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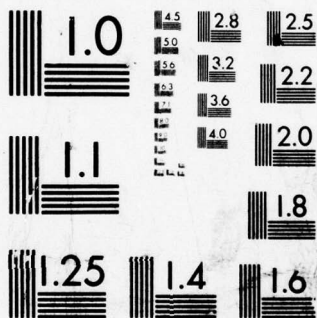
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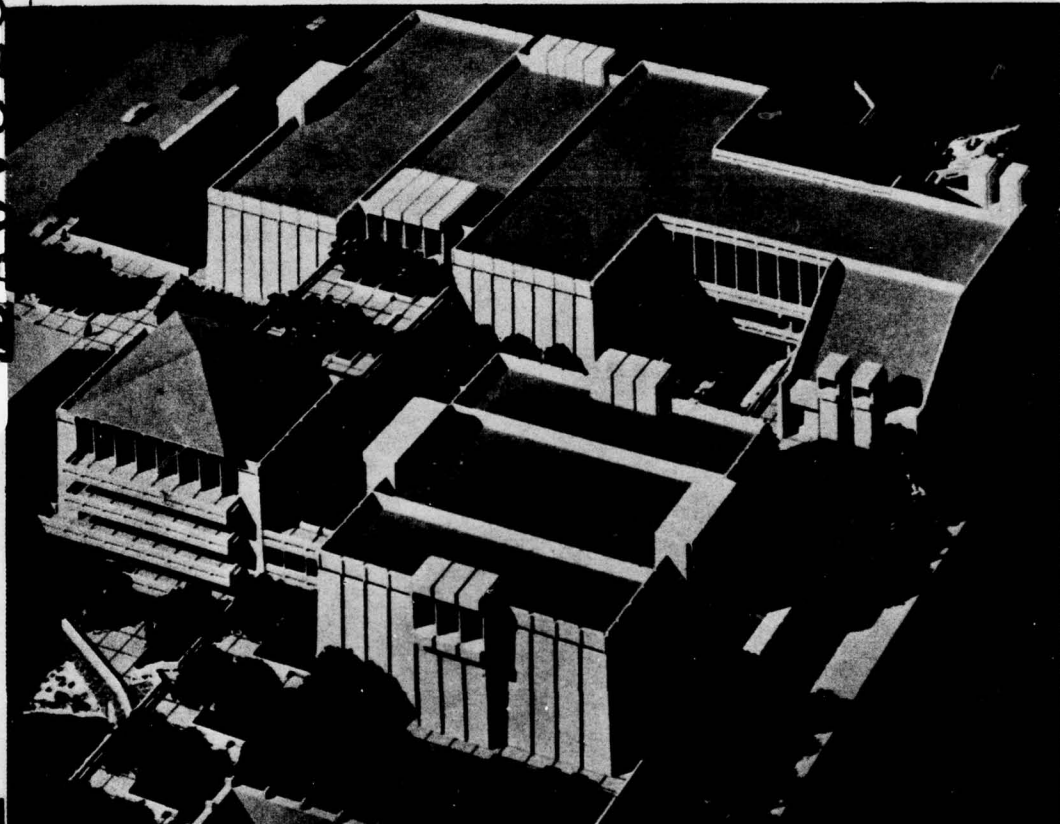
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ELECTRICAL ENGINEERING DEPARTMENT

ATMOSPHERIC TURBULENCE EFFECTS ON THE TEMPORAL  
SPECTRAL DENSITIES OF OPTICAL SIGNALS

FINAL REPORT

DA 073231



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This summary report describes the major efforts and results obtained during the contract period. The objectives were to extend the applicability of optical methods of crosswind sensing to obtain operation under strong turbulence conditions, and to investigate the effects of motion on the optical speed measurement. Two optical windspeed instruments designed to be unaffected		

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CONT

by strong turbulence were built and tested. One design was based on the measurement on the time delay required to obtain a peak in the crosscorrelation function derived from intensity fluctuations, and the second design was based on fluctuations of the beam angle of arrival. Both instruments were tested over 2 km paths and the operation was unaffected by increasing turbulent strength. An instrument, using an optical beam and spatial filters at the transmitter and receiver, was built to demonstrate the feasibility of the technique to profile cross-path windspeeds along the beam. The device was tested to path lengths of 500 m and operated satisfactorily. A study was conducted on the errors produced in an optical wind speed measurement due to motion of the receiver and/or beam source.

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ATMOSPHERIC TURBULENCE EFFECTS  
ON THE TEMPORAL SPECTRAL DENSITIES  
OF OPTICAL SIGNALS

Grants: DAHC04-75-G-0102  
DAAG29-78-G-0027

FINAL REPORT 7/31/79 FR1-79-UA-66

By

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Grant Awards and Duration

Grant number DAHC04-75-G-0102 covered the period from 1 June 1975 to 31 March 1978. The expenditures from grant funds during that period totaled \$53,293.00.

Grant number DAAG29-78-G-0027 covered the period from 1 April 1978 to 31 May 1979 during this period the expenditures totaled \$25,559.00.



Statement of Problem:

The cross-correlation function obtained from the observation of intensity fluctuations at two or more points within a coherent optical beam has been used to determine the wind speed normal to the optical axis. The technique yields good results when the measurements are made under conditions of weak turbulence. The turbulence can be expressed through the variance in the intensity of the optical signal. This variance depends upon the path length, the refractive index structure function, and the reciprocal wave length of the signal frequency. The optically measured strength of turbulence is related to the product of these three parameters when each is raised to an appropriate power [1]. If this value approaches 0.3 the optically measured turbulence is considered strong. Under strong turbulence the variance of the intensity fluctuations attains a maximum value, and "saturation" exists.

Difficulties have been encountered in attempting to extend the wind measurement technique to long ranges as strong optical turbulence is often encountered. The problem is that the measured values obtained for wind speed depend upon a calibration technique based on the shape of a cross-correlation function derived from a theory based on weak turbulence conditions.

During conditions of high optical turbulence the shape of the correlation function changes and, in fact, is dependent upon the path length and the strength of the turbulence. This shape change voids the instrument calibration. As a consequence these optical instruments will not yield good wind speed estimates under "saturation" conditions.

The purposes of the research conducted were to (a) develop techniques and instrumentation which could be used to measure crosswind magnitudes and be able to operate satisfactorily under conditions of both weak and strong turbulence and (b) investigate the effects of source and/or receiver motion on the optical measurements of crosswind magnitudes. To satisfy the first requirement, the basic measurement concept had to depend on characteristics other than the shape of the correlation function used to describe the intensity fluctuations. To determine those properties which could be used to extract the desired measurement under strong turbulence, it was proposed to relate the spectral characteristics of the intensity fluctuations and the angle of arrival fluctuations to the wind speed. The latter fluctuations were investigated as the correlation function depends mainly on larger turbulent cell sizes and the path weighting differs from the weighting obtained for intensity fluctuations. Thus

the effects of saturation differs in the two measurement techniques. An adjunct to the desired measurement capability was obtaining wind profile information over the optical path.

#### Technical Summary

At the initiation of the first grant, techniques had been developed to use the observed intensity fluctuations in an optical beam to obtain a measurement of the average wind speed normal to the beam. One accepted technique uses a bistatic configuration of a low power visible laser transmitter and a receiver consisting of two or more closely spaced photodiodes [2]. The signals from the photodiodes are cross-correlated and, the slope of the correlation function is then related to the magnitude of the cross path wind speed. This technique works with acceptable accuracy during conditions of weak to moderate turbulence over short (500m) optical path lengths. However, over longer paths (up to 2 km) the performance of the optical instrument degrades as turbulent strength increases.

Field experiments were conducted to determine the extent and causes of the performance degradation. Most of the tests were conducted at the Atmospheric Sciences Laboratories, Biggs Optical Range. The range provides optical paths of 0.5 and 2 km with a linear array of closely spaced anemometers along the path. The anemometer

array was used to evaluate the optical instrument performance. In addition, differential temperature and solar radiation instruments were provided as well as multi-channel magnetic analog tape and strip chart recorders.

Where possible, the unprocessed detector outputs, intensity fluctuations and angle of arrival fluctuations were recorded on the analog tape. This allowed retention of all optical signal data so the data could be processed by different techniques in the laboratory. The results could then be compared with those obtained from the anemometers and other sensors.

Signals used to obtain the log-amplitude variance and the covariance of intensity fluctuations were processed through low pass filters prior to calculating the variance to examine the temporal filtering effects as a function of the upper cutoff frequency. Measurements of log-amplitude variance, showed strong evidence that the saturation effect was essentially independent of the filter cutoff frequency. By filtering the signals used to obtain the covariance or correlation functions, one could obtain relatively accurate wind speed measurements in strong turbulence, but it involved increasing the instrument gain with increasing strength of turbulence [3].

It has been shown [4] that saturation effects can be explained through the degradation of wave coherence as

it propagates through the turbulent medium. The loss of coherence changes the shape of the correlation function [5] and consequently the spectral content of the observed signals depends upon the optical path length and the strength of turbulence. For operation over a long path and strong turbulence, any wind instrument dependent upon coherent wave properties would require an input of the magnitude of turbulence from a separate, independent measurement device.

Due to the above limitations the techniques studied to develop optical wind speed instruments were limited to a) time delay measurements associated with a cross-correlation function, b) the use of large aperture systems ( $>3 \lambda L$  [6]), and c) the use of noncoherent signal sources. With (c) the signal to noise ratio was relatively poor and the spectral content of the received signal depended upon the spatial Fourier spectrum of the source scenes [7].

Three instruments, each employing measurement of a different parameter, were designed, constructed and field tested. The descriptions of each are given below:

(a) The first instrument completed used a time measurement to determine the spread or width of the cross-correlation function developed from intensity fluctuations sensed by two small photodetectors [8]. The instrument provided real-time wind measurements and did show relative

resistance to saturation effects. The calibration of the instrument did not require adjustment with increasing turbulent intensity. Because of the shorter time delays encountered in measuring correlation function changes at the higher wind speeds the device performed best at speeds greater than 3 m/s. This lower speed characteristic would establish a minimum speed threshold for the particular instrument. A correction factor was developed to account for the expected decay of the turbulent structure during time delay, but it was not implemented in the device hardware. Incorporation of the correction factor would lower the minimum speed threshold.

b) The second instrument was a large aperture device (14 cm) which sensed angle of arrival fluctuations [9,10]. Resistance to saturation was expected as the beam arrival angle is influenced primarily by the larger turbulent cells (on order of the beam width or larger) and the device can use either a coherent or noncoherent light source. The theoretically derived path-weighting function showed that the winds closest to the signal source would dominate the measurement. Changes in the autocorrelation function derived from a signal proportional to the beam's angular fluctuations are related to the wind speed. Real time wind speed variations obtained from this device closely matched those obtained from anemometers near the

signal source [11]. While the speed variations obtained from the optical instrument compared well with values from the anemometer, the former values contained a fixed offset. This was easily compensated to provide a close match in average speed as well as a match in variations of speed.

c) The third instrument used spatial filtering to demonstrate the feasibility of obtaining wind profiles with a single optical instrument. A noncoherent source was used to provide a beam whose intensity fluctuations were observed in a plane normal to the beam axis. This technique utilizes spatial filters at both the transmitter and receiver [12]. The filtering action uniquely specifies the path position and perturbing cell size of the inhomogeneity producing the observed intensity fluctuations. A simplified theory has been developed for determining the required filter characteristics [13]. The theory leads to a graphical construction which specifies some of the filter characteristics. By this technique, the measured frequency of the intensity fluctuations is related to the wind speed at the specified path location. Wind speeds were measured with two different models of this instrument over path lengths of 60 and 500 meters. The values obtained compared favorably with the speeds obtained from anemometers located at the filter tuned path position.

Additionally, it was found that the wind profile maintained its structure in time, sufficient to track the motion of its major features along the anemometer array.

All measurements of the wind speed described above are generally made with the source and receivers in fixed positions. The expected errors in wind speed measurement caused by source and/or receiver motion were studied [14]. Generally it was concluded that errors due to source motion can be minimized through the adjustment of the receiver geometry i.e., controlling the weighting function. Receiver motion can be compensated through the use of a "sleuable" array.



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6. Smith, J., Effects of Source and Receiver Motion on the Optical Measurement of Wind Speed, Technical Report, Electrical Engineering Department, U.T. El Paso, March 1979.

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