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REMOTE ATMOSPHERIC PROBING BY GROUND-TO-GROUND LINE-OF-SIGHT OPTICAL METHODS

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ABSTRACT

We describe qualitatively the optical effects arising from refractive-index variations in the clear air and discuss the possibilities of using those effects for remotely sensing the physical properties of the atmosphere. The effects include scintillations, path-length fluctuations, spreading of a laser beam, deflection of the beam, and depolarization. The physical properties that may be measured include the average temperature along the path, the vertical temperature gradient, and the distribution along the path of the strength of turbulence and the transverse wind velocity.

Line-of-sight laser-beam methods are clearly effective in measuring the average properties, but less effective in measuring distributions along the path. Fundamental limitations to the resolution are pointed out and experiments are recommended to investigate the practicality of the methods.

1. INTRODUCTION

This paper deals with the optical effects arising from variations of the refractive index of the clear atmosphere. It does not consider the effects of absorption or scattering by either aerosols or molecules. Thus, there will be no discussion of radiometry, spectroscopy, or spectrophotometry.

The atmospheric effects that remain include the modification of the optical path by the mean refractive index along the line of sight and the distortion of an optical wave by the temporal and spatial variations in the refractive index. Sections 2 through 4 summarize those atmospheric effects that may be relevant to the problem of remote probing. The remaining sections describe briefly some methods for using the effects.

2. EFFECTS OF TURBULENCE

2.1 The Refractive-Index Variations

The twinkling of stars and the variable blurring of their images in a telescope are caused by the small-scale and rapidly varying density fluctuations associated with atmospheric turbulence. Density is the pertinent physical property because the optical refractivity, n-1, is proportional to density. In the open atmosphere the variation in density of a small parcel of air depends only on variation of its temperature because pressure differences are smoothed out with the velocity of sound. Thus, in what follows, we shall be safe in making no distinction between the refractive-index fluctuations and the temperature fluctuations. Notice, however, that these fluctuations are not necessarily identical to the velocity fluctuations measured by the hot-wire probes so commonly used in studies of turbulence. If the atmosphere is in neutral thermal stability, i.e. if the temperature lapse rate is adiabatic, strong mechanical turbulence may exist with little or no optical effect.

The direct relationship between temperature fluctuations and optical effects suggests the use of small, high-speed thermometers to measure directly the strength and the structure of turbulence as it affects light waves. Resistance thermometers having dimensions less than a millimeter and response times less than a millisecond are regularly used by ERL in Boulder to "calibrate" the atmosphere whenever optical measurements are in progress (see Ochs, 1967).

As we shall see later, the thermal irregularities that are most effective in producing optical effects range in size from a few millimeters to about ten centimeters. Over this range of sizes, and indeed to much larger scales, the turbulence follows closely the Kolmogorov-Obukov model which predicts that the power spectrum of temperature fluctuations will vary as the -5/3 power of the wave number. Measurements made at Boulder have shown the "inertial sub-range," in which the -5/3 spectrum holds, to extend to irregularities as small as 2 or 3 mm. At smaller sizes, the spectrum steepens as viscous damping destroys the turbulence.

2.2 Intensity Effects on a Light Wave

Let us consider the behavior of a light wave as it travels outward from a point source through the turbulent atmosphere (Figure 1). The wave front is initially spherical, as at A. Upon passing through irregularities to reach position B it becomes distorted. Since absorption and wide-angle scattering are negligible, the energy density of the wavefront B is still uniform and equal to its free-space value. Thus an ordinary square-law detector located at B would be unaffected by the irregularities and incapable of measuring them. The irregularities in the wave front can, of course, be measured by a phase-sensitive detector such as an interferometer.

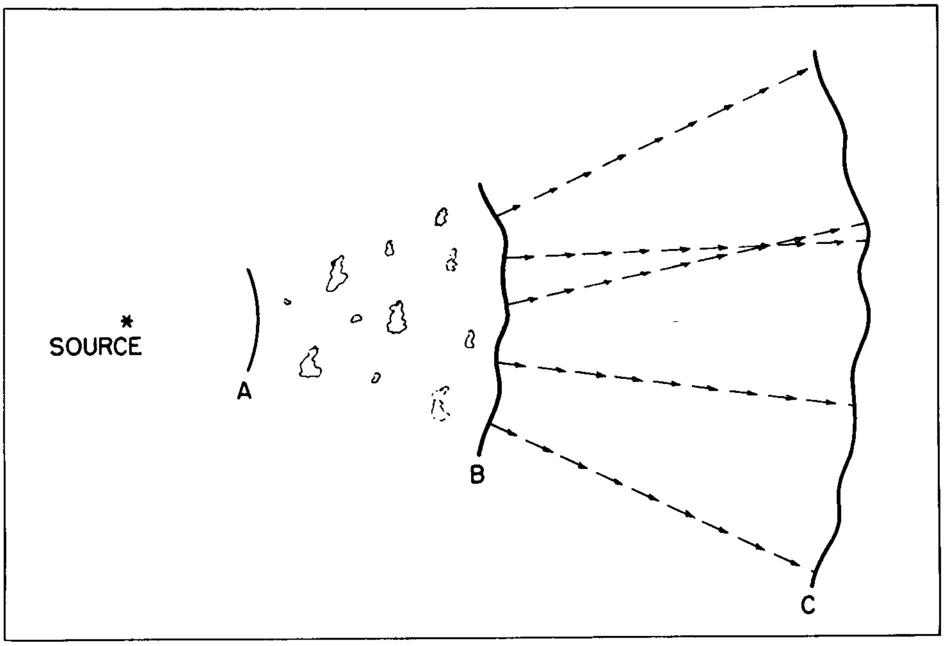

Figure 1. Schematic diagram of the propagation of a spherical light wave through a turbulent atmosphere. Phase fluctuations at B develop into phase and intensity fluctuations at C.

As the wave progresses from B toward C, the various portions of the distorted wave front travel in slightly different directions and eventually begin to interfere. The interference is equivalent to a redistribution of energy in the wave and causes intensity fluctuations (scintillations) which can be detected by a square-law detector. On the way from B to C the wave front passes through additional refractive-index irregularities and so suffers additional phase perturbations. These new irregularities are, however, relatively ineffective in producing intensity fluctuations.

Let us examine the criteria that determine which of the turbulent irregularities along a line of sight are most effective in producing intensity fluctuations. In Figure 2, consider an irregularity of radius r at an arbitrary point A on the line of sight between the source S and the receiver R. That irregularity can be fully effective in producing intensity variations only if the extreme ray paths, SAR and SBR, involving it differ in length by at least half a wavelength, i.e. the irregularity must be at least equal in size to the first zone of a Fresnel zone plate situated at A. This minimum effective size is, in fact, the optimum size for the irregularity. Larger irregularities at the same point are rendered ineffective by the smaller ones just as a lens is rendered ineffective by a ground-glass surface.

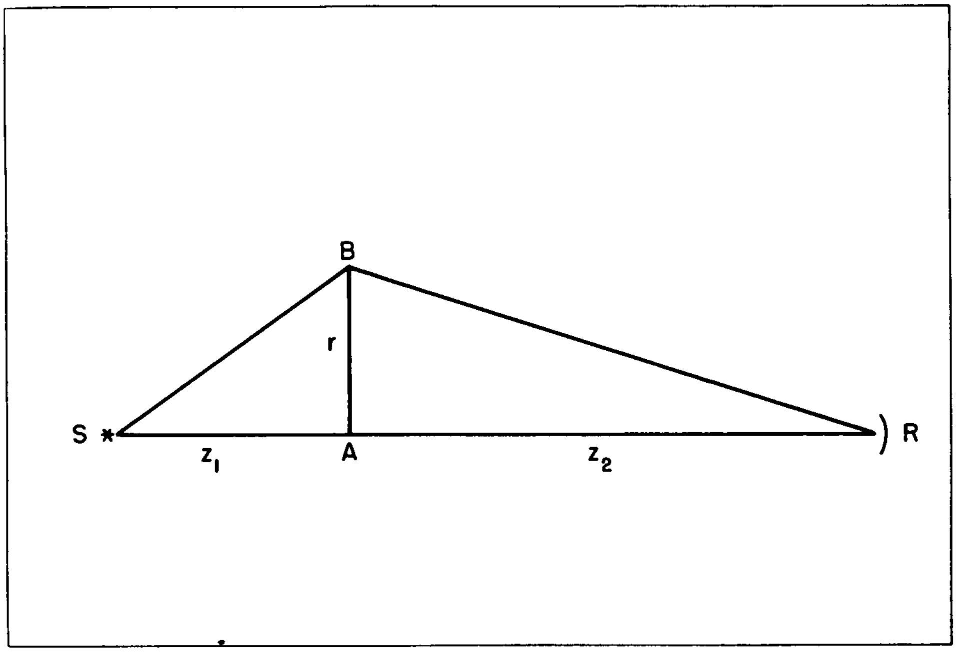

Figure 2. The geometry involved in determining the irregularity size most effective in producing scintillations.

Working out the geometry of Figure 2, we find that the radius of the most effective irregularity is $r \approx \sqrt{q\lambda}$, where λ is the wavelength and $q = \frac{z_1 z_2}{z_1 + z_2}$ depends upon the position of A. This radius is plotted in Figure 3 for a wavelength of 6328 Å and a path length of 10 km.

If we assume, for the moment, that the turbulence is uniformly distributed along the path and has a Komogorov spectrum, it is clear that the mean-square fluctuation of refractive index attributable to irregularities of optimum size varies systematically along the path. There is, therefore, a weighting function that expresses the relative effectiveness of turbulence in producing intensity fluctuations as a function of position along the path. From Figure 3 it is clear that this weighting function must reach a maximum at the midpoint of the path and must drop symmetrically to zero at the ends. An expression for this function has been derived (Fried, 1967a). It is

$$E = \int_0^{-\infty} x^{-11/6} \sin^2\left(\frac{q\lambda}{4\pi} x\right) dx \;.$$

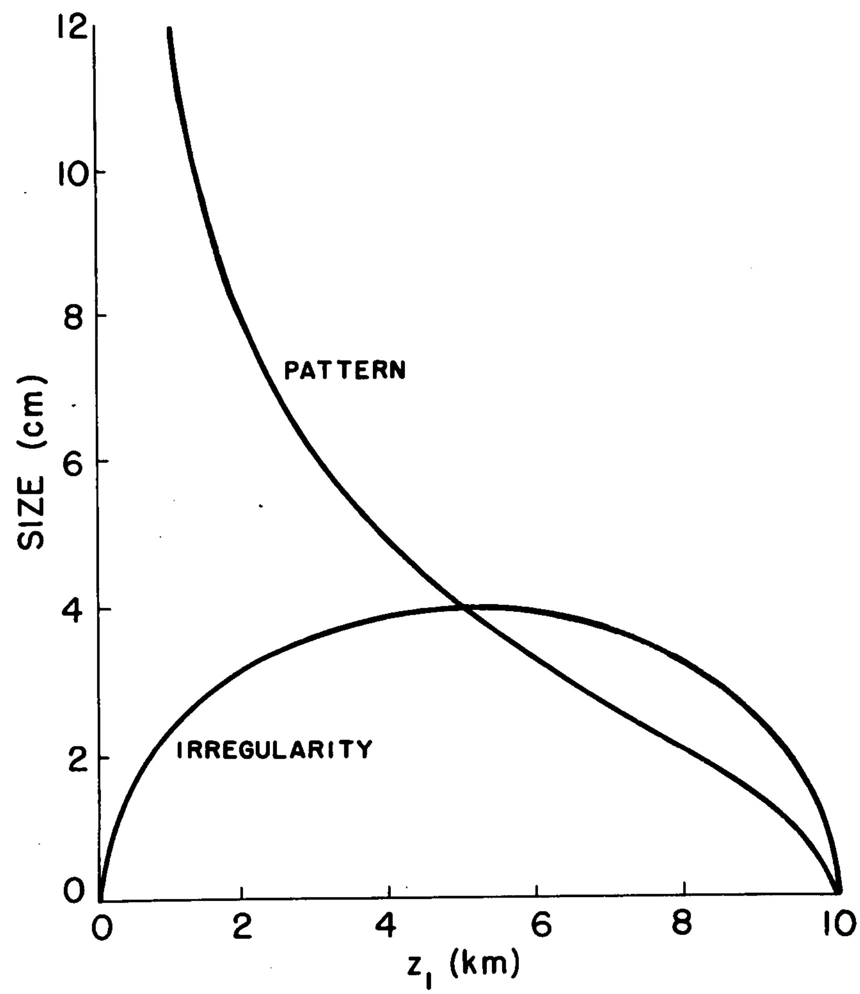

Figure 3. The radius of the most effective irregularity at various points along a 10 km path, and the resulting pattern size.

Figure 4 compares this integral, evaluated numerically as a function of position along the path, with the best-fitting parabola. In summary, the relative effectiveness of a uniformly turbulent atmosphere in producing intensity scintillations is approximately a parabolic function of position along the path, being a maximum at the midpoint and zero at the ends.

Next, let us examine the scale sizes of the intensity patterns at the receiver due to the optimum-sized refractive-index irregularities located at various points along the path. Referring to Figure 5 and recalling that the

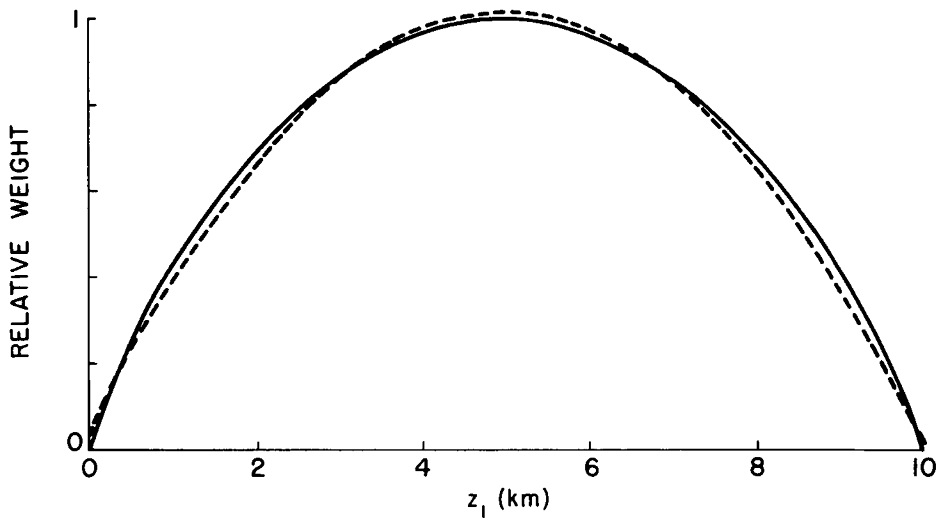

Figure 4. The relative effectiveness of Kolmogorov turbulence at various points along a 10 km path in producing intensity fluctuations. The dashed curve is the best-fit parabolic approximation.

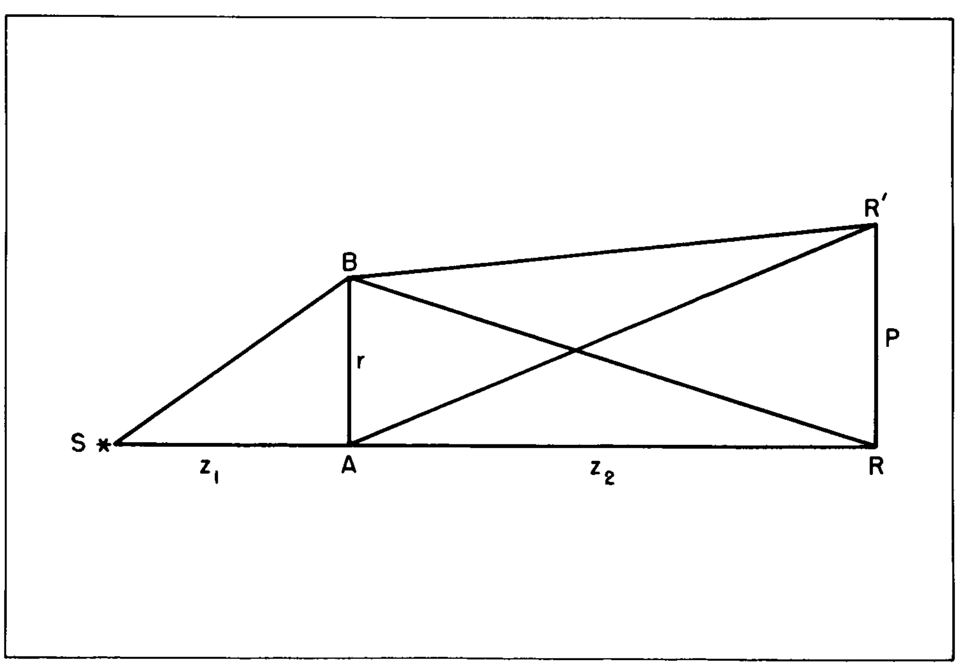

Figure 5. The geometry involved in determining the pattern size produced by the most effective irregularities.

radius r of the optimum-sized irregularity of A was such that SBR exceeded SAR by a half wavelength, we can see that the size p of the pattern at the receiver is determined by the requirement that SBR' must equal SAR'. Then, when destructive interference is present at R, constructive interference will occur at R'. Working out the geometry, we find that the pattern is larger than the turbulent irregularity by the factor $p/r = \frac{1}{2}(1 + z_2/z_1)$. The pattern size p is shown in Figure 3 for a 10 km path.

We have seen that the diffraction process that produces intensity fluctuations in the light wave selects only certain optimum sizes from the broad spectrum of irregularities available in Kolmogorov turbulence. The optimum size selected depends on the position along the path, and each position produces a predominant, and unique, pattern size at the receiver. When the weighting function shown in Figure 4 is combined with the pattern-size function of Figure 3, there results the composite spectrum of sizes observable in the intensity pattern. Notice that, for turbulence distributed uniformly along the path, this composite spectrum of sizes depends only on the wavelength and the path length; it is not indicative of any preferred size of turbulent eddies in the atmosphere. An expression for this spectrum, or rather, its Fourier transform, the covariance function, has been derived by Fried (1967b), and is compared with observational data in Figure 6. In the figure,

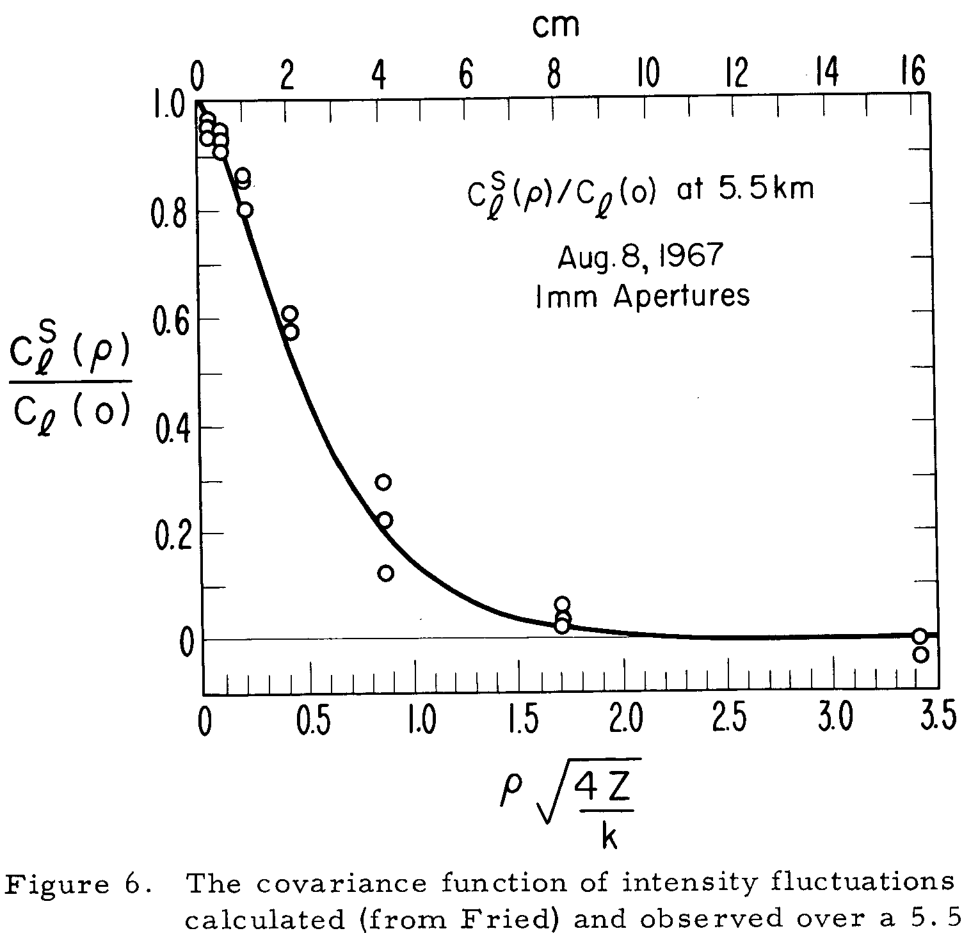

Figure 6. The covariance function of intensity fluctuations calculated (from Fried) and observed over a 5.5 km path.

the normalized covariance of log-amplitude measurements made on spaced detectors is plotted as a function of detector spacing p.

The temporal fluctuations of intensity observed at a point arise from two causes. First, the intensity pattern at the receiver plane is continuously changing in detail because of the random velocities of the various turbulent eddies in the atmosphere. Second, the entire pattern drifts past the detector as the result of the transverse component of the mean wind. The power spectrum of intensity fluctuations is closely related to the spatial spectrum of the intensity pattern, and derived from it by including the effect of the mean transverse wind. As in the case of the spatial spectrum, the power spectrum resulting from uniformly distributed turbulence depends only on the wavelength of the light and the path length, shifted in frequency in proportion to the transverse wind velocity.

Incidentally, though the topic is outside the scope of this paper, the power spectrum changes radically if raindrops enter the beam. This effect has not been investigated but might prove useful in remotely measuring the presence of rain, or maybe even the drop size distribution.

As we have seen, the spectrum of pattern sizes and the power spectrum of temporal fluctuations depend on the wavelength of the light, but they are not ordinarily indicative of any preferred size of turbulent eddies in the atmosphere. Thus, when dealing with a Kolmogorov spectrum of turbulence, we should not expect to obtain independent information by observing on two or more wavelengths simultaneously. However, such multiple-wavelength observations might prove useful in investigating departures from the Kolmogorov spectrum. A possible application is the use of short paths and multiple frequencies to observe the steepening of the turbulent spectrum for small eddies where viscous damping becomes effective.

2.3 Optical Path Length Fluctuations

The cumulative effect of the phase distortions of the wavefront combines with the random velocities of the turbulent eddies to produce temporal fluctuations in the phase of the received light wave or, what is equivalent, changes in the optical length of the path. Over short paths where the intensity effects are not fully developed, the path-length changes can be measured by interferometry. A typical 4-second sample of such measurements over a 25-meter path is shown in Figure 7. The second-to-second fluctuation of such a path is of the order of a few parts in 10^8 after long-term (10-second) trends have been removed.

As the path length is increased so that the intensity effects become well developed, interferometer measurements begin to suffer from ambiguities during the intensity minima. Then it is more convenient to measure path length by modulating the light beam, much as Fizeau did with his toothed wheel when measuring the velocity of light. With a modulated beam, the group path length rather than the phase path length is measured because of the optical dispersion of air. A 110-second sample of such a measurement, using 10 cm modulation wavelength over a 5 km path, is shown in Figure 8. Here the second-to-second fluctuation is a few parts in 10^9 after the slow drift is removed.

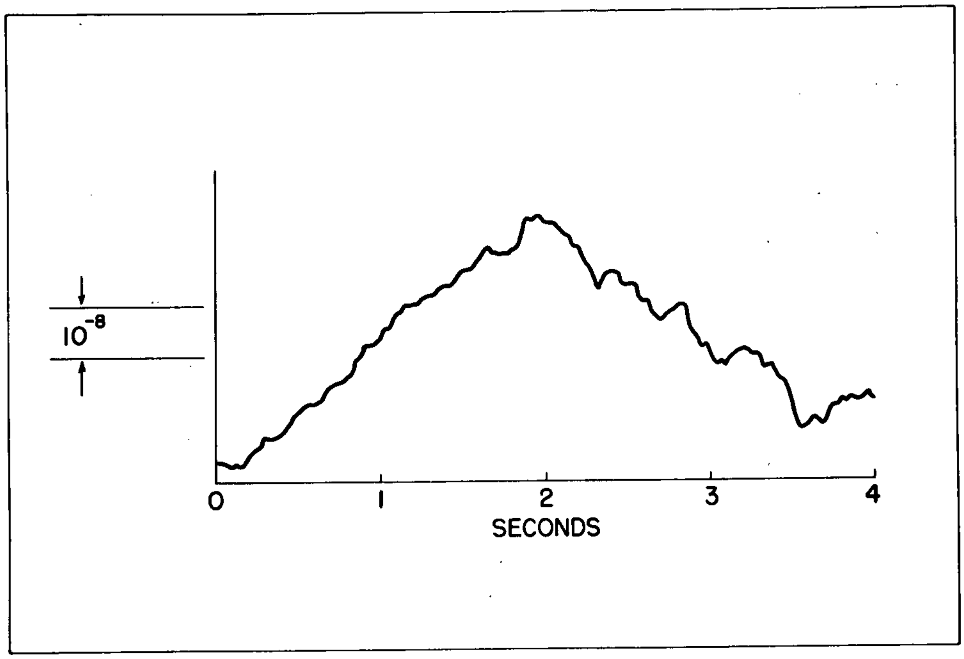

Figure 7. A typical four-second measurement of optical path-length changes over a 25 m path.

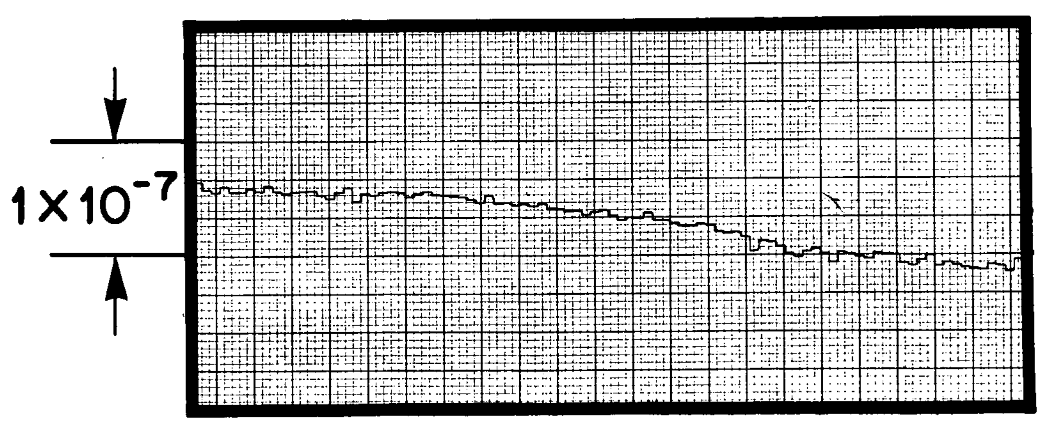

Figure 8. A typical 110-second recording of optical path-length changes over a 5 km path. The individual measurements are one-second averages.

2.4 Spreading of a Laser Beam

If the light is restricted to a narrow beam from a well collimated laser, the phase fluctuations in the wavefront which, at position B of Figure 1, cause portions of the wave to propagate in slightly different directions will produce a measurable spreading of the beam. Rigorous analysis of this effect is surprisingly difficult, though an approximate geometrical solution has been presented by Beckmann (1965).

The weighting function for beam spreading is very different from that for intensity fluctuations. We can see its approximate nature from the following simple argument. Referring to Figure 9, consider a laser source L which,

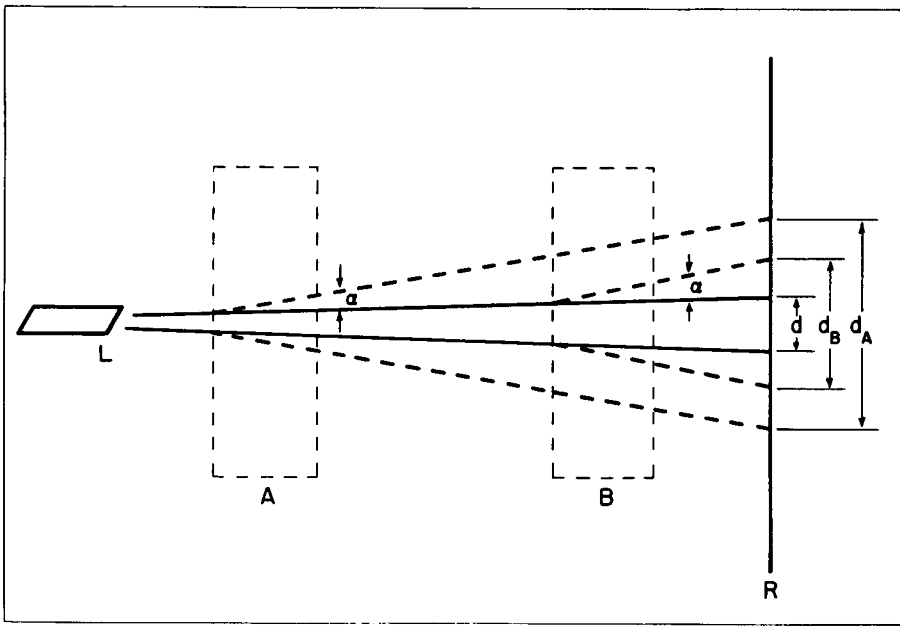

Figure 9. The geometry involved in determining the relative effectiveness of turbulence at various points along the path in producing beam spread.

in the absence of an atmosphere, would produce a spot of diameter d on the receiving screen R. If a parcel of turbulent atmosphere (not a single refractive-index irregularity but a complete, bounded region containing a Kolmogorov spectrum of irregularities) were inserted in the beam at point A, it would cause some additional beam spreading of angle α and would result in a spot at R of diameter d_A. If, instead, the same parcel of turbulent atmosphere is located at point B, the beam spreading caused by it will still have the same angle α, but now the spot on the receiving screen will be only d_B in diameter. Thus, if the inherent angular divergence of the laser beam is much smaller than the atmospheric effect α, the weighting function that describes the effectiveness for beam spreading of turbulence at various positions along the path is linear. It is a maximum at the laser and drops to zero at the receiver.

Figure 10 shows the typical diurnal variation of beamwidth as measured over 5.5 and 15 km paths near Boulder, Colorado. The laser beam was expanded and collimated so that its intrinsic divergence was only 5 μrad. The average height above ground of the paths is 50 and 80 m respectively.

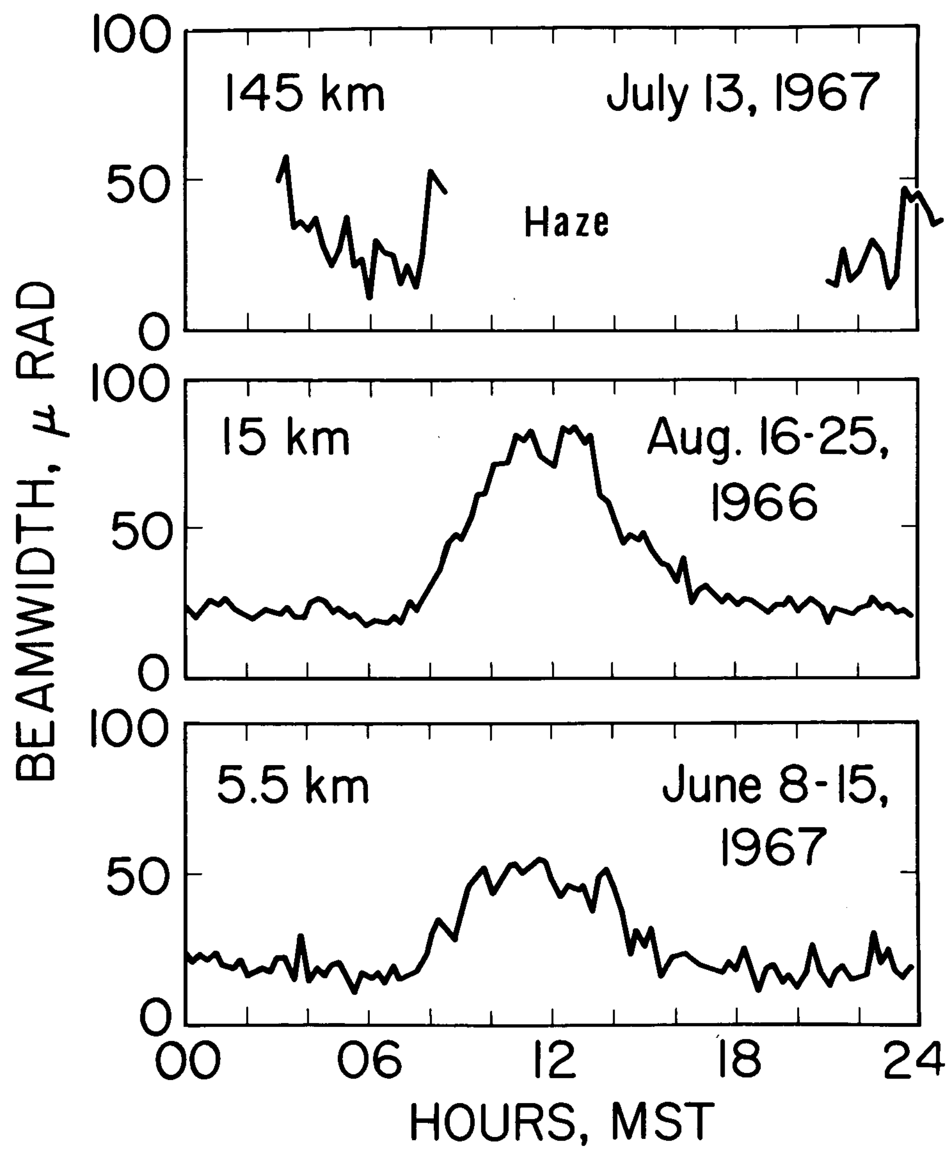

Figure 10. Typical diurnal variation of beam width observed over three paths near Boulder, Colorado.

Figure 11 presents some slight evidence in support of a linear weighting function for beamwidth. The line and the solid dots show the close relationship between beamwidth observed over an irregular 5 km path on a sunny summer afternoon and the mean square temperature fluctuation measured along the beam with a high-speed thermometer mounted on an airplane. Here,

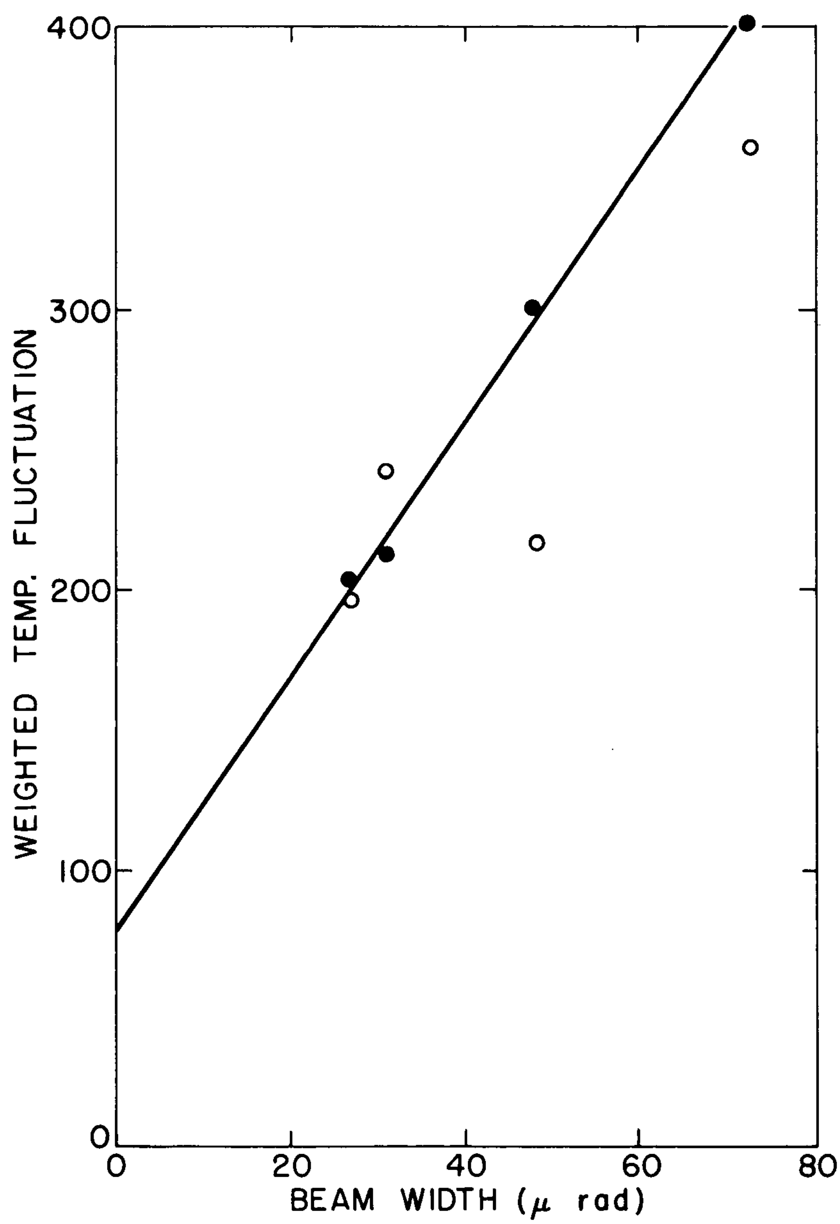

Figure 11. The dark circles show the close relationship between observed beamwidth and properly weighted airborne measurements of turbulence along a 5 km path. The open circles show how the relationship deteriorates when an improper weighting function is used.

linear weighting of the temperature measurements has been used, counting the fluctuations near the laser most heavily and those near the receiver not at all. The open circles show how this close relationship is lost if reverse linear weighting is used, as would be appropriate were the laser and receiver interchanged. Although the experiment is still to be done, we may infer that the beamwidth would be very different on this path if measured in the opposite direction.

3. EFFECTS OF LARGE-SCALE REFRACTIVE-INDEX VARIATIONS

Large-scale variations in the refractive index of the atmosphere are primarily controlled by temperature and barometric pressure. The large-scale phenomena that are most important to ground-to-ground optical propagation are changes in the average temperature along the path, changes in the barometric pressure, and changes in the vertical gradient of temperature. Minor effects result from changes in the water-vapor content of the atmosphere and from horizontal temperature gradients.

A laser beam sufficiently narrow to be dominated by turbulent spreading typically wanders from its mean position by several times its own diameter. This wandering is primarily in the vertical direction because of the predominance of vertical temperature gradients. Figure 12 illustrates this effect with

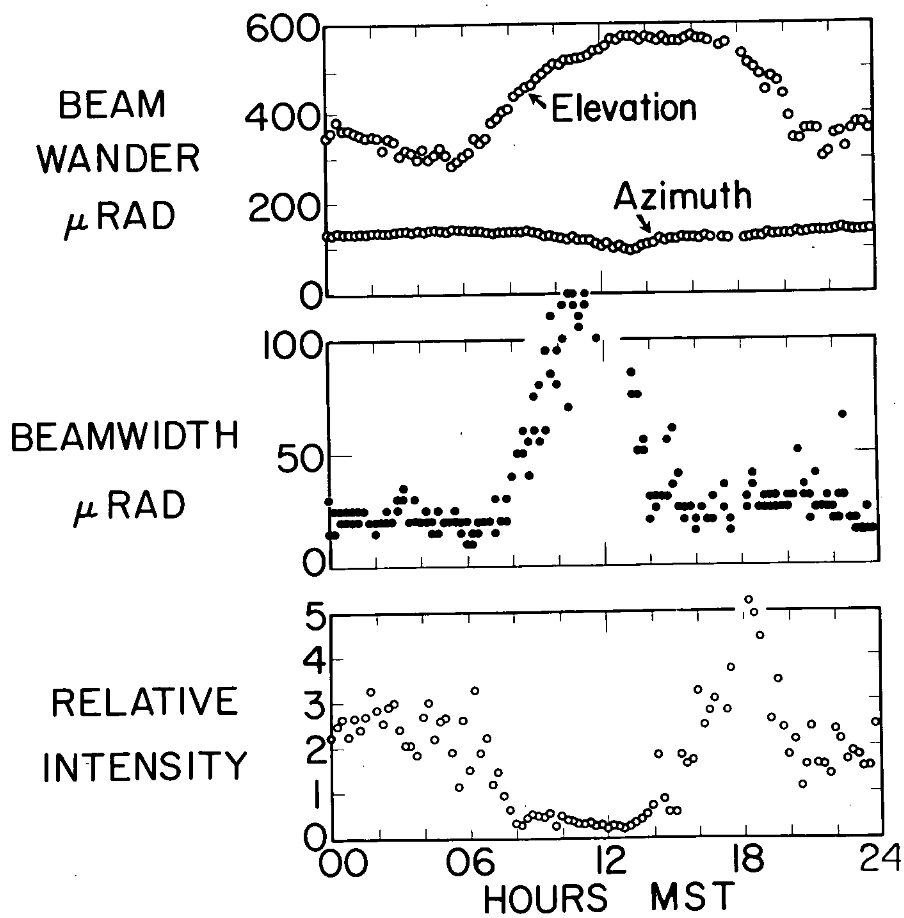

Figure 12. A typical day's measurements, made every 15 minutes, of beam width and beam wander over a 15 km path.

a series of beam positions measured every 15 minutes during a typical day. When, upon occasion, the beam passes through a temperature inversion, the vertical deflections are greatly enhanced as in the case of a mirage. In addition, it is common in these cases to observe nearly periodic vertical oscillations, presumably caused by gravity waves.

The average density of the air along the path determines the optical path length. A change of 1 K in temperature or of 3 mb in pressure is sufficient to affect the optical path length nL by one part in 10^6. Notice that this is several hundred times greater than the second-to-second fluctuation typically caused by turbulence. Figure 13 shows an example of this effect measured over a 3 km round-trip path. The reference temperature was measured with a thermometer at the center of the path. Δ (nL) is the difference in optical path length between red light and blue light.

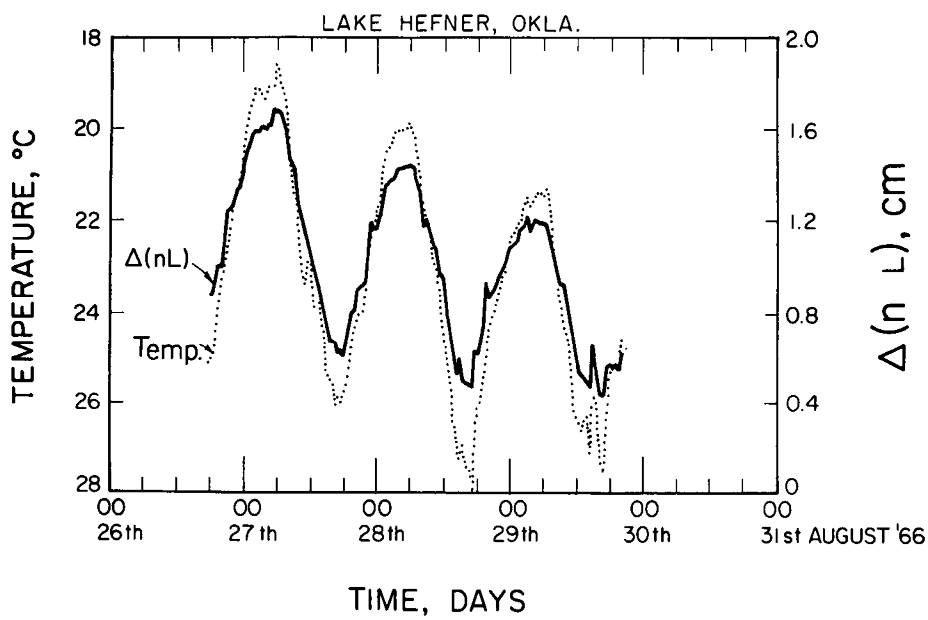

Figure 13. The relationship between optical path length over a 1.5 km path and the temperature measured at the midpoint. In this plot the relative scales have not been properly adjusted, so the variation of path length appears too small.

4. POLARIZATION EFFECTS

In theory, the turbulent irregularities in the atmosphere should depolarize a linearly polarized light wave. The effect has been calculated by Saleh (1967) and estimated to be about 10^{-9} per km. He was unable to observe the depolarizing effect of the atmosphere on a 2.6 km path, even with an equipment sensitivity of -42 db. We conclude that at the present time polarization effects are of no practical interest for optical remote sensing of the clear atmosphere using line-of-sight paths.

5. THE DETERMINATION OF AVERAGE TEMPERATURE

If we assume that the barometric pressure is known, the average temperature along a fixed open-air path can be determined by comparing the optical path length with the known true geometrical length. The apparatus for doing this could, in principle, be as simple as that shown in Figure 14. This is a

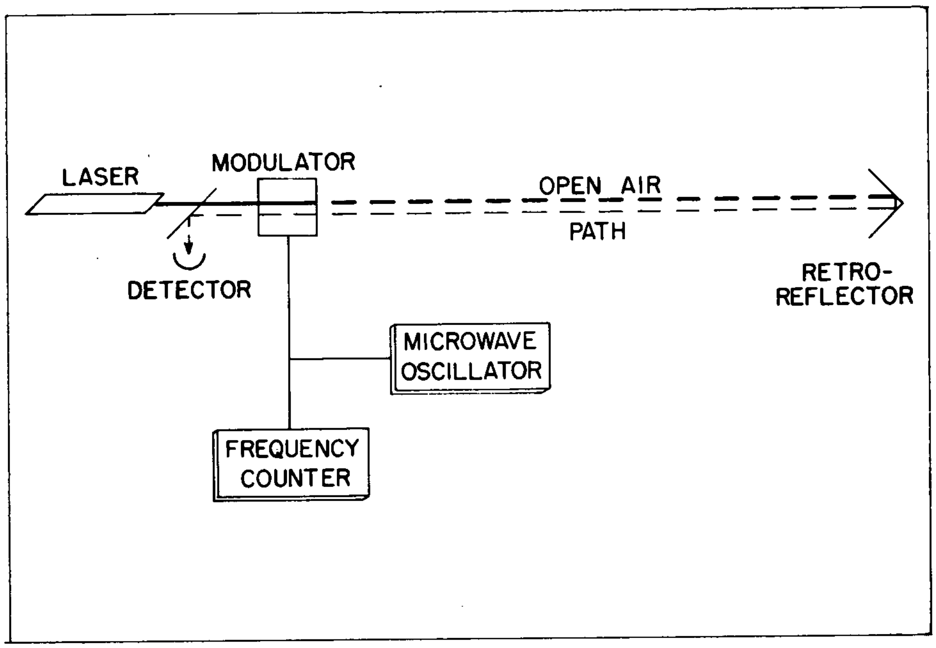

Figure 14. A block diagram of a simple device for measuring average temperature over a fixed path.

modern version of Fizeau's classical experiment. A laser beam is passed through an amplitude modulator and traverses the open-air path to a retroreflector. It returns through the modulator and is deflected by a beam splitter to a detector. A small adjustment of the modulation frequency is made to minimize the detector output, and the modulation frequency is then measured by the counter. In practice, it would be desirable to provide a means for servo-controlling the oscillator to maintain a null output. The frequency read from the counter provides the optical path length. This can be converted to temperature given only the barometric pressure.

We have already noted that the second-to-second fluctuation in path length caused by turbulence corresponds to a temperature change of less than 0.01 K along the whole path. Thus, turbulence will not be a limitation to measurements of average temperature unless the required accuracy is better than about 0.1 K. For 0.1 K temperature accuracy, the barometric pressure must be measured to 0.3 mb. and both the modulation frequency and the fixed geometrical length of the path to 1 part in 10^7. The effect of varying composition of the air, particularly the effect of water vapor, has been discussed in detail by Owens (1967a). For temperatures near 20° C., a relative humidity error of 15 percent results in a temperature error of 0.1 K.

Determination of the geometrical length to one part in 10^7 is at, or perhaps just beyond, the limit of the state of the art, and requires the averaging of a large number of optical measurements taken under various carefully measured weather conditions. In summary, absolute temperature measurements with an accuracy of 1 K or, perhaps, 0.1 K are feasible, and temperature-difference measurements to 0.01 K are possible if the humidity along the path can be measured sufficiently well.

If the path is not fixed, or if the path length is unknown, a more complicated variant of the optical path-length method can be used, utilizing the dispersion of the atmosphere. In round numbers, the atmosphere reduces the velocity of blue light by 330 parts per million while it reduces the velocity of red light by only 300 ppm. Both these numbers are proportional to atmospheric density and therefore, for a given barometric pressure, inversely proportional to temperature. Simultaneous measurement of optical path length with both red and blue light provides the two equations needed to solve for the path length and the temperature. A discussion of this method and its accuracy has been given by Owens (1967b). Briefly, temperature measurements to 1 K are feasible and, with a little elaboration to remove ambiguities, would produce as a byproduct distance measurements accurate to one part in 10^6.

A quite different application of the two-frequency principle suggests itself and is now being investigated in Boulder. Simultaneous measurement of apparent path length with optical and microwave frequencies over a fixed path yields the average temperature and the average water-vapor content. The method has been described by Bean and McGavin.

6. THE DETERMINATION OF VERTICAL TEMPERATURE GRADIENT

The beam wandering discussed in section 3 and illustrated in Figure 12 provides a direct indication of temperature gradients along the path. The predominant temperature gradients are in the vertical direction so it is these that are most readily measurable. The sensitivity of the method increases in proportion to path length and, for a 10 km path, a temperature gradient of 1 k/100 m. results in a beam deflection of about 75 μrad. This angle is comparable to moderately strong turbulent broadening of the beam and is easily measurable.

7. THE DETERMINATION OF TURBULENCE ALONG THE PATH

We have seen in section 2 that the turbulence along the path must be weighted linearly to account for its effect upon beamwidth, while it has a symmetrical, nearly parabolic weight in its effect upon intensity fluctuations. If the turbulence is uniformly distributed along the path there will be a fixed relationship between beamwidth and log-amplitude variance, at least until the turbulence becomes sufficiently strong to saturate the scintillations. If the turbulence is not uniformly distributed, this relationship will not hold in general. Thus, the simultaneous observation of beam spread and log-amplitude variance

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can be used to check the uniformity of the turbulence along a path. There is not, however, enough information in such a pair of measurements to invert the integral and learn any appreciable details of how the turbulence is distributed along the path.

The covariance function of intensity scintillations was shown in Figure 6. The discussion in section 2 showed how this function (or its Fourier transform, the spatial spectrum of the fluctuations) results from the combined effects of the turbulence along the path. The turbulence at each point contributes to the spectrum a limited range of pattern sizes distributed closely around the sizes shown, for example, in Figure 3. Accordingly, if turbulence were absent over a portion of the path, the spectrum of the intensity fluctuations would be distorted in a characteristic way. Figure 15 illustrates this

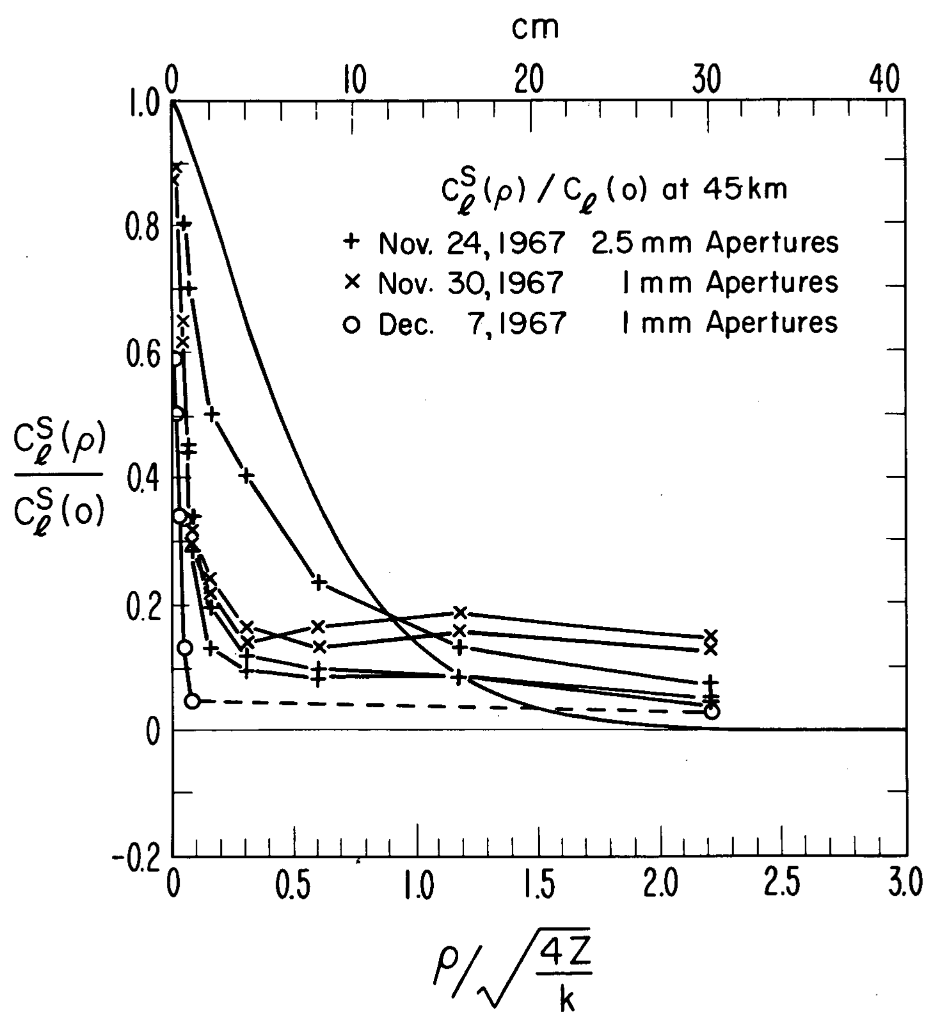

Figure 15. Measurements of the covariance function of scintillations over a 45 km path demonstrate poor agreement with the theoretical curve. This is explained by the concentration of turbulence near the end-points of the path.

effect with measurements taken over a 45 km path near Boulder, Colorado. The smooth, unmarked curve is the theoretical covariance function for uniformly distributed turbulence, taken from Fried (1967b) and plotted for the particular path length and wavelength. The six broken curves, connecting observations made on three different nights, differ systematically from the theoretical curve. The sharp spike with a width of less than 1 cm represents small-scale structure caused by turbulence near the receiver. The long tail, sometimes even peaking in the vicinity of 18 cm, represents large-scale structure caused by turbulence near the transmitter. The absence of scale sizes between these two extremes indicates an absence of turbulence at the middle of the path. This is exactly what might be expected because the path lies between two mountain tops and, except near the end points, is never less than 150 meters above the ground. It is well known that turbulence generally decreases rapidly with height above the ground; Hufnagel (1966) indicates that the turbulence may be expected to have 1600 times less optical effect per unit path length at 150 meters height than at ground level.

Thus, we have a possible method for determining the distribution of turbulence along the path. Like so many remote-sensing techniques, it involves the inversion of an integral to obtain the desired answer. The measurements, themselves, are statistical in nature and so contain a random element, i.e. they are inherently noisy. The noise cannot be reduced indefinitely by extending the observation period because the open atmosphere is notorious for yielding non-stationary time series. Although guesses can be made at the present time, it remains for experiment to disclose how accurate the method can be. Such experiments are in progress at Boulder. Our expectation is that the turbulence distribution can be represented in terms of a third or fourth order polynomial, but probably not in much more detail. Inclusion of beam-spread measurements might yield a slight improvement.

8. THE DETERMINATION OF TRANSVERSE WINDS

As a uniform wind blows across the path, it is obvious that the pattern drift velocity will be greater for a pattern caused by irregularities near the laser than for a pattern arising near the receiver. Also, as shown in Figure 3, the former pattern will have a larger scale. Thus, for a uniform wind, the large-scale intensity fluctuations will drift past the receiver more rapidly than will the fine-scale structure.

Now consider the correlation between the intensity fluctuations observed by two point detectors separated by a variable horizontal distance transverse to the optical path. For any given time lag there is a spacing of the detectors that will maximize the correlation. The ratio of this spacing to the time lag determines the drift velocity of those components of the intensity pattern having a size comparable to or larger than the detector spacing. (Notice that the drift velocity is not the same as the apparent velocity that would result from holding the spacing fixed and varying the time lag to maximize the correlation. The difference between these two velocities has been discussed at length by Briggs, Phillips and Shinn (1950)). It has proved possible to check these ideas with a laboratory setup where two hair driers were arranged to blow hot, turbulent air across a 10-meter laser beam. It was quite easy to observe a bi-modal time-lagged correlogram, the two humps corresponding to the air streams from the two fans. Outdoor experiments, calibrated by a large number of anemometers, are in preparation.

The correlation between the two detectors is a surface parametric in time lag and detector spacing. From the theory of wave propagation through turbulent media it must be possible to express this correlation as an integral of the transverse wind velocity and the strength of turbulence along the path. The determination of wind velocity from scintillation observations then becomes the familiar remote-sensing problem of inverting the integral. Notice that the wind determination is intimately tied to the determination of the distribution of turbulence. As in the previous problem, we can only guess what will be the practical accuracy achievable by this method. Once again, we must deal with observations that are, by their very nature, severely contaminated by noise. Again I suspect that the best we can do may be to determine the coefficients of a third or fourth order polymonial describing the distribution of transverse wind velocities along the path.

9. SUMMARY

We have presented, in a mostly qualitative manner and with heuristic arguments, a description of the principal effects of the clear atmosphere upon optical propagation. Several of these phenomena offer possibilities for the remote sensing of atmospheric properties, and we have mentioned in particular the measurement of average temperature, average vertical temperature gradient, and the distribution of turbulence and transverse wind velocity along the path. The first of these has been tested in the field. The second and third have been demonstrated qualitatively with outdoor data, and the fourth has been demonstrated only in the laboratory.

Observation of integrated effects over a line-of-sight path is naturally more practical for the determination of average values over the path than it is for the determination of distributions along the path. While the former may confidently be pursued, the latter should be approached with cautious optimism. We have seen that the appropriate weighting functions and the spectrum of turbulence are smoothly varying. This means that the contribution to the integral from a parcel of atmosphere located at a particular point on the path is irrevocably mixed with the contribution from nearby parcels. Thus it is, in principle, impossible to determine distributions in great detail. We have guessed that four or five independent parameters will be the limiting resolution, but actual tests must be made in the open atmosphere.

ACKNOWLEDGEMENTS

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