WIND VELOCITY MEASUREMENTS BY OPTICAL SCINTILLATIONS METHODS

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Abstract

Scintillations-based optical techniques for the measurement of the atmospheric transverse average wind velocity are re-examined. Three different methods for the processing of the resultant time-lagged covariance function are compared to in-situ anemometer measurements. A correlation index of 0.89 - 0.95 is obtained between the optical and anemometer results and it tends to increasing with the measurement time constant. Some degradation in the accuracy of the optical methods is observed when the spacing between the detectors is either much smaller or much larger than the Fresnel zone [AL]^{1/2}.

I. INTRODUCTION

Consider Fig. 1 where a laser illuminates two detectors through a few hundred meters of atmospheric turbulence. The output of each detector will fluctuate as a result of the optical intensity scintillations generated by the turbulent refractive-index inhomogeneities ("eddiess") which are dragged by the atmospheric wind across the line of sight. If the two detectors are transversely close enough, the eddies responsible for the fluctuations at the output of detector 1 at time t1 will not change by much by the time they become responsible for the fluctuations at the output of detector 2 at a later time t2. Quantitatively, it can be expected that the temporal cross-correlation function between the outputs of these two detectors will peak at a certain time delay which is related to the path-averaged wind speed component, perpendicular to the line of sight but parallel to the two detectors1-3. Several algorithms have been proposed for the actual extraction of this wind speed component from the time-lagged cross-correlation function3-4.

It is the purpose of this paper to compare three of these algorithms, namely the peak method, the zero slope method, and the autocorrelation method4, with respect to their accuracy and ease of implementation. In Section II we briefly review the theory of optical remote sensing of the atmospheric cross-wind and describe in more detail the above-mentioned three algorithms. We have also developed a simple optical system. Section III, which uses the described principles to measure the atmospheric transverse wind velocity. Section IV presents the experimental results as obtained in field tests and also includes a discussion of the relative accuracy of the different methods.

II. THE THEORY OF CROSSWIND MEASUREMENT TECHNIQUES

It is well-known from previous works1-8 that the normalized time-lagged cross correlation function of log-amplitude, for a spherical wave propagating through homogeneous and isotropic weak turbulence is given by

\[ f(\rho, r) = \frac{C_X(\rho, r)}{C_X(0, 0)} = \frac{2.33k^4/4L^{11/6}}{B(11/6,11/6)} \int_0^L dz \int_0^{\infty} dK K^{-8/3} J_0 \left( \frac{\rho z}{L} - \nu(z) r \right) \sin \left( \frac{2z(L-z)}{2kL} \right) K_3 \]  

(1)

\( \rho \) is the transverse distance between the detectors, \( r \) is the time delay argument, \( k \) is the optical waven-
Figure 1: Time delay to the peak and correlation slope method of wind velocity measurement.

Figure 2: Examples of TLA and TLC with 3 processing techniques we use: $t_p$ - time of peak of TLC; $t_f$ - time when TLA equals 0.5; $S_0$ - slope of TLC at $t=0$.

umber, $L$ is the propagation range, $v(z)$ is the that component of the wind velocity, at range $z$, which is both perpendicular to the transmitter-receiver line-of-sight and parallel to the line connecting the detectors,
and $B(a,b)$ is the Beta function. In Eq.(1) we also assumed that the random refractive index of the atmosphere can be modelled as a statistically homogeneous and isotropic random field, having the Kolmogorov-type spectrum$^8$

$$\Phi(K)=0.033 C_n^2 K^{-11/3}$$

(2)

$C_n^2$ is the refractive-index structure constant. In deriving Eq. (1) use was made of Taylor's "frozen turbulence" hypothesis which states that for sufficiently short time periods the refractive-index irregularities in the atmosphere are drifted with the wind with no change in shape. The above formulation is valid only for weak integrated turbulence, i.e., when the so called Rytov parameter $\sigma_X^2$ does not exceed 0.3. For a spherical wave this parameter is given by the relation$^1$

$$\sigma_X^2=0.124 C_n^2 \frac{k^7}{\pi L^{11/6}}$$

(3)

Experimentally it is preferable to measure the covariance function of the irradiance $C_1(\rho, r)$ rather than $C_X(\rho, r)$. But as long as $\sigma_X^2$ is small enough and the intensity fluctuations are distributed according to a log-normal law, $C_1(\rho, r)/C_1(0, 0)$ and $C_X(\rho, r)/C_X(0, 0)$ are approximately equal and Eq. (1) can be used to describe either one.

We may now describe some of the major remote sensing techniques of the atmospheric average crosswind.

Three of them are:

a) The peak method - Typically, the normalized time-lagged covariance (TLC) function has a principle peak at a time lag $r_p$, see Fig. 2. The relation between $r_p$ and the transverse wind velocity $v(z)$ can be derived from Eq. (1) by solving

$$\left. \frac{\partial f(\rho, r)}{\partial r} \right|_{r=r_p}=0$$

(4)

For simplicity, let us assume that $v(z)$ is constant along the propagation path, i.e., $v(z)=V$. Under this assumption

$$\frac{\partial f(\rho, r)}{\partial r} = \frac{V \cdot 2.333 K^{7/6} L^{11/6}}{B(11/6, 11/6)} \int_0^\infty dK \int_{-L/2}^{L/2} \frac{dz}{2K^{7/3}} \frac{dz}{2V} \left[ K \left( \frac{z^2}{2L} - Vr \right) \right] \sin^2 \left( \frac{(z^2+L/2)(z^2-L/2)}{2K} \right)$$

(5)

where the range variable $z$ has been replaced by $z'=z-L/2$. Obviously, for $r$ obeying

$$r=r_p = \frac{\rho}{2V}$$

(6)

the integrand over the $z'$ variable is odd and $\partial f(\rho, r)/\partial r=0$, thereby certifying that $r=r_p$ is an extremum point - a maximum in our case.

Physically this result is clear since the time needed by an irregularity to pass between the two detectors spaced a distance $\rho$ depends on its distance, $z$, from the point source: $r_{pass}=\rho z/VL$, the average of which over the propagation path is $r_p$ of equation (6).
c) The \( r=0 \) slope method - The slope of the normalized TLC function at \( r=0 \)

\[
S_0 = \frac{\partial f(\rho, r)}{\partial r} = \frac{2.33k_b/\rho L^2}{B(11/6, 11/6)} \int_0^L dz \ v(z) \left[ \int_0^\infty dK \ K^{-5/3} J_3 \left( \frac{\rho z}{L} \right) \sin^2 \left( \frac{z(L-z)}{2KL} K^2 \right) \right]
\]

\[
= \int_0^L dz \ v(z) W(z)
\]

(7)

is therefore related\(^{1,2}\) to the transverse wind velocity through the weighting function \( W(z) \). The shape of \( W(z) \) depends on the parameter \( \beta = 0.5 \cdot r / \sqrt{KL} = \rho / \sqrt{KL} \) which is the ratio of the detector separation to the radius of the first Fresnel zone. For \( \beta \approx 0.5 \) the weighting function is approximately uniform along the path and \( S_0 \) is proportional to the average wind velocity

\[
S_0 \propto \bar{V} = \frac{1}{L} \int_0^L dz \ v(z)
\]

(8)

If on the other hand \( W(z) \) is significant only in the vicinity of \( z=z_0 \), \( S_0 \) will be related to \( V = v(z_0) \).

In a previous work\(^*\) we have given an alternative and computationally more useful expression for \( S_0 \):

\[
S_0 = V \cdot U(\beta) \cdot \sqrt{\frac{K}{L}}
\]

(9)

where \( U(\beta) \) is a universal function which can be computed a priori for all \( \beta \), and \( V \) is the average transverse wind velocity in that path portion for which \( W(z) \) has a maximum for the \( \beta \) used in the experiment.

c) The autocorrelation method - When the effect of the drifting turbulent "eddies" is measured with only one detector, one can form the normalized time-lagged autocorrelation (TLA) function of the laser irradiance, Fig. 2. Obviously, this function is symmetric around its maximum at \( r=0 \). The value \( r_f \) where the function equals 0.5 is also controlled by the wind velocity \( V \). Mathematically we can find the connection by solving the equation:

\[
f(\rho=0, r=r_f) = 0.5
\]

(10)

It is easy to see that if we replace \( v(z) \) by a constant wind velocity \( V \), the solution must be:

\[
V = \text{const} \frac{1}{r_f}
\]

(11)

where the constant must be found numerically.

Physically, Eq. (11) expresses the fact that the higher the wind velocity the shorter is the time required to sweep the spatial transverse correlation distance of the intensity fluctuations across the single detector. As a result, the narrower is the width of the autocorrelation function and \( r_f \) is smaller. Since it involves the use of only one detector this technique appears to be simpler, but its main disadvantage is that it gives us only the absolute value of the wind velocity with no direction information.
III. EXPERIMENTAL SET-UP

The experimental set-up is shown in Fig. 3. Its main building blocks are: (a) The light source; (b) The receiver; and (c) Data processing. The light source is a TEM₀₀ single mode, He:Ne CW laser with a power output of 7 mW, operating at a wavelength of 0.6328 μm. The receiver apparatus consists of two approximately point detectors (φ300μm), located behind and perpendicular to a large beam-splitter. Each detector can be translated in a direction perpendicular to its line of sight. In this way it becomes possible to simultaneously measure two locations on the laser spot with a relative distance of as short as zero and as long as the width of the beam-splitter. A calibrating aperture is inserted in front of the system in order to define the zero position where the two detectors sample the same point in the center of their field of view. The use of point detectors eliminates the reduction of the scintillation variance due to spatial averaging, and so enables the verification of the basic first order scattering theory under weak integrated turbulence conditions.

![Diagram of experimental set-up](image)

Figure 3: Schematic representation of the experimental set-up and the experimental system of the wind speed measurement.

The signals from the receivers are sampled and digitized by a 12 bit A/D digitizer which is synchronized by microcomputer software interrupts. The rate of data sampling is 10kHz for each receiver. Two propeller anemometers along the path give an in-situ measurement of the cross-wind. A personal computer is used for the complete data collection and also for the analysis.

IV. EXPERIMENTAL RESULTS AND CONCLUSIONS

Field tests were performed in the day time during the summer of 1987. Measurements were made using a 100 meter path over a flat and uniform sea sand area, where $C_n^2$ is approximately constant along the optical path. All the data collecting instruments were placed in the same height of 1.5m above the ground. The laser atmospheric-induced pattern was first sampled with a 2mm distance between the detectors and for a
time period of 1 sec. For each laser intensity measurement, a background intensity measurement was also made, in order to filter out the influence of the non-correlative background noise on the laser intensity TLC function. The same procedure was followed for displacements of 4 mm, 6 mm, and 8 mm between the point detectors and was repeated several times during the day. The accumulated raw data was used to form the TLC functions, from which the cross-wind component was computed using the three methods described in Sec. II.

Fig. 4 shows some of the optical results superimposed on the averaged readings of the two anemometers. The degree of fitness was estimated using the correlation index, $\gamma$, between $V_{\text{optic}}(t)$ and $V_{\text{anemom}}(t)$,

$$
\gamma = \frac{\int_{-\infty}^{+\infty} [V_{\text{optic}}(t)-\bar{V}_{\text{optic}}(t)] [V_{\text{anemom}}(t)-\bar{V}_{\text{anemom}}(t)]dt}{\sigma_{V_{\text{optic}}} \sigma_{V_{\text{anemom}}}}.
$$

(12)

where $\bar{V}$ denotes the average velocity and $\sigma_{V_{\text{optic}}}$ and $\sigma_{V_{\text{anemom}}}$ are the standard deviations of $V_{\text{optic}}(t)$ and $V_{\text{anemom}}(t)$, respectively.

![Figure 4: Experiment comparison of the 3 methods to anemometers measurement of the average wind velocity. Distance between transmitter and receiver is 100m and averaging time is 1 sec.](image)

Fairly high values of $\gamma$ were obtained in all experiments. A correlation index of 0.89 was obtained between the averaged anemometer readings and the peak and slope methods. Its value increased to 0.95 when the anemometer readings were compared to the autocorrelation method. For averaging times longer than 1 sec., the statistical fluctuations in $V_{\text{optic}}(t)$ decreased and the correlation indices between the anemometer data and the results of the 3 optical methods were all in excess of 0.95.
The autocorrelation method appears to provide the most accurate data. This is consistent with previous work\textsuperscript{4}. The less accurate results obtained from the peak method under short time averaging are probably due to a fluctuating wind along the propagation path. The autocorrelation method is more immune to the effects of a non-zero wind-velocity variance.

The slope method, while being slightly less accurate than the autocorrelation method, still provides better results than the peak method. This experimental finding can be attributed to the fact that the transverse wind velocity computed by the slope technique is actually a weighted average of the wind velocity along the path with the proper weighting function \( W(z) \) of Eq. (7). This function is not uniform along the path and as mentioned before, it emphasizes some regions of the path more than others, depending on the geometrical parameters of the system. But in the meteorological determination of the wind velocity we used a simple average of the readings of the two anemometers, i.e., we used a uniform weighting function. These different weighting techniques can explain part of the discrepancy between the results of the slope method and those of the anemometers.

In a thorough study of the experimental data obtained by the slope method it has been found that the accuracy decreases when \( \rho < [\lambda L]^{1/2} \) or \( \rho > [\lambda L]^{1/2} \), where \( \rho \) is the distance between the detectors. To explain this behavior we note that when \( \rho < [\lambda L]^{1/2} \) the most effective "eddies" are on the order of magnitude of the inner scale of turbulence, \( \ell_0 \), and the use of the Kolmogorov spectrum is no longer valid\textsuperscript{7} for the calculation of the correlation function. On the other extreme when \( \rho > [\lambda L]^{1/2} \), the validity of the Taylor frozen-in hypothesis could be in question.

In summary, in this paper we have tested three scintillations-based optical techniques for the measurement of the atmospheric transverse average wind velocity, namely: the peak method, the zero slope method, and the autocorrelation method. While the autocorrelation method provided the best accuracy, it does not provide information on the wind direction. In these experiments the slope method and the peak method had approximately the same accuracy. The slope method, though, is the easiest and requires the least number of data points.

5. REFERENCES