AFAL-TR-65-79
Part II

ATMOSPHERIC PROPAGATION STUDIES AT OPTICAL, MILLIMETER, AND MICROWAVE FREQUENCIES

Part II. The Mechanism of Scintillation

Paul B. Taylor
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TECHNICAL REPORT AFAL-TR-65-79, PART II
MARCH 1965

Contract No. AF33(615)-1265

Air Force Avionics Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report is based on research performed by the University of Dayton Research Institute under Air Force Contract 33(615)-1265 between January 1, 1964 and January 20, 1965. It constituted Part II of subject report and should be read in conjunction with Part I (issued concurrently) which describes experimental procedure and results obtained to date.

Persons concerned for the Air Force are Paul W. Springer, Group Leader, Propagation Section, Environment Branch, Electromagnetic Warfare Division, Air Force Avionics Laboratory, AVWE, Wright-Patterson Air Force Base; and Robert A. Simons, Project Engineer under Project 4062, Task 02.

Persons concerned for the University of Dayton Research Institute are Nicholas A. Engler, Project Supervisor; Istvan P. Peteranecz, Project Engineer; and the author.

This report was submitted by the author March 30, 1965.

ABSTRACT

The scintillation of received signals propagated through some ten miles of atmosphere on narrow beams (one at an optical frequency, the other at a microwave frequency) have been reported in Part I. The present report reviews several explanations which might account for the phenomena.

It is found that the scintillation observed in the microwave signal is not out of line with the statistical theories of propagation through a randomly homogeneous atmosphere which have been proposed by others. However, a precise description of the mechanism is still wanting.

The scintillation observed in the optical signal is more violent than any previously reported, and shows characteristics at variance with the statistical theories of the atmosphere presented in the literature--namely, in the occurrence of short intense bursts of signal superimposed on a low-level randomly fluctuating background.

Scintillation in analogous phenomena, especially that of radio and optical stars, shows indications of similar traits. The several explanations which have been proposed are mutually at variance, and none stands up well under criticism.

Further experiment and study is required if a tenable explanation is to be established.

This technical documentary report has been reviewed and is approved.

LIONEL W. ROBERTS
Lt Colonel, USAF
Chief, Electronic Warfare Divisio

The present experiments of subject contract deal with narrow microwave and light beams received over a ten-mile horizontal path through the atmosphere. The light beam was from a gas laser source. The signals received from it show violent and rapid fluctuations of intensity. These fluctuations are so violent as to interfere seriously with the use of such a system as a carrier of information. These fluctuations have been observed previously by other experimenters, although perhaps in not so pronounced a form. The present experimental path was deliberately chosen so as to cover a long distance horizontally through air which, on occasion, could be substantially disturbed, so that the effects of such disturbances upon the propagation of signals might be studied.

No adequate discussion of scintillation of laser beams or of microwave beams is available in the literature, and the present report will hardly succeed in filling the want. It attempts to state the facts, to pose the problems which require an answer, and to present the partially successful explanations which have been offered for more or less analogous phenomena. The discussion will relate chiefly to the optical phenomena.

The phenomena observed in the reception of the laser beam is a violent rapid fluctuation in intensity of the received light as recorded by a photocell. The received signal is marked by intense flashes of light of very short duration separated by relatively long intervals of quiescence. During the quiescent periods a weak, randomly fluctuating background signal is received. The peaks of the flashes may rise 20 to 30 db above the background and may endure for perhaps twenty-five milliseconds at intervals of hundreds of milliseconds. The emitted laser beam itself is known to be steady in intensity in time, but is not uniform in distribution over the face of the laser. Observers report the beam near the source to be steady in time over a path of tens of feet at least. The fact that the beam near the source shows so little spread is evidence of uniform phase over the face of the laser. The fluctuation of the received signal is certainly due to irregular fluctuations of distribution of the index of refraction in the intervening atmosphere in space and time. The effect is also assuredly connected with the extreme narrowness of the laser beam and the small aperture of the receiving telescope.

The observed effect may be identified as an extreme form of the recognized phenomenon of scintillation, which appears in a variety of circumstances. Scintillation is a fluctuation of brightness of the image in a receiving system of a sufficiently pointlike source observed over a sufficient distance through the terrestrial atmosphere.

Scintillation is to be distinguished from shimmer, which is the apparent change in position of an object as seen through a considerable distance in the atmosphere, a change also fluctuating in time. Shimmer and scintillation occur together, but have many points of difference. Shimmer is common to

both extended and point sources. (Scintillation occurs only for point sources.) Shimmer is independent of the aperture of the receiving system. (Scintillation is dependent.) The fluctuations in shimmer are incoherent with the fluctuations of scintillation. Shimmer is adequately explained by the gross average changes in the direction of the gradient of the index of refraction in the atmosphere. Shimmer is observed in the present experiments, but calls for no further discussion.

Scintillation appears intimately connected with narrowness of beam. The beam must be narrow in three senses: the angular spread of radiation from a geometrical point in the source must be small; the angular spread of the source as observed at the receiver must be small; the angular spread of the receiver as observed at the source must be small. Thus, for scintillation to be observable, an extremely limited bundle of rays seems to be required.

Some measurement of the laser beam width is appropriate at this point because the extremely narrow beam which our laser radiates must contribute in some way to the development of the scintillation.

The simple expression for angular beam width α from a circular source of uniform phase and intensity and diameter d for a wave length λ is given as

$$\alpha = 1.2 \frac{\lambda}{d} .$$

This is for the far field. Strictly, this is the angle from axis to first minimum on one side. It serves reasonably well for full beam width down to half power. The wave length of the laser used is 6.3×10^{-5} cm, the nominal diameter is .8 cm, giving

$$\alpha = 9.6 \times 10^{-5} \text{ radians.}$$

The dimensional beam width W at a range R of 10.26 miles is

$$W = \alpha R$$
$$= 5.2 \text{ ft.}$$

Since the intensity distribution over the face of our laser is observed to fall off towards the edges, the nominal diameter is not realized. A more realistic estimate of laser aperture would be .4 cm, yielding an angular beam width of 19.2×10^{-5} radians and a beam width at the receiver of 10.4 ft. The transverse width over which our beam can be observed at ten miles is 30 feet or more.

A phenomenon analogous to atmospheric scintillation is the moving pattern of light and shade to be observed on the bottom of a pool. This pattern is created by ripples on the water surface of the pool. It is seen only when the sun is shining, and is correctly ascribed to refraction of the sun's rays by the ripples. The curvatures of the surface are such that lens action takes place with a focal length comparable to the depth of the pool. This produces an irregular but distinct moving pattern of bright and dark blotches on the bottom of the pool.

A similar effect is shown in the reflection of sunlight by the ripples of a pool onto the underside of an overhanging bridge. Here the pattern can be an irregular net of bright lines. Ray theory and familiar lens principles are adequate to account for the effect. It may be noted that, while direct observation of the water surface may enable one to distinguish definite wave trains traveling with observable velocity and direction, all correspondence between light pattern on the bottom and wave pattern on the surface is lost. This is true also of the pattern observed by reflection. This loss of correlation is a point which careful statisticians stress, but which some others gloss over. It is to be noted that in this case refraction takes place at one surface only (which is known). Presumably the effect takes place over only a limited range of depths. If the explanation is correct, it would not be observed in a shallow pan or in a very deep pool. The angular spread of the sun (1/2 degree) is not too great to prevent this form of scintillation. The ray bendings are greater than 1/2 degree.

Scintillation produced by the atmosphere is a much more complicated effect than that produced by water ripples. The water ripples have been mentioned here only by way of an introduction to the subject. Their refractive effect can be considered as understood and to bear resemblance to atmospheric scintillation, but the explanation adequate for ripples does not fit the atmospheric case.

The phenomenon of scintillation by atmospheric inhomogeneities differs from scintillation by water waves in the order of magnitude of the fluctuation of refraction. For water waves, the variation of ray bending may be of the order of degrees; for atmospheric disturbances, the variation of ray bending is of the order of seconds, or at most minutes.

When atmospheric refraction is considered, the variation in time of transit from one ray to a neighbor may be exceedingly small. The fact that the Michelson star interferometer performs as well as it does implies that, under favorable seeing conditions of the atmosphere, the relative phase fluctuation between two rays as much as ten feet apart may be under half a cycle of light. This follows from the known ability of the interferometer to to produce a stable interference pattern for such a ray separation.

Atmospheric irregularities causing scintillation cannot be assigned to any one particular level as in the case of water ripples. However, atmospheric scintillation is dependent on ray direction to a much greater degree than is scintillation from water ripples. It is greater for horizontal rays than for vertical rays. This fact may be interpreted as showing that the known greater inhomogeneity of the lower atmosphere is the primary source of the effect.

The atmospheric inhomogeneity effective in the index for optical propagation is that of density, which in turn is caused by irregular temperature distribution. At microwave frequencies, the presence of water vapor modifies the index; however, it is uncertain whether its distribution is sufficiently irregular to contribute to scintillation. This is one of the questions which, it was hoped, these experiments might answer.

The phenomenon of atmospheric scintillation has been studied most extensively in its effect on the astronomical observation of stars and planets. These effects bear many points of resemblance to laser scintillation. For point sources (stars) within 30 degrees of zenith, scintillation may be observed, but usually it is rather slight. With increasing zenith angle, scintillation increases to more or less a saturation limit at about 75 degrees. When an energy-frequency spectrum of scintillation is prepared, it is seen that the saturation limit is more pronounced for high frequencies of scintillation than for low. Shimmer also increases with azimuth angle, but continues to increase for angles greater than 75 degrees.

The dependence of star scintillation on zenith angle can be explained as due to the fact that the major inhomogeneities of the atmosphere are at low altitudes and are decidedly striated. Often layers of sharp vertical variation of refractive index may be observed only a hundred or so feet deep and extending for many miles horizontally. In such cases, a vertical ray through the stria will show no bending, since it runs parallel to the index gradient. A horizontal ray, on the other hand, shows maximum bending, since it runs perpendicular to the gradient.

Horizontally, these strata of sharp gradient show waviness, and these waves travel, just as do water waves. A bundle of rays running for any distance along such a stria could be expected to show marked differential refraction between rays of the bundle which initially lay very close together.

Figure 1 may make this clear. Two rays are shown. At A and B respectively, they are parallel. The lower ray from B then enters a stratum of low optical density (warm air), while the upper ray continues through normal air. After emergence from the stratum at D, the lower ray has gained on the upper--which is now at C. The two rays have converged, and the signal intensity has increased. A very slight rise in the stratum

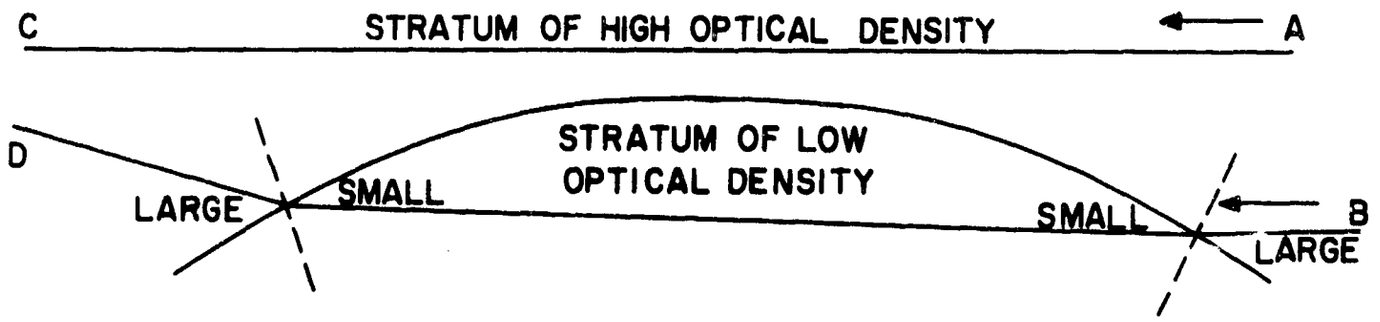

Figure 1. Differential Refraction of Rays in Strata of Dissimilar Optical Densities.

boundary (one or two feet) may alter drastically the relative refraction of the two rays.

The above mechanism may well operate on starlight as it travels many miles through the atmosphere. However, there is no evidence that the small scale inhomogeneities of the atmosphere are striated. Indeed, if they are like the visible clouds, they often are not striated.

It is commonly noted that a star scintillates much more violently than a planet at the same zenith angle. The effect is therefore to be ascribed in some way to the angular diameter of the source. The angular diameter of Betalgeuse (large for a star) is .05 second, that of Jupiter (typical planet) may be as great as 50 seconds. Both of these angles are small by ordinary standards of visual observation, since the aperture limit of resolution of the human eye is as great as 47 seconds of arc. However, in proportion, the angular diameter of Jupiter is a thousand times that of Betalgeuse.

The small-angle mechanism that is commonly offered to account for star scintillation may be made clear by reference to Figure 2. (See Minnaert, Reference 1.)

Here a bundle of rays is shown initially closely parallel. Part of them pass through a refracting prism A-B, and are bent to the left. Rays to the right of B are not so refracted. There then lies a little region below B through which no ray passes. Whether or not such a region is set up depends on the sharpness of cut-off of refraction at B, on the degree of bending along A-B, and on the angular spread of the rays. Since the angular spread of rays from Jupiter (50 seconds) is enough to forestall scintillation, we infer that the differential bending caused by ordinary fluctuating atmospheric inhomogeneities are of the order of less than 50 seconds of arc.

The above explanation is not complete until the performance of the receiving mechanism is analyzed. It is necessary to explain why the scintillation is observed through a small aperture and not through a large one. It is commonly accepted that a small aperture, as at C-D, lying in the weakened part of the ray field would receive a weak signal, while a wider aperture E-F would receive a nearly uniform signal. There is a weak link in this chain of reasoning. The aperture E-F has higher resolving power than aperture C-D, and the cone of rays which contributes to a point image is narrowed. Rays which fan out more than the angular limit of resolution produce an extension of the spot size but no increase in brightness. An aperture of 3 cm accepts a spread of rays of 4.7 seconds to form a point image, as against the 47 seconds spread accepted by a 3 mm aperture. It thus appears that the reduction of scintillation by a large aperture can be due only to the averaging of density of rays all in one direction over a large cross section, rather than averaging rays in a wide cone. One might argue that the acceptance of rays over a wide cone by a small aperture to form a point image should equally well effect a smoothing average.

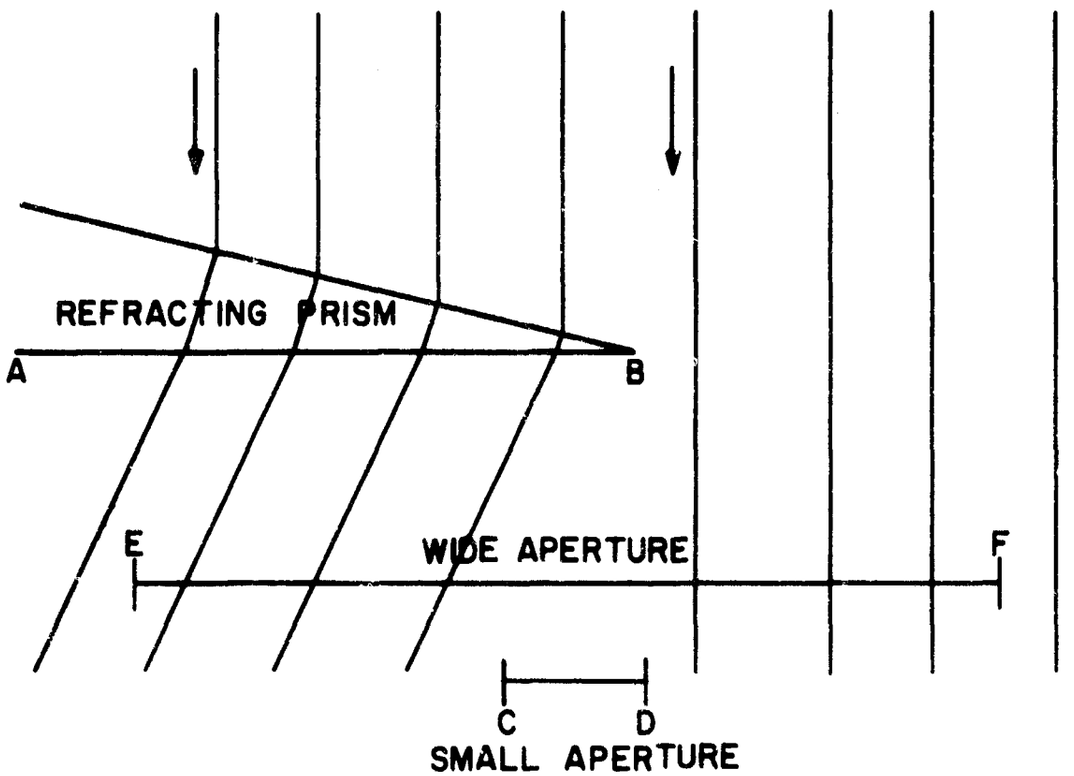

Figure 2. Partial Refraction of a Beam of Closely Parallel Rays.

The angle of resolution of a lens (which is the angle considered above) is not to be confused with the angular field of a lens. The angular field may encompass many degrees, and is in all cases much larger than the angle of resolution.

The above explanation would seem to apply only to differential refraction taking place close to the receiving aperture. It would appear that the action of intervening atmospheric inhomogeneities would be to blur the sharpness of refractions taking place distant from the receiver. It is fairly obvious that refraction irregularities distributed along a ray path have a high probability of spreading the radiation and a low probability of ever bringing it together again.

F$\ddot{u}$rth[2] has shown that the fluctuations of starlight are not randomly distributed. His method is to take the time-intensity record of the image brightness and form the after-effect function $\Delta(\tau)$.

$$\Delta(\tau) = \overline{|f(t+\tau) - f(t)|}$$

where $f(t)$ = intensity at time t.

τ = a time delay fixed for one averaging over the sample. The vertical bars denote absolute value, and the horizontal bar denotes averaging over the duration of the sample. For large τ, $\Delta(\tau)$ approaches a limit $\Delta(\infty)$. The reduced after-effect function $\delta(\tau)$ is defined by

$$\delta(\tau) = \Delta(\tau) \; / \; \Delta(\infty).$$

The nature of the fluctuation in a given sample is then characterized by carrying out the summation for a wide range of τ's, the operation being carried out over the whole sample, once for each τ.

The $\delta(\tau)$ function provides a very sensitive test for periodicity of fluctuation. A truly random (Rayleigh) fluctuation will show a plot of $\delta(\tau)$ versus τ rising monotonically from

$$\delta(\tau) = 0 \text{ at } \tau = 0$$

to a saturation value

$$\delta(\tau) = 1 \text{ at } \tau = \infty.$$

If, however, the signal is characterized by sharp peaks of average duration t_o and average time separation T_o, the plot will show a maximum of $\tau = t_o$ and a minimum at $\tau = T_o$. (See Figure 3.)

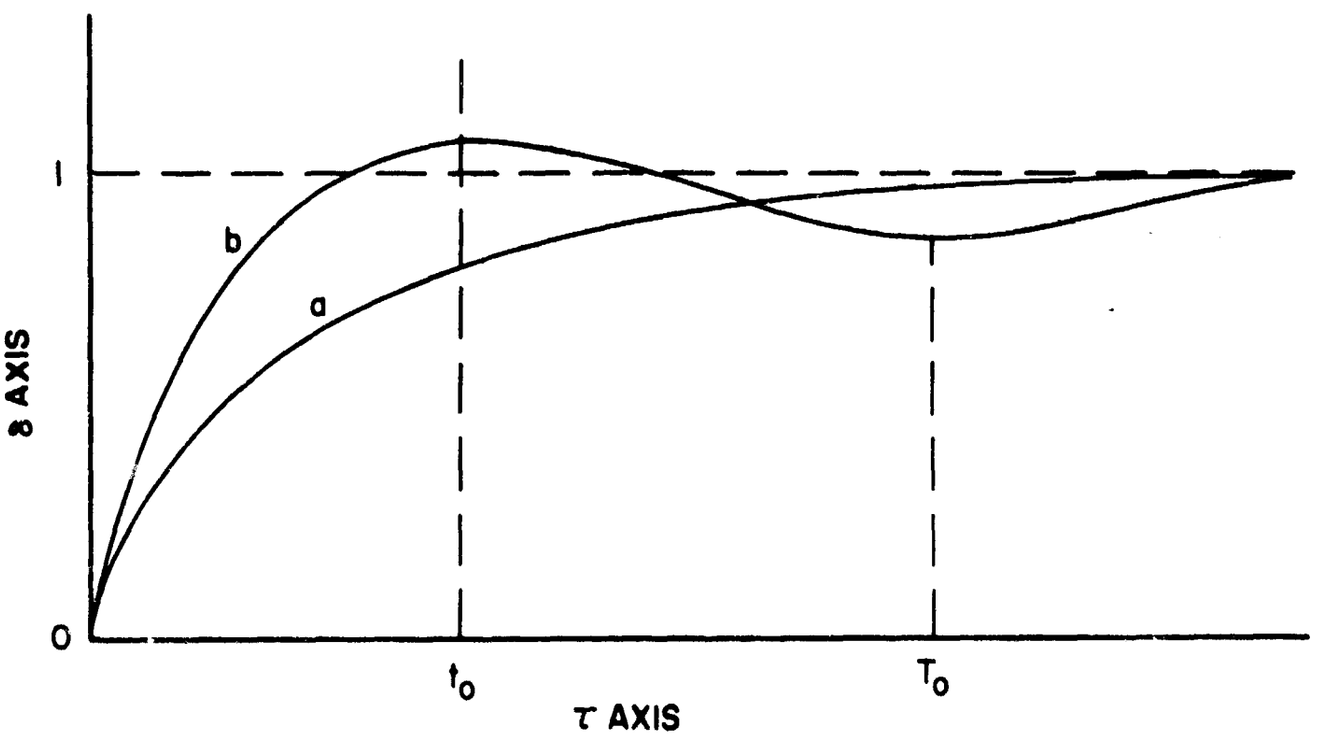

Figure 3. Reduced After-effect Function (a) for a Purely Random Process, (b) for a Process Consisting of an Almost Irregular Sequence of Pulses of Duration t_o and Average Interval T_o.

If the periodicity is sufficiently pronounced, the harmonics of t_o and T_o also will show. By this means Fürth demonstrated the presence of periodicities in the scintillation of starlight. The results of his method of reduction applied to data of observation are shown in Table I which is taken from his paper. Both t_o and τ_o decreased with telescope aperture from an aperture of 36 inches to an aperture of 6 inches, but increased again for a three inch aperture.

Two other quantities can be deduced from plots of the after-effect function. The build-up and decay time for the pulses θ is computed from the slope of the initial part of the curve. The (reciprocal) sharpness of the pulses ϵ is computed as θ/t_o. It will be seen from Table I that the sharpness measure increased as the aperture decreased.

TABLE I

Characteristic values of duration t_o, quasi-period T_o, relaxation time θ, and sharpness measure ϵ, for the train of pulses responsible for the fluctuations of starlight observed through 36, 6, and 3 inch apertures, respectively.

Aperture (inches)	t_o(sec)	T_o(sec)	θ(sec)	$\epsilon = \theta/t_o$
36	0.04	0.10	0.03	0.75
6	0.02	0.035	0.009	0.45
3	0.03	0.06	0.006	0.20

Fürth quotes Minnaert and Houtgast[3] as estimating the characteristic relaxation time of their fluctuation records of starlight and finding values of pulse build-up time between .01 and .02 second for apertures somewhat less than three inches. Fürth then writes:

"Butler[4] and Ellison and Geddon[5] further observed that their records with the smallest apertures showed very high and steep narrow peaks of duration between .005 and .01 second, which they interpret as sudden flashes. However, the appearance of high and narrow peaks is a common feature of all continuous fluctuation records and can easily be accounted for on the basis of the general theory of fluctuations."

The author disagrees with Fürth's last statement for the following reason: High, narrow peaks are not common features of any of the recognized models of statistical fluctuation. Furthermore, in making this statement, Fürth is at odds with his own interpretation of scintillation observations made earlier in his paper.

It is important to notice that the periodicities of light fluctuation, as determined by Fürth, vary significantly with aperture. They are always longest for the largest aperture. The relaxation time θ and sharpness measure ϵ decrease progressively with aperture. If distorted patterns of radiation travel with the wind across the face of the receiving lenses, then a complete change of radiation pattern must take place over a larger interval of time for the larger lens, and the integrated reception progresses more gradually at the larger lens. The results, however, might depend largely on the exact mechanism of integration.

To describe the operation of a large lens as an averaging process is to present a misconception. A large lens does not blur; it sharpens. Radiation theory stresses the fact that a large cross section of wave front is necessary in order to reconstruct true image of the source from which the wave came. If the intervening medium has distorted the wave front, the large lens can do no better than receive the distorted wave front and reconstruct the distorted apparent source which the wave front represents. The large lens cannot correct the distortion inherent in the wave front. It does, of course, use light received over the whole aperture to construct each point of the image. The small lens receives only a small fragment of the distorted wave front. The resultant destruction of image may be much more drastic than any simple linear addition of effects would predict. An example of the reverse of such operation is the fairly well-known experiment of placing a zone plate in front of a small lens to increase its stigmatic property far above that determined by its relative aperture. The zone plate would correspond to atmospheric distortion. This is not to say that the explanation of the sharp pulsing of the received laser beam has been found; it only suggests another possibility to explore. The received laser signal certainly suggests some sort of on-off mechanism in the atmosphere which is different from a true random process as commonly understood.

The explanation of star scintillation as a diffraction phenomenon rather than a refractive is championed in a paper by Fellgett[6]. However, that author does not attempt a complete explanation. An explanation based on such a mechanism has already been hinted at above in the mention of the zone plate.

The advantages of an explanation based on diffraction are many. Provided considerable coherence exists in the incident beam, there is required only slight point-to-point fluctuation in the magnitude of refractive index in the intervening medium in order to generate spatial interference patterns in the beam. These interference patterns can present large variations in intensity. All narrow beams tend to develop spatial coherence, even though the primary source may be essentially incoherent. Thus the light from the star Betelgeuse is coherent at entry to the earth's atmosphere over a five foot area. Interference patterns, once set up, tend to persist throughout the subsequent path of the beam. Since their angular dimensions persist, their spatial dimensions increase. On the other hand, focussing mechanisms tend to be pronounced only at the focus of the effective converging surface. Beyond the focus, the radiation again fans out over an ever-widening cone.

Observations over the cross section of a laser beam which had passed horizontally through a mile or so of atmosphere have been carried out by the Ohio State Research Foundation (private communication). The beam was allowed to fall on a flat matte surface, and was viewed by a movie camera. The camera was focussed on the matte, and the whole surface lay within its field of view. The light distribution over the whole cross section of the beam was thus observed. It appeared as ragged patches of uneven brightness with random changes in form but with a certain amount of observable common motion. This motion is interpreted as correlated with motion with the wind of "frozen in" atmospheric inhomogeneities. Some of the observed irregularity might be charged to the matte surface, but other experiments with a mirror of high quality and a non-laser source have yielded similar patterns.

An unsteady refracting plane located close to the laser source by which the beam as a whole has the direction of its axis changed randomly offers an attractive explanation. It is particularly attractive in that it is an on-off mechanism. When the beam covers the receiver, full signal is received; when it does not, none is received. For the mechanism to apply, the angle of bending must be greater than the angular spread of the beam at the receiver, or the angle at the source subtended by the receiver, whichever is greater. In the present experiment, it has been shown that the beam does swing; but it has not yet been shown that the angle of swing is greater than the beam spread.

Tatarski[7] reported on the fluctuation of light beams received over horizontal paths varying from 250 to 2000 meters. His beam had an angular width of 2×10^{-3} radians, aperture limited. At 2000 meters this corresponds to a linear spread of 4 meters. It was thus a much broader beam than the laser beam reported in our present report. He does not mention any spikiness in the received fluctuation. He considered that the fluctuations obeyed a log-normal distribution. He studied correlation between fluctuations in received signals observed over adjacent paths. With a separation between

receiving systems of only .8 cm, the coefficient of correlation at 2000 km was only .58, decreasing with wider separation. At a separation of 3 cm or greater the correlation became slightly negative. This is the sort of correlation that would result from a wandering beam. (When the beam is over one receiver it is not over another, if the two are separated by a transverse distance greater than the beam diameter.) However, in Tatarski's experiment, the separation of receivers was never so great as the computed beam diameter. The negative correlation found in his case might still be explained on the basis that, if light is diverted by any mechanism whatsoever into one region, it is necessarily diverted away from some neighboring region at the same time.

The scintillation of radio stars has many points of similarity to optical scintillation, although the wave lengths are much larger. It is generally agreed that at these wave lengths the refractive layer is the E layer of the ionosphere. Little[8] and others have offered a diffraction mechanism to explain the effect. Singleton[9] has offered a lens explanation.

Scintillation of radio signals received from satellites is also observed. Yeh and Swenson[10] have obtained records of such signals as received by spaced receivers. The received signals correlated well, if an appropriate time delay was introduced into one of the records. This was confirmation of the existence of a relatively constant pattern of atmospheric inhomogeneity moving with the wind.

The received microwave signals of the present experiment show fluctuation of much weaker amplitude than found for optical signals. The microwave signal does not show short-time flashes such as those observed in the laser-generated signal. The beam spread, though broad in comparison with that of the laser, is still narrow by ordinary standards. A beam swinging mechanism to explain the fluctuations of microwave signal would be difficult to justify, because of the beam spread. Likewise, a purely interference mechanism seems improbable, since great differential time delays would be required to generate displacements of wave front of half a wave length at microwave wave lengths. There remains a focussing mechanism. Lenses formed in the atmosphere with very slight curvature and correspondingly long focal length might focus an image of the source on the receiving antenna. But there are distinct limitations to what focussing can do. In the present experiment the object distance and image distance must add up to 10.26 miles (if the image spot is to land on the receiving antenna). If the image distance is greater than the object distance, the image is larger than the object, and vice versa, but for any given lens aperture, the image brightness is constant. Thus, change in brightness can be brought about only by change in effective aperture of the hypothetical lens formed by the atmosphere. Such a line of reasoning makes it appear highly improbable

that atmospheric inhomogeneity supplies a mechanism to focus on the receiver anything recognizable as an image of the source (microwave or laser).

The outcome of this disucssion may be summarized as follows. Both optical and microwave beams show scintillation under the following conditions:

1. Limited beam spread (the limitation may be effected either by aperture limitation or by initial spatial coherence.)
2. Small receiving aperture.
3. Propagation through an optical inhomogeneous atmosphere.

The scintillations of a microwave beamed signal received over a ten-mile horizontal path through the free atmosphere are severe enough to degrade the information-carrying character of the beam, but are not severe enough to destroy the information in speech. The scintillation appears to be Rayleigh distributed.

The scintillation of a narrow optical beam from a laser received over the same path is characterized by short violent bursts. These bursts are not inherent in the laser, but are produced by the intervening atmosphere. The bursts are too spasmodic to permit the fluctuations to be described as Rayleigh distributed, or as belonging under any other of the recognized statistical distributions. They appear explainable only on the basis of some on-off mechanism which resides in the atmosphere. The known inhomogeneity of the atmosphere does not seem to supply such a mechanism.

Scintillation of a beam from a laser source has much in common with that from a distant star, except that the fluctuations are more violent and spasmodic. Possibly, this extreme effect is related to the smaller diamete of the laser beam near its entrance into the atmosphere.

Scintillation appears only in beams in which high correlation of phase exists across the beam (at least at some point along the path). In narrow beams, this may be shown to occur of necessity at a sufficient distance from the source. Starlight reaches the earth as a broad beam, but still with high correlation over a considerable cross section. Irregularity of atmospheric index of refraction over a cross section of such a beam introduces phase variation in any subsequent cross section, and to some degree spreads the beam and weakens the intensity. A mechanism by which this process could cause the intensity at a fixed point to rise momentarily far above an average level is required, but is not apparent.

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