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# New Experimental Data on Atmospheric Propagation

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*Summary.* An experiment has been performed to measure directly the effect of atmospheric turbulence on spherical wave propagation of light on a vertical path. The results permit determination of the magnitude of the effect at a variety of locations and under different conditions. Agreement is found with the functional form predicted by the inertial theory of turbulence. General agreement is found with scattering data obtained by a low-frequency radar and with predictions of some turbulence profile models. The results also demonstrate some reasons for poor agreement with time integrating sensors.

When light propagates through the atmosphere, local temperature-induced density fluctuations of the atmosphere produce time- and space-dependent phase wrinkles in the transmitted wavefront. These random phase errors lead to limitations on the image quality that will be recorded by a camera or telescope collecting the propagated light. The nature of the imaging effects depends on the size of the observing aperture and the direction of propagation. Because the statistical distribution of the density fluctuations in the atmosphere shows a layering with altitude, the effect on image quality will differ whether the observing aperture is located near the bottom of the atmosphere or the top of the atmosphere. The effect also depends on whether an object at infinite distance, such as a star or planet, or an object at a finite distance, such as the earth's surface, is being observed.

The scale and distribution of atmospheric density fluctuations near the earth's surface are dominated by local geographic effects. The turbulence effects at high altitudes are dominated by the interchange of atmospheric energy that is driven by the long-term solar energy balance. This leads to an asymmetry between the "looking-up" astronomical observation and the "looking-down" terrestrial observation. Many analyses have been made of the statistics of parallel-beam astronomical observations in order to quantify such "seeing" effects. Because the net effect of propagation through turbulence is an integrated effect along the propagation path, the separation of high- and low-altitude effects on the wavefront is not readily possible in the case of looking-up along the parallel beams. The propagation geometries of the finite and infinite object distances introduce quite different weighting of the relative contributions to the image quality of turbulent layers at various altitudes.

In the experiments reported here we directly measured optical propagation on a vertical path with the geometry indicated in Fig. 1. In addition, the data reveal a separation of high-altitude turbulence effects that describes the isoplanatism, or spatial stability, of images obtained by looking up through the atmosphere. The results also confirm several aspects of the theory relating optical propagation errors to free atmospheric turbulence.

The description of the propagation of light through the turbulent atmosphere has reached a high degree of mathematical refinement. The state of the art in this subject has been summarized in several reviews [see (*1*)]. Directly measured data on light propagation are somewhat sparse, however, largely because of the difficulty of measurement. A mathematical model based on the inertial theory of turbulence describes the propagation process. The magnitude of the effects observed depends on the values of the physical parameters, such as temperature distribution and wind velocity profile, which must be entered into the model. There are difficulties in measuring these parameters in a manner pertinent to the propagation problem. Therefore, direct measurement of optical propagation serves both as a confirmation of the theory and a method of establishing the functional level of turbulence effects. Confirmation of the influence of the above mentioned physical parameters is also possible.

Many calculations have been made predicting the statistics of the logarithm of amplitude scintillation and phase front error due to propagation of plane and spherical waves through the atmosphere with light, medium, and saturated turbulence. The parameters relating these optical effects to the local meteorology are obtained from the statistical descriptions of the index of refraction due to local density variations in the atmosphere. These are usually described in terms of a structure function. The most direct interaction with optical effects is through the structure constant that scales the strength of the refractive index fluctuations. This constant, which is, in fact, a

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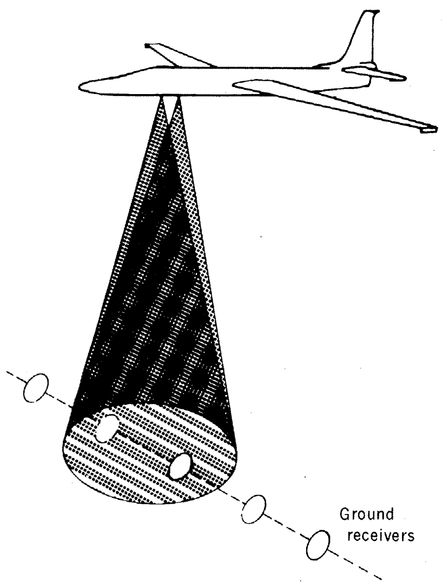


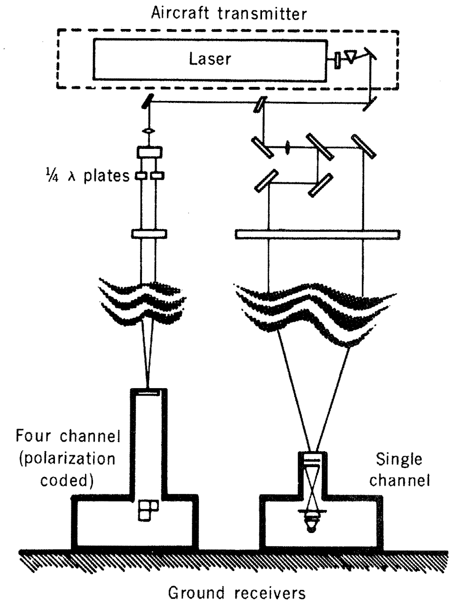


Fig. 1 (left). Geometry of the experiment. A pair of point sources on the aircraft formed fringes on the ground in the region of overlapped beams. Pairs of detectors were compared to reject errors due to aircraft motion and boundary layer turbulence. Fig. 2 (right). Diagram indicating the simultaneous operation of the experiment in two different modes.

variable with position in the atmosphere, describes the amplitude of the density fluctuations in the atmosphere. The refractive index structure constant is most often measured in terms of the temperature structure constant describing the associated temperature variation from point to point in the atmosphere. The density and index of refraction obtained from the related temperature structure constant are found to be spatially and temporally varying along the path of propagation of light through the atmosphere.

Many measurements have been made of temperature variations, and attempts have been made to correlate this to optical propagation. This has met with degrees of success ranging from excellent to very poor. One case of importance is that of a vertical propagation path. Unlike a horizontal path, along which one can place thermal sensors at many positions, a vertical path approximately 15 kilometers high cannot be readily monitored. Attempts have been made to measure the temperature structure constant of the atmosphere by the use of thermosondes. These thermosondes consist of separated, sensitive temperature sensors, which are carried by a balloon to high altitudes. The temperature difference between the sensors is recorded as a function of time and altitude. The temperature structure constant determined for this separation can then be converted to a density or refractive index structure constant.

This structure constant can be used in established formulas to predict the power spectrum of log amplitude fluctuations that would be observed when light propagates through the atmosphere. It is obvious, however, that these measurements are averages both in time and in space and are not necessarily representative of what is happening along a given propagation path.

It is therefore of interest to make some direct optical measurements of propagation on a vertical path, both to investigate correlation with balloon-borne instruments or other measurements of the structure constant of the atmosphere, and independently to obtain some statistics regarding the propagation of phase fronts vertically through the atmosphere. The result of such an experiment provides summary data describing phase propagation and coherence on propagation through the atmosphere. This gives information regarding the spatial stability or isoplanicity of imagery that can be obtained on looking out through the atmosphere, as well as a measure of the limits on imagery that may be produced with an aperture looking downward through the atmosphere. The latter is of special interest to the problem of two-way optical communication.

The aim of such an experiment is to obtain direct statistical values that can be used to predict propagation characteristics in either direction (up or down) on a vertical path. Such information should be correlated with other measures in so far as possible, and the results should be in a relatively simple form for descriptions of the overall statistics of propagation.

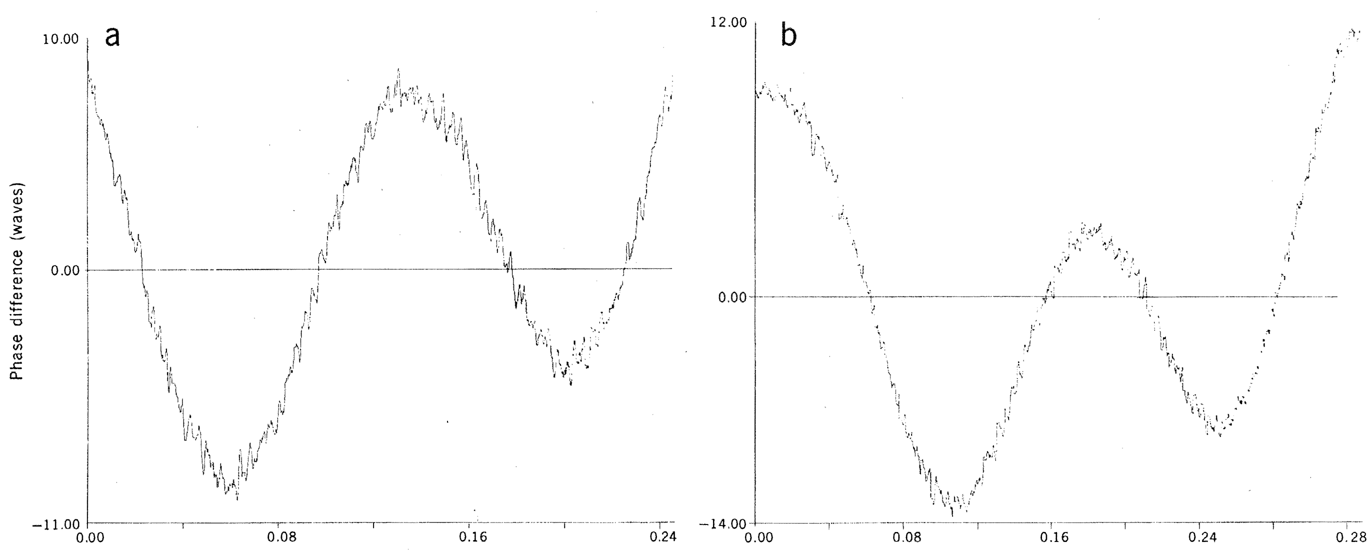


Fig. 3. Wavefront phase difference plots from single-channel detectors located (a) 150 feet north and (b) 50 feet north of the ground station.

The particular experiment to be described here was carried out by a group from the Optical Sciences Center of the University of Arizona in cooperation with the U.S. Air Force and for certain portions in cooperation with the Aeronomy Laboratory of the National Oceanic and Atmospheric Administration at Boulder, Colorado. The experiment has successfully answered questions about the general statistics of vertical propagation.

The method used was designed to investigate specifically the upward spherical wave propagation of light from the ground to high altitudes. Two pairs of separated coherent point sources were located on a high-altitude aircraft. The sources were illuminated by the 0.514- and 0.488-micrometer light from a 2-watt argon laser. Light from these point sources was propagated to the ground and received by a light detector. (Several detectors were used each time in the experiment.) Since point-to-point reversibility for phase and amplitude variations occurs, the geometry of two points at altitude and one on the ground permits determination of the phase structure characteristics of the wavefront between the source and receiver. The phase errors are weighted in terms of the propagation from a single point source on the ground, toward a large collector or receiver at high altitude. The geometry of the experiment is shown in Fig. 1.

An alternative interpretation in terms of an interferometric measurement is also indicated in the figure, since the two point sources act as the sources in a Young's double slit or double point interference experiment. As the aircraft carrying the point sources translates across the ground, the fringe pattern generated on the ground translates along with the aircraft. In the absence of any atmospheric variation effects or aircraft motion errors, a set of constantly spaced fringes are obtained and produce a single temporal frequency output from a detector on the ground as the aircraft flies by. In the presence of turbulence or aircraft disturbances, a frequency modulation of these fringes is obtained. Computer processing of the signals allows determination of the phase difference between the two points on the wavefront, and further processing permits direct calculation of the actual phase front that would have been obtained. Since the vehicle is moving at a significantly greater velocity than the atmosphere, application of the frozen atmosphere hypothesis that describes stationary statistics is applicable.

Figure 1 also indicates another important point in the experiment. Since light from the point sources spreads as it approaches the ground, several detectors can be used to look at independent atmospheric paths. The outputs of these detectors can then be subtracted from each other in pairs, and common mode effects such as boundary layers or instability of the aircraft platform can be removed

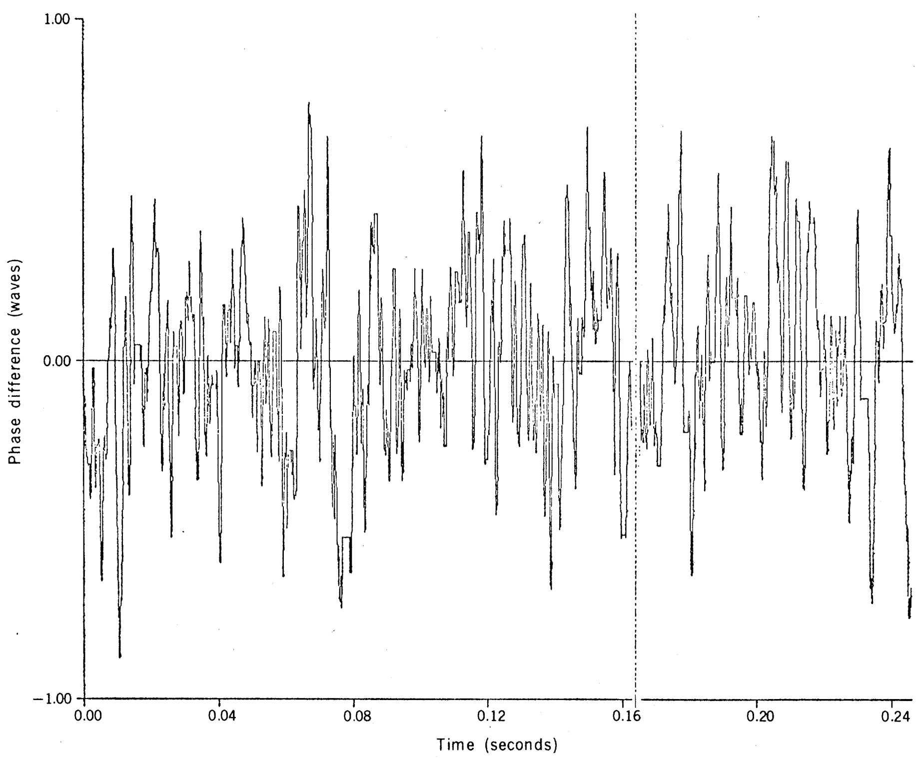


Fig. 4. Plot of the result of subtracting the data in Fig. 3, a and b.

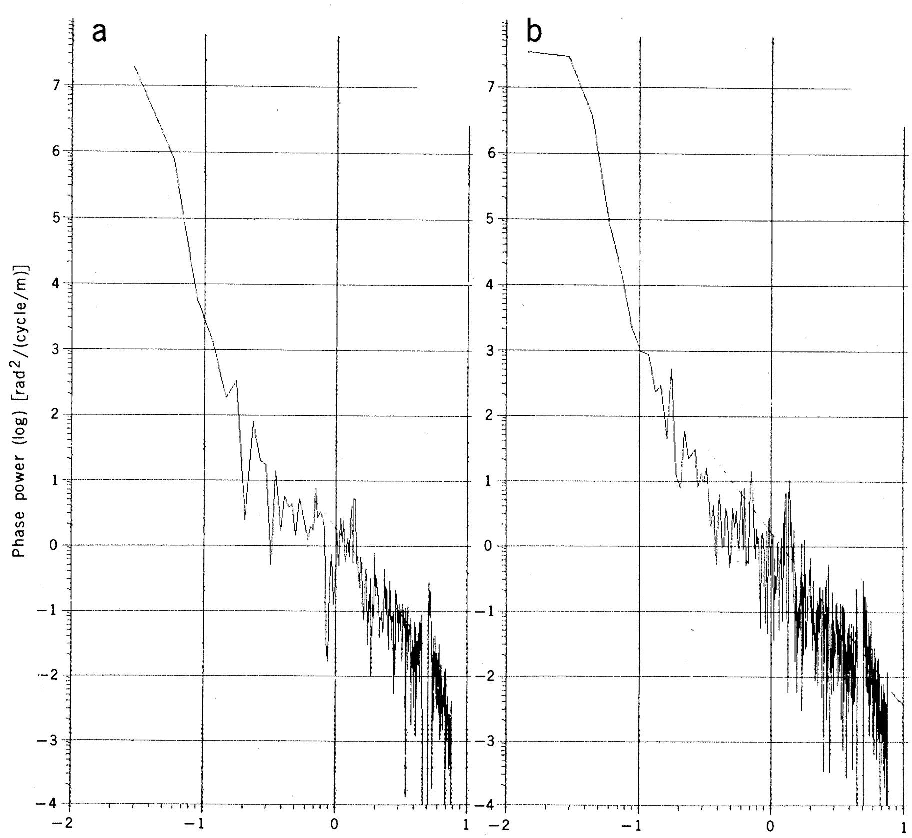


Fig. 5. Phase power spectra obtained from processing the wavefront difference data in Fig. 3. (a) Data for the 150-foot north detector and (b) for the 50-foot north detector.

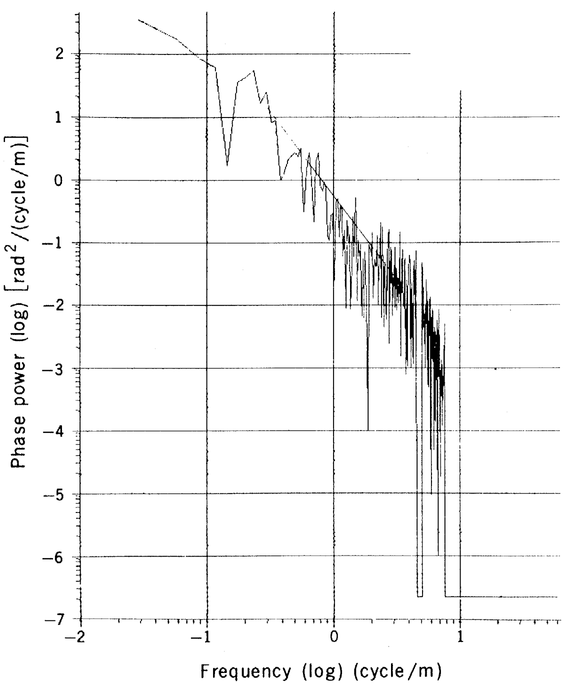


Fig. 6. Phase power spectrum obtained from the single-channel experiment. Note the change in scale.

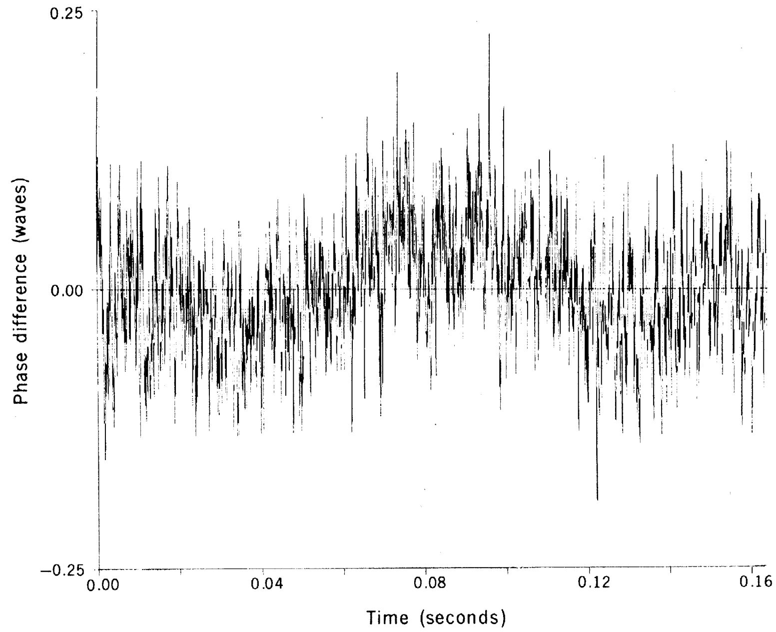


Fig. 7. Subtracted wavefront difference data for the four-channel experiment.

from the data. Thus all the data that remain can be attributed to free atmospheric turbulence.

Figure 2 indicates the solution to an additional factor. The measurement made depends on the source separation. The long distance of propagation indicates that some cases of turbulence saturation might be encountered that cause frequent dropouts of intensity and a loss of the continuous phase record required to establish the statistics. Two experiments were carried out simultaneously. Light from the argon laser was split into two bands. The green light at 0.514 $\mu$m was used to form two point sources that were circularly polarized in opposite directions. This polarization coding could be decoded by using several four-channel detectors that looked at four polarization signals of which two pairs of each were in quadrature. This allowed unambiguous recovery of phase errors through zeros of intensity produced by scintillation. The 0.488-$\mu$m line output of the argon laser was used to form a pair of point sources of variable separation that were detected by single-channel detectors. The results of both experiments were compared. The closeness of the wavelengths assures negligible atmospheric effect difference due to dispersion, but the difference in separation of the sources allowed data to be obtained simultaneously with two different source separations.

The experiment was flown several times during a period of 3 years from 1974 through 1977. Locations in Arizona, Florida, California, and Colorado were used. The Boulder, Colorado, experiment was carried out in conjunction with a 40-megahertz atmospheric sounding radar used to measure directly the radio refractivity structure constant of the atmosphere. This was corrected for humidity effects and compared with the direct optical data with very good success.

The above description appears simple, but the experiment was not, as anyone involved in atmospheric measurements and aircraft experiments can attest. It is pertinent here to discuss what the exper-

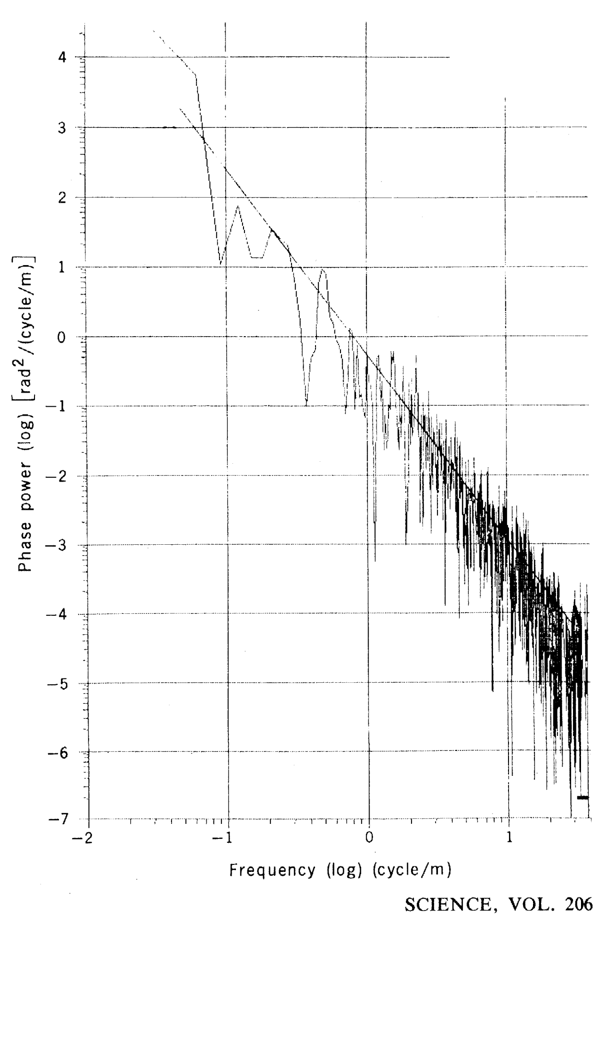


Fig. 8. Phase power spectrum obtained from the data of Fig. 7. Compare with the single-channel data in Fig. 6.

iment indicated that is new regarding the statistics of atmospheric propagation. Sample outputs of the experiments are included in Figs. 3 through 8. Figure 3, a and b, shows two wavefront difference plots as a function of time obtained in May 1976 in Florida. These were taken with the single-channel experiment, and represent measurements obtained from detectors located 15.2 and 45.7 meters north of the center line of the detector array. The large prominent 4.5-hertz variation is due to motion of the experimental package within the aircraft. This turned out to be a significant indicator that good data were being taken. Subtraction of the two curves yielded Fig. 4, which is the difference between the two paths. The atmospheric turbulence data are contained within this signal. The very fast high-amplitude fluctuations are due to noise in the experiment. Figures 5 and 6 show the single-channel phase power spectrum description of the individual wavefront data in Fig. 3. There appears to be a consistent slope only at higher spatial frequencies, as would be expected from the vehicle motion contamination. Figure 6 shows a single-channel phase power spectrum of the differenced data. Note that a slope of minus eight-thirds, as is theoretically predicted, can be seen over the range from 0.1 to almost 10 cycles per meter. These particular data were taken at an altitude of 17 kilometers, and numbers were later scaled to a common altitude of 20 km for comparison. It is significant that although the data are noisy, the linear slope on the logarithmic plot appears valid over almost two orders of magnitude in frequency and three orders of magnitude in phase power.

The next figures show data taken on the four-channel experiment, with a separation of 20 m between the sources. Figure 7 shows the difference between the two phase-difference data. Note that the vertical scales indicate measurement accuracies in the experiment of approximately 0.01 wavelength difference in phase between the two sources. Figure 8 shows a phase power spectrum of the difference between the two signals. Here again a specific slope is clearly visible, and it is important to note that the two experiments give similar values for the magnitude of the phase power spectrum at 1 cycle per meter. This can be used as a convenient index for the level of turbulence.

The above data are representative of one set of data from one pair of detectors at one of several hundred successful passes on which data were collected during this experiment. The data collected at several experimental sites indicate a

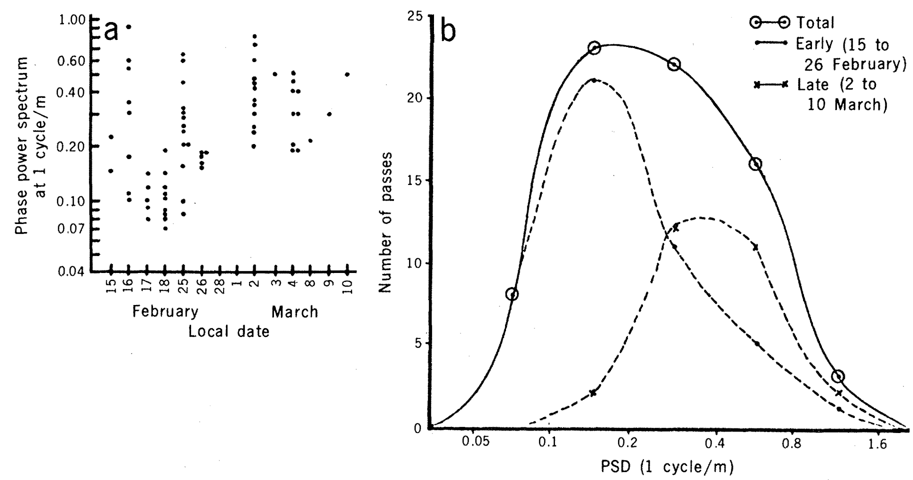


Fig. 9. (a) Plot of observed values of phase power spectrum at 1 cycle per meter obtained at Truckee, California, in February 1977. (b) Histogram of the data in (a); *PSD*, power spectral density.

Gaussian or normal distribution of values for the phase power spectrum at 1 cycle per meter. When normalized to an altitude of 20 km the phase power spectrum varied from about 0.07 to 0.13 radians squared per cycle per meter. According to formulas provided by Fried (*2*), this indicates coherence widths from 0.7 down to 0.13 m with a mean of approximately 0.35 m. Figure 9 shows a plot of data taken at Truckee, California, in February 1977. Figure 9a is a plot of the points obtained on each date. The missing dates were times when heavy snowfall during a weather change occurred. As can be seen, the data appear to be randomly distributed but in two groups, with some difference in the mean prior to and after 1 March. Figure 9b shows a histogram of the data. This can be considered typical of data observed in the experiment.

Fairly rapid variations of the phase power spectrum, always well within the range of the average data, occur as a function of time of day during the experiment. This indicates that rapid variations in the refractive index structure constant occur and that the average data obtained by balloon-borne thermosonde measurements are not representative of the nature of the atmosphere on a vertical path. For this reason, only approximate matching of data with thermosonde data taken during the experimental time was possible. Most of the data were obtained between sunrise to an hour or two after local noon time.

The noise level for data in this experiment was about a full order of magnitude below the levels of phase power spectrum recorded in the experiment. This was demonstrated by moving detectors successively closer together during a sequence of passes and demonstrating that

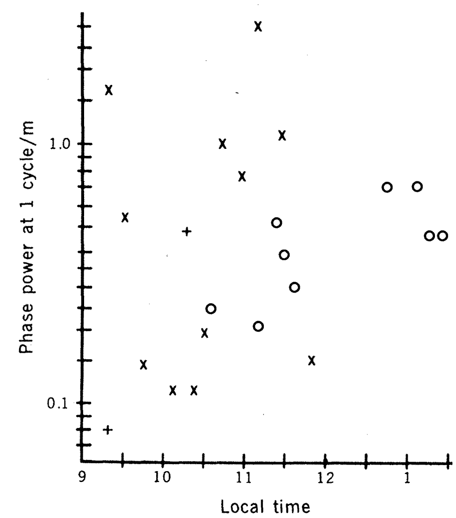


Fig. 10. A sample comparing optical data (○) and radar-derived optical phase power spectra (x and +) taken at Boulder, Colorado, in August 1977.

when the detectors were within 4 centimeters of each other, the atmospheric effect disappeared and all that remained was noise in the measurement.

Of note is the comparison between measurements of profiles of radio refractive index structure constants taken with a radar (*3*). The series of data taken at the Sunset radar site near Boulder, Colorado, in August 1977 indicated good agreement with the optical data. We show an example of this in Fig. 10, in which the phase power spectrum value at 1 cycle per meter is plotted against local time. The radar data provided measures of refractive index structure constant, which were used in carrying out an integration along the vertical path to compare with the optical data. Figure 10 shows the optical data as a series of circles and the radar data as +'s and x's plotted on the same scale. As can be seen, the points overlap each other, and in general show a factor of about 3 between the optical and radar data. This describes the agreement between the two independent measurements of atmospheric propagation (*4*).

A comment is in order on Fig. 10. The calculation of the profile depends on adjustment of the radar cross sections by means of a series of empirical constants. A principal contributor is the humidity, which is obtained from coordinated rawinsonde launches. Difficulties with this coordinated data reduced the overlap between the time sequences of radar and optical data. The +'s and x's on the figure indicate data taken with east- or west-directed radar beams, respectively.

This is the only direct measurement of the phase front statistics on vertical path propagation that is available. Other experiments have generally produced measurements of log-amplitude fluctuations that were used to infer the phase statistics. The matching of the power spectral distributions obtained on several hundreds of passes shows that the theoretical predictions regarding the inertial theory of turbulence are correct. In fact, this experiment has shown the presence of small jogs in the phase power spectrum that have been predicted theoretically and indicates an interchange of energy between log-amplitude scintillation and phase power content.

In conclusion we can say that this current work provides a reliable body of experimental data that supports the theoretical predictions of the inertial theory of turbulence. Furthermore, this work establishes levels for the statistical behavior of the atmosphere on the basis of direct optical measurements. From the nature of the measurements and the correlation with the very-high-frequency measurements, it is seen that averaged thermosonde sounding of the atmosphere to establish propagation data is of such a nature that it does not adequately describe the optical propagation observations.

The above-stated numbers described a possible average state of the atmosphere. Because the measurements generally fitted normal distribution over about 95 percent of the range, it can be presumed that these measurements characterize the atmosphere, within the latitude range studied, quite well. No significant difference would be expected for different geographic locations. Since the weighting with altitude for the upward-going spherical wave case studied here requires very little weighting at low altitudes, this indicates little dependence on local orographic turbulence characteristics, as would be expected. The consistency of the data that were taken both in the mountains and the deserts and shore area confirmed this behavior.


**References and Notes**

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# Terminal Cretaceous Extinction

## Scenario for a Catastrophe


Stefan Gartner and James P. McGuirk


A number of mechanisms have been proposed for the massive extinction of biota at the Cretaceous-Tertiary transition some 65 million years ago. Most of them were reviewed recently (*1*). Two additional mechanisms have been proposed, however, since that review was compiled—the "greenhouse" mechanism (*2*) and the Arctic spillover model (*3*). In the first of these, McLean has proposed that the large land and marine reptiles as well as the marine plankton (plant and animal) and many marine invertebrates became extinct at the end of the Mesozoic era because of an increase in surface temperature of the earth, this increase being the result of an elevated carbon dioxide level in the atmosphere (greenhouse effect). McLean's mechanism is at variance with data regarding this event (*4*) and it presents a line of reasoning that is subject to debate (*5*). The second mechanism, proposed by Gartner and Keany, requires that the entire world ocean was covered by a layer of low density water that originated from a fresh or brackish Arctic Ocean, and that the drastically reduced salinity at the surface and intense oxygen depletion beneath the surface water caused the more or less instantaneous extinction of much of the marine biota. Citing recent studies of the paleomagnetic record across the Cretaceous-Tertiary boundary (*6–8*) and a detailed assessment of the vertebrate succession (*9*), Gartner and Keany concluded that the marine extinctions and the terrestrial extinctions probably were not simultaneous. This conclusion may have been incorrect (*10*), and here we will explore this point more fully.

Briefly, the mechanism proposed by Gartner and Keany requires that the Arctic Ocean became essentially isolated from the world oceans in latest Cretaceous (late Maastrichtian) time, probably by a combination of tectonism and a gradual regression of shelf seas. Because of excess precipitation and runoff, the salt water was flushed from the basin making the Arctic Ocean a fresh or brackish body of water. When rifting was initiated between Greenland and Norway some 65 million years ago, salt water from the North Atlantic intruded into the Arctic basin, while at the same time the lighter Arctic Ocean water spilled out over the North Atlantic and beyond into the South Atlantic and, through the Tethyan and Caribbean seaways, covering the entire ocean surface with a layer of water of low salinity. This low salinity layer caused the extinction of most of the stenohaline planktonic organisms that lived at the surface, whereas beneath the surface layer depletion of dissolved oxygen had a severe impact on organisms with a high oxygen requirement, benthos as well as nekton (*11*). Stable isotope data from late Cretaceous


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