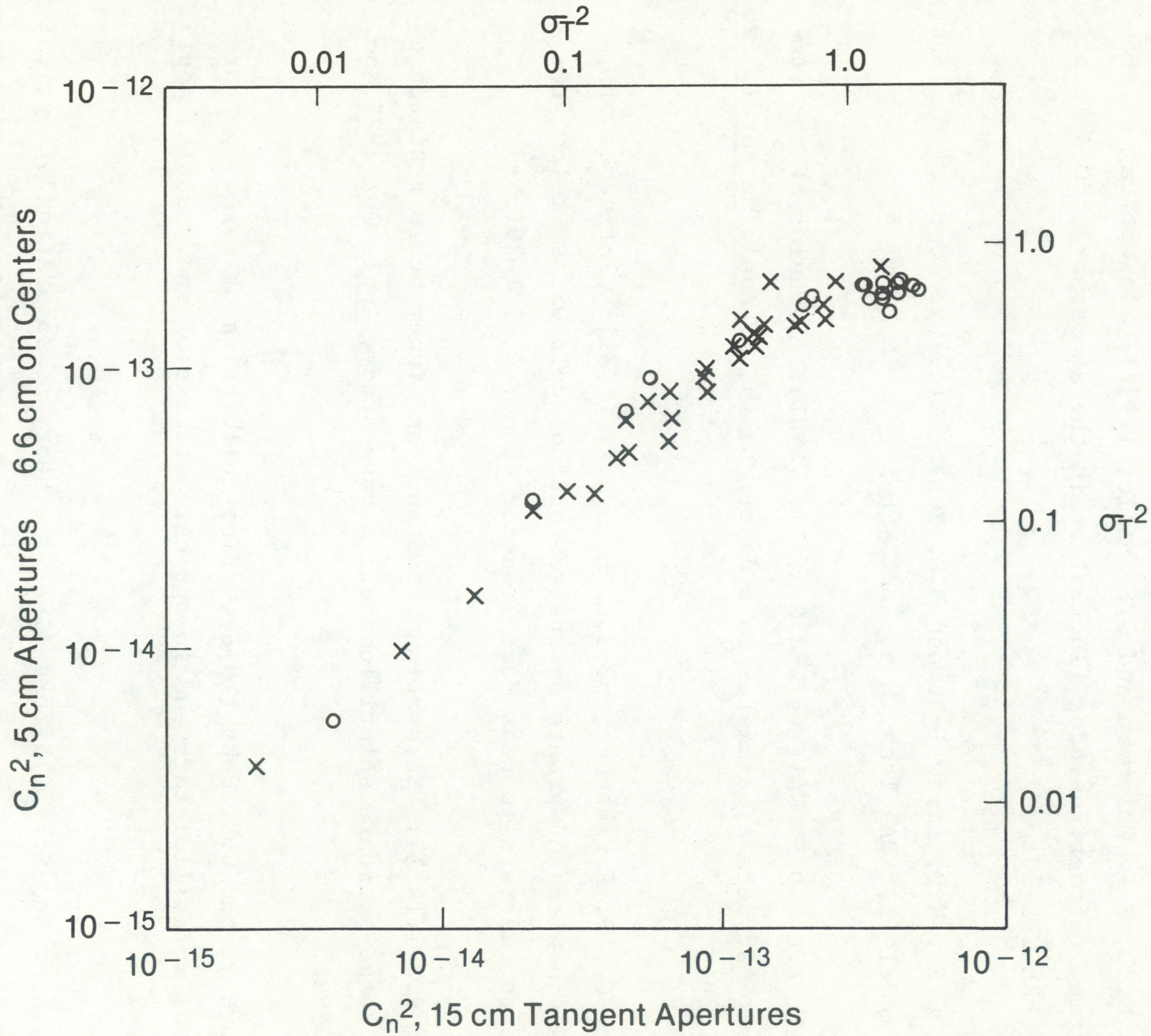

Fig. 16. Comparison of 5 and 15 cm dual-aperture scintillometers on a 1000-m path. A circled dot indicates a 15-min daytime average; an X indicates a 15-min nighttime average.

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