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An Optical Scintillometer for Simultaneous Measurements of Atmospheric C_n^2 and Winds

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Laser scintillations produced due to the inhomogeneities present in the atmosphere can be used for measuring refractive index structure parameter (C_n^2) as well as wind velocity. The present paper deals with the description of an optical scintillometer developed at the Indian Institute of Tropical Meteorology (IITM), Pune, India for simultaneous measurements of path-averaged C_n^2 and crosswinds. Different evaluation techniques and their relative merits for wind estimation from optical scintillometer observations are discussed. The results show good agreement between the scintillometer evaluated winds and the winds measured simultaneously by using propeller anemometer at the same location. In addition, this paper explains the effect of C_n^2 and wind fluctuations along the pathlength on the derived wind information from scintillometer observations.

Indexing terms : Laser scintillations, Atmospheric turbulence, Crosswinds.

AN electromagnetic wave propagating through the lower atmosphere will be distorted by variations of the refractive index along the propagation path causing the random fluctuations in the received signal flux. These fluctuations are manifested as scintillations or variations in the intensity of the wave. Besides thermal currents and gravity waves, wind is also a major reason for such fluctuations as it causes drifting and mixing of turbulent eddies [1-3]. In the past, this drift in scintillations patterns, produced due to naturally occurring refractive index irregularities has been utilized by many researchers for wind estimation using radio and optical wavelengths [2, 4-9].

With the advent of lasers, there has been considerable improvement in the wind measuring techniques due to their coherence and monochromacity. In early seventies, Lawrence *et al* [2] and Ochs *et al* [8] have successfully constructed and implemented wind sensing systems based on laser beam scintillations. The basic idea involved in these systems is to interpret quantitatively the drift in the scintillation patterns arising due to atmospheric irregularities as representing the average wind velocity across an optical beam by using suitable detectors. Based on this principle, we have developed a laser scintillometer for the estimation of transverse wind blowing across the laser beam. The technique essentially involves the measurement of the drift in two scintillation patterns observed simultaneously with two equal-aperture detectors which are separated from the source by a distance and spaced perpendicular to the line-of-sight-path. In this paper we present the results of crosswinds obtained from the scintillometer observations using different techniques of analysis and their compatibility with the average wind measured by an anemometer at the experimental location. The relationship between turbulence and optically derived winds has been discussed by estimating C_n^2 from the same scintillometer data used for wind sensing. The effect of wind fluctuations along the propagation path on the crosswind has also been studied by using the concurrent anemometer data.

SCINTILLOMETER AND DATA ANALYSIS

The scintillometer used in the present experiment has been described in detail by Devara *et al* [10]. However, the main specifications of the set-up for simultaneous measurement of path-averaged crosswinds and C_n^2 have been presented in Table 1. In order to monitor the scintillation patterns simultaneously from two detectors D_1 (channel 1) and D_2 (channel 2), two parallel beams were generated at the source by spitting the laser beam into two by means of a precision beam splitter, and each beam was directed on to the respective detectors which are separated by a distance of 60 m from the laser source. A propeller anemometer was installed (in north-south direction) at the centre of the optical pathlength. The average wind values measured by the anemometer during the experiment were utilised for obtaining the proportionality constants for the wind evaluation techniques and for comparison with the scintillometer derived winds. The scintillometer experiment was conducted on the terrace of the Institute's building which is at about 13 m AGL. The observations were collected on 11 clear sky days during January-April 1991 and on 4 days during November-December 1992. From the available simultaneous scintillometer and anemometer recordings, about 24 were considered for the results reported in this paper. Each scintillometer record, having a length of 15 seconds, was sampled at an interval of 0.25 seconds and subjected to the correlation analysis. The auto and cross-correlograms thus generated have been utilised for the estimation of crosswinds. Up to 12 time lags (20% of the total number of observations) have been considered in the correlation analysis of the data.

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TABLE 1 Specifications of the laser scintillometer

Transmitting system	
Laser	Helium-Neon (Spectra-Physics Model 159)
Wavelength	632.8 nm
Output power	5 mW
Beam divergence	0.951×10^{-4} mrad
Beam diameter	0.8 mm
Beam splitter	OFR Model SA-50 × 75
Receiving system	
Two Photomultiplier Tubes	RCA Model 6199
Photomultiplier gain	$\geq 10^6$
Amplifier	AD Model 515J
Separation from the transmitter	60 m
Separation between the detectors	1.65 m
Data acquisition	Multichannel Yokogawa Model 3063-61 chart recorder/Digital printer

Using the data recorded with one of the channels of the scintillometer, C_n^2 was computed by following the formula suggested by Tatarski [11]

$$C_n^2 = 8.1\, \sigma_x^2\, L^{-11/6}\, k^{-7/6}$$

where σ_x^2 is log amplitude variance of the laser beam intensity fluctuations, k ($= 2\pi/\lambda$) is wavenumber, λ being the wavelength of the laser used and L is the optical pathlength.

CROSSWIND SENSING TECHNIQUES

If two detectors D_1 and D_2 are placed perpendicular to the propagation path and parallel to the direction of wind velocity, the fluctuations of an optical wave at the detector D_1 (or D_2) at time t will be drifted to the detector D_2 (or D_1), depending on the direction of wind, at a delayed time $t+\tau$. Thus the fluctuations at the two detectors at a delay time τ are expected to be strongly correlated. The time lagged covariance function of the amplitude scintillations of the system consisting of one source and two equal-aperture detectors is derived from the spatial covariance function suggested by Lee and Harp [12] as

$$C\chi(\rho, \tau) = 4\, k^2 \pi^2 \int_0^L dz \int_0^\infty dK\, K\, \phi_n(K,z)$$

$$\times \sin^2 [K^2 z\, (L-z)/(2kL)]\, J_o\, (K\, |\, \rho\, z/L - V(z)\, \tau\, |)$$

where $V(z)$ is the velocity at the path position z, $\phi_n(K, z)$ is the Kolmogrov spectrum for the homogeneous isotropic turbulence, K is the two-dimensional wavenumber and J_o is the Bessel function of zero-order. Using this equation the normalised time-lagged auto- and cross-covariance functions have been obtained and are used for computing the crosswind by employing the following techniques.

Peak technique

The time lag at which peak is obtained in the cross-correlogram gives the wind velocity as $V_p \sim \rho / \tau_p$, where τ_p is the time delay at the peak of cross-correlogram and ρ is the separation between the two detectors, D_1 and D_2.

Briggs technique

As suggested by Briggs and Spencer [7] the lag at which the auto and cross-correlograms cross each other gives a measure of wind velocity and it is denoted by $V_b \sim \rho / 2\, \tau_c$, where τ_c is the time delay at the crossover.

Frequency technique

The width of the auto-correlogram at half power points gives the wind speed as $V_f \sim \rho_o / \tau_f$ where τ_f is the time delay at the half-maximum of the auto-correlogram and ρ_o is the transverse phase coherence length which is normally be obtained from the slope of the time lag covariance curve at zero time delay [13]. The peak and Briggs techniques give information on the magnitude and direction of wind directly while the frequency technique gives the wind magnitude only. The proportionality constants in the above techniques depend on the type of optical beam (convergent or divergent or collimated) and also on the strength of turbulence, and have been obtained by comparing the scintillometer-derived winds with those of anemometer as described in the section to follow.

RESULTS AND DISCUSSION

A typical correlogram constructed from the scintillometer recordings obtained on 27 March, 1991 is shown in Fig 1*a*. Also plotted in the figure are crosswinds estimated by using the peak, Briggs and frequency techniques versus simultaneously measured winds by anemometer during the experimental period. Wind speed with negative sign indicates northerly wind as the laser beam path was aligned in the east-west direction. The best-fit lines obtained from the regression analysis of the data are shown in the figure as solid lines, the slopes of which are generally considered as, more or less, proportionality constants for the individual wind sensing techniques. Table 2 summarizes the results of the analysis of wind data presented in Fig 1*b*, 1*c* and 1*d*. It can be seen from the table that V_p shows maximum correlation with V_{anemo}. Hence we have confined to the peak technique for better comparison with anemometer-derived winds in the further discussion of results. In addition, the measured winds and associated standard deviations of V_p and V_{anemo} show that the overall agreement between the scintillometer and anemometer-derived winds is very good.

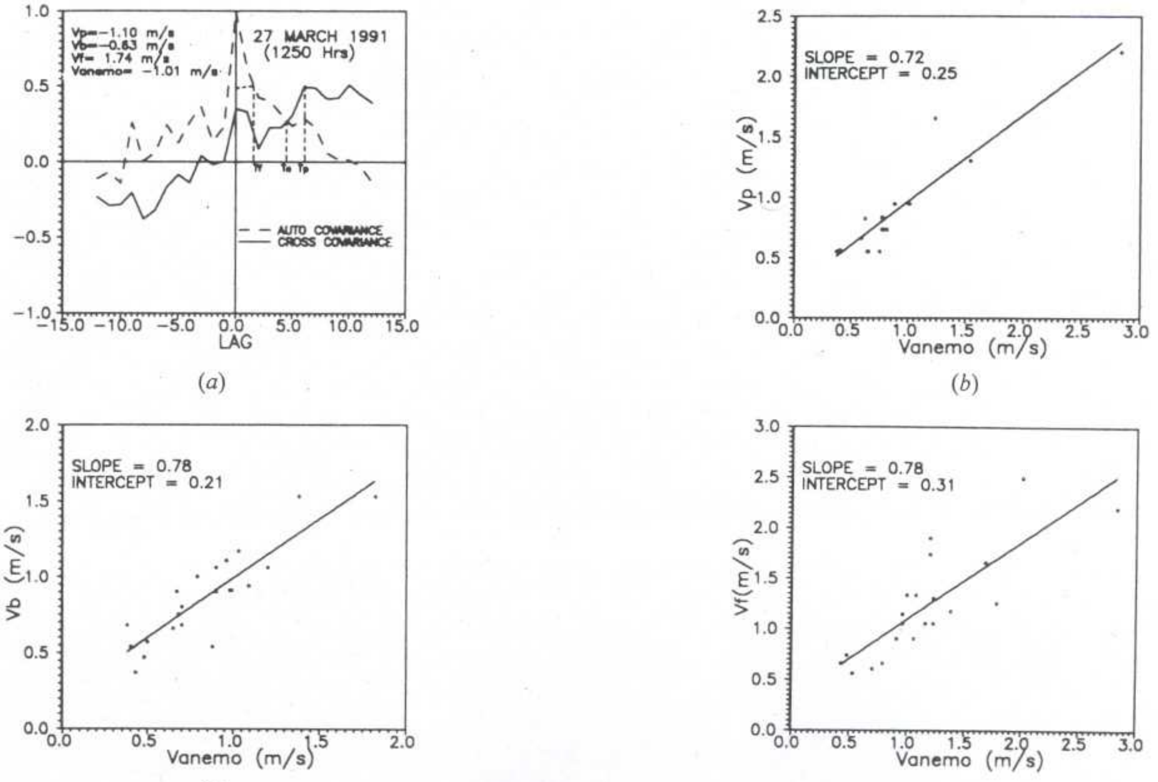
TABLE 2 Performance of crosswind evaluation techniques with respect to anemometer

Parameter	Peak	Briggs	Frequency
No of scintillation records	18	24	21
Average of scintillometer-derived wind speed (V_{scint}, m/s)	0.87	0.87	1.22
Standard deviation of V_{scint}	0.44	0.29	0.52
Corresponding average anemometer-derived wind speed (V_{anemo}, m/s)	0.87	0.84	1.17
Standard deviation of V_{anemo}	0.55	0.33	0.55
Correlation (r) between V_{scint} and V_{anemo} variations	0.93	0.88	0.82

The effect of detector separation on the covariance functions and associated crosswind estimations was also studied by conducting experiments with minimum possible detector separations. With the present acquisition and sampling rate of the scintillation data, crosswind speeds up to a maximum of 0.4 and 0.8 m/s can be estimated, respectively, using detector spacings of 0.1 and 0.2 m. However, higher ranges of crosswind speeds are possible with larger separation between the detectors and vice versa; hence the sensitivity of the scintillometer can be set as per the experimental requirements.

As the optical wind estimation techniques involve the interaction of turbulence and electromagnetic radiation, the study of the effect of C_n^2 which is a measure of atmospheric turbulence is of paramount importance. By keeping this in view, C_n^2 was measured simultaneously with the crosswind using the scintillation data recorded with one of the channels of the scintillometer.

Table 3 gives the comparison of V_p with V_{anemo} for the data collected at different periods on some selected days of observations. The corresponding C_n^2 values are also given in the table. It can be seen that, by and large, winds measured by the scintillometer and the anemometer compare well when C_n^2 is high. However, this correspondence appears to have strong relationship with the sensitivity of evaluation techniques to C_n^2 and wind fluctuations along the pathlength. This is consistent with the observations of Ting-i Wang *et al*, [13] that the wind and C_n^2 fluctuations affect the performance of the peak technique.



(*a*) (*b*)

(*c*) (*d*)

Fig 1 (*a*) Time-lagged auto- and cross-correlograms obtained on 27 March, 1991 (see text for definitions of τ_f, τ_c, τ_p, V_p, V_b, V_f and V_{anemo}). Comparison of anemometer-derived winds with crosswinds determined from peak (*b*) Briggs (*c*) and frequency (*d*) techniques during January through April 1991

TABLE 3 Comparison between V_p and V_{anemo} and their association with C_n^2

Date Time (LST)	V_{anemo} (m/s)	V_p (m/s)	$\left\lvert \frac{(V_p \sim V_{anemo})}{V_{anemo}} \right\rvert$	C_n^2 $(\times 10^{-12}\ m^{-2/3})$
08.02.1991				
(1652)	0.65	0.55	0.16	1.98
21.02.1991				
(1542)	− 0.62	− 0.82	0.32	0.82
27.03.1991				
(1250)	−1.01	− 0.94	0.07	4.54
(1251)	−2.83	−2.20	0.22	1.67
(1253)	0.59	0.66	0.12	8.39
(1322)	0.81	0.73	0.15	2.74
(1708)	− 0.77	− 0.73	0.05	4.74
01.04.1991				
(1409)	0.40	0.56	0.35	2.50
(1411)	0.78	0.73	0.06	1.95
02.04.1991				
(1100)	0.64	0.55	0.14	3.31
(1320)	− 0.62	− 0.82	0.32	4.95
(1345)	− 0.77	− 0.83	0.08	13.70
05.04.1991				
(1520)	− 1.54	− 1.30	0.16	9.11
(1607)	0.75	0.55	0.27	1.11
(1625)	− 0.88	− 0.94	0.07	4.13

CONCLUSION

The scintillometer set-up described in this paper has been successfully implemented and operated in real atmospheric turbulent conditions. The crosswinds derived from the scintillometer compare with the anemometer evaluated winds at the same location within the experimental limitations. The scintillometer described here can measure wind speeds ranging from 0.02 to 6.6. m/sec. However, this range can be set as per the experimental requirements by properly selecting the separation between the two detectors and associated data acquisition parameters.

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