Study of Laser Scintillation in Different Atmospheric Conditions

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ABSTRACT

Laser scintillation observations were carried out over a flat surface in different atmospheric conditions on 33 separate days during March 1990–April 1991 and were analyzed and studied. The principal results of the analysis reveal (i) marked seasonal variations in optical turbulence (through the measurement of refractive-index structure function C_n^2) and scintillation intensity (measured in terms of percent modulation P_m) with maximum C_n^2 or P_m during winter (December–February) and minimum during premonsoon (March–May) seasons; (ii) close correspondence among the variations in C_n^2, P_m, and atmospheric temperature; (iii) lower values of C_n^2 during cloudy sky as compared to clear sky conditions; and (iv) agreement between the observations and theory in respect of the pathlength dependence of C_n^2 and P_m. The results are discussed with reference to the possible meteorological origin of turbulence, and the importance of the study for making measurements of optical turbulence remotely over inaccessible regions is highlighted.

1. Introduction

The effect of atmospheric turbulence on propagation of electromagnetic radiation in the atmosphere has received renewed interest in the last three decades mainly because of its degrading effects on optical communications. This degradation benefitted the scientists by providing a means to study atmospheric turbulence and wind structure. We consider here the phenomenon of laser beam intensity fluctuations, also called *scintillation,* characterized by changes in refractive index of the medium. Refractive-index fluctuations are caused almost exclusively by fluctuations in temperature, since pressure variations are relatively small and are rapidly dispersed (Lawrence and Strohbehn 1970). The index of refraction depends almost exclusively upon temperature for optical frequencies, whereas for radar frequencies it depends on both temperature and humidity (Strohbehn 1968; Dewan 1980).

The influence of turbulent fluctuations of refractive index on optical wave propagation has been comprehensively treated by Tatarski (1961). Scintillation effects in laser beam characteristics due to atmospheric turbulence have impeded the full practical utilization of lasers for lidar, telemetry, and other applications. Although influence of turbulence in the atmosphere on laser beams can be minimized by an appropriate selection of spectral and geometrical parameters for the lasers and detectors, corrective methods would greatly help to remove the influence of turbulence on the laser beam propagation.

The feasibility of determining characteristics of atmospheric turbulence through the estimation of C_n^2 from laser scintillation measurements in several line-of-sight propagation experiments has been extensively studied by many investigators (Fried et al. 1967; Portman et al. 1968; Consortini et al. 1970; Strohbehn 1978; Coulter and Wesely 1980; Zuev 1982). The behavior of laser scintillation over longer pathlengths during different stability conditions and their association with meteorological parameters near the ground have also been studied (Fried et al. 1967; Portman et al. 1968; Clifford et al. 1974). In our earlier papers (Devara et al. 1992; Sharma et al. 1992), we reported on some initial results of the measurements made over optical pathlengths of 30 and 60 m above a flat surface and for cases in which C_n^2 varied by several orders of magnitude from 10^{-14} to 10^{-12} $\mathrm{m}^{-2/3}$. In the present paper, we communicate the results obtained from the simultaneous measurements of helium–neon laser scintillation and atmospheric temperature carried out over the same flat surface, which is 12.5 m above ground level, during the period from March 1990 to April 1991 at Pune (18°32′N, 73°51′E; 559 m MSL), a tropical urban station.

2. Scintillometer data and analysis

The scintillometer used in the experiment basically consisted of a Spectra-Physics model 159, CW (continuous wave), 5-mW helium–neon laser (0.6328-μm wavelength) as the light source and an RCA model 6199 photomultiplier-based refracting telescope as the receiver. The laser beam divergence was 0.951×10^{-6} sr and the beam diameter was 0.8 mm. A narrowband interference filter of 1-nm FWHM (full width at half maximum) was used in the receiver to eliminate the

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entry of light at wavelengths other than that of the laser into the photomultiplier tube. The diameter of the receiver aperture was 1 mm. The laser beam path was 1.1 m above a plane, hard cement surface that is about 12.5 m above the ground (the terrace of the Institute's building). The horizontal extent of the terrace was 100-m × 120-m open surface. The experimental site is free from upwind surfaces, and the edge of the terrace on upwind side is about 80 m from the beam path. As the optical path was very close to the cement surface, it may be considered to be occupied by nearly isotropic and homogeneous turbulence. In the case of the dual pathlength experiment, two beams were generated from the laser by using a high-precision beam splitter (Optics for Research model SA-50 × 75) and directed onto two identical receivers, installed at 30- and 60-m distances from the laser source in the same horizontal direction. The separation between the two beam paths was 1 m; both were 1.1 m above the surface. More details of the laser scintillometer used in the experiments are given by Devara et al. (1992).

The scintillation data were recorded at 1-s intervals for a period of 1 min. Such 1-min datasets were collected every 30 min. In each set, the data were corrected for background noise by introducing a chopper into the laser beam path. Along with the scintillation data, simultaneous dry-bulb temperature observations were also made (at 30-min intervals) at two levels, 0.75 and 5.20 m above the cement surface and close to the laser beam path. Using scintillation data thus collected, P_m and C_n^2 were computed to study the nature of turbulent variations in the air layer above the cement surface, which itself is about 12.5 m above the ground, during different seasons and different atmospheric conditions. The method of computation of the above two parameters is briefly explained below.

a. Percent modulation

According to Portman et al. (1962), the percent modulation P_m is defined as the ratio of the mean peak-to-peak amplitude of the fluctuating component of the optical signal to its average level. This quantity gives a measure of the intensity of fluctuations (scintillation intensity) independent of changes in brightness due to atmospheric variations.

b. Refractive-index structure function

The complete mathematical derivation of the model that describes the influence of turbulent fluctuation of refractive index on optical wave propagation can be found in Tatarski (1961), Portman et al. (1968), and Coulter and Wesely (1980), and a brief description of the underlying theory with the specific assumptions and conditions is given in Devara et al. (1992). The variance of the log-amplitude, σ_x^2, for a spherical wave propagating through a statistically homogeneous and isotropic refractivity field is given by

$$\sigma_x^2 = 0.124 k^{7/6} L^{11/6} C_n^2,$$

where C_n^2 is the path-averaged value of $C_n^2(z)$, with a weighting function $[(z/L)(1 - z/L)]^{5/6}$, z/L being the normalized path position; z is the position of the eddy along the beam pathlength; $k = 2\pi/\lambda$ is the wavenumber of the optical beam at wavelength λ; and L is the pathlength.

It is known that for a point transmitter and detector, the most effective eddy sizes over any pathlength are on the order of a Fresnel-zone size ($\sqrt{\lambda L}$) when the inner (l_0) and outer (L_0) scales of turbulence satisfy the inequality $l_0 \ll \sqrt{\lambda L} \ll L_0$. In the above computation of C_n^2, the inner scale is normally assumed to be very small or zero for many practical purposes (Ochs and Hill 1985). Moreover, the quantity, C_n^2 gives a measure of turbulence in the atmosphere, and its relationship with σ_x^2 is valid only when the integrated value of the latter is small ($\leqslant 0.3$). The most effective size of the turbulent eddies varies from Fresnel-zone size in the weak turbulence case to wave-coherence length in strong turbulence (Wang et al. 1978).

As scintillation saturates in the case of longer pathlengths (due to increasing strength of refractive turbulence), while depending strongly on l_0 in the case of short pathlengths, the above proportionality between σ_x^2 and C_n^2 fails and the associated weighting function and calibration of the scintillometer will have to be modified suitably. Alternately, as suggested by Wang et al. (1978), the same weighting function and calibration can be used in weak as well as in strong refractive turbulence conditions by employing a system with relatively large incoherent transmitter and receiver optics. Because of smaller aperture diameters and short pathlengths used in the present experiment, the possibility for the saturation of scintillations would be less (Clifford et al. 1974) and the weighting function will vary significantly with l_0. In the entire dataset, only on 5% of the occasions was σ_x^2 found to exceed 0.3. The path-averaged C_n^2 values for the datasets where $\sigma_x^2 > 0.3$, however, have been corrected for this effect by using the weighting functions that have been obtained by following the work of Wang et al. (1978).

Our observational program was to conduct the scintillation experiment once a week. But due to unfavorable weather conditions, particularly during the monsoon months of June, July, and August, observations could be obtained only on 31 days spread over the period from March 1990 to February 1991. The scintillation data from 0700 to 1800 LST thus collected for the pathlength $L = 60$ m have been used to study the daytime temporal and seasonal variations of P_m and C_n^2. During the initial phase of the study, the temperature data were obtained at single level (0.75 m) with a view to investigate the effect of temperature variations on scintillations. It was found that C_n^2 increased when the rate of change of temperature was at least 1.5°C h^{-1} (Devara et al. 1992). Subsequently,

TABLE 1. Seasonal mean P_m, C_n^2, and rate of change of temperature.

Parameter	March–May	June–September	October–November	December–February
$\lvert \Delta T/\Delta t \rvert$ (°C h^{-1})	1.0	0.6	1.2	1.8
P_m (%)	13.16	16.43	26.18	28.09
C_n^2 ($\times 10^{-12}$ $m^{-2/3}$)	0.312	0.445	1.397	1.501

temperature measurements at second level (5.20 m) have also been made to examine the influence of vertical temperature gradients on scintillation.

To examine the dependence of P_m and C_n^2 on L, data collected simultaneously over two pathlengths, 30 and 60 m, on four different days (19 December 1990, 2 January, 16 April, and 24 April 1991) have been used in the analysis. Further, to investigate the behavior of P_m and C_n^2 during lapse (daytime) and inversion (nighttime) conditions, measurements carried out for 24 h at 30-min intervals on four days (7 October and 12 December 1990, 2 January and 24 April 1991) have been used. The vertical temperature differences ΔT ($T_{5.20} - T_{0.75}$) are computed to infer lapse and inversion conditions and are used to explain variations in P_m and C_n^2 during day and night. The scintillation data obtained during a cloudy-sky day (31 August 1990) are compared with the data obtained on a clear-sky day (21 November 1990) to study the daytime temporal variation of C_n^2 during different sky conditions. The results obtained are presented and discussed in the following section.

3. Results and discussion

a. *Daytime temporal and seasonal variation of P_m and C_n^2*

To examine the seasonal variations, daily mean P_m and C_n^2 computed from the scintillation data obtained during daytime (0700–1800 LST) on 31 days for the period from March 1990 to February 1991 are taken and their means for premonsoon (March–May), southwest monsoon (June–September), postmonsoon (October–November), and winter (December–February) have been computed and shown in Table 1. Seasonal mean hourly rate of change of temperature ($\lvert \Delta T/\Delta t \rvert$) at the 0.75-m level are also shown in the same table. It is observed that daytime P_m and C_n^2 are maximum during winter and minimum during premonsoon and monsoon seasons. It appears that $\lvert \Delta T/\Delta t \rvert$, which is a measure of the heating or cooling rate, also follows similar seasonal variation.

Annual mean daytime temporal variations of C_n^2 and P_m along with the $\Delta T/\Delta t$ curve are shown in Fig. 1. It is observed that P_m starts increasing from about 18% in the morning to about 27% in the afternoon hours and decreases to 20% in the evening hours. On some specific days, the increase at noontime has been found to be more prominent. It is also observed that C_n^2 values are higher when the rate of increase of surface temperature is significant. When $\Delta T/\Delta t$ is negative, C_n^2 starts decreasing. Thus, daytime temporal and seasonal variations of both P_m and C_n^2 are closely associated with the heating and cooling rates in the surface layer.

b. *Scintillation observations during lapse and inversion conditions*

Scintillation measurements were made at 30-min intervals for 24-h periods to examine the behavior of P_m during lapse as well as inversion conditions. Figure 2a shows temporal variations in P_m from 0700 LST 12 December 1990 to 0700 LST 13 December. To smooth out the short-term variations and to examine the diurnal trend, five-point moving averages have been obtained and shown in the figure as a dashed curve. Temporal variation of the simultaneously measured vertical temperature difference ($T_{5.2} - T_{0.75}$) is also shown in the figure. On this day, lapse conditions (average decrease of temperature with height) prevailed almost throughout the day and inversion conditions (average increase of temperature with height) existed throughout the night in the surface layer. As described in the previous section, P_m started increasing after sunrise hours and showed a broad maximum in the afternoon hours. Here P_m started decreasing around the time when at-

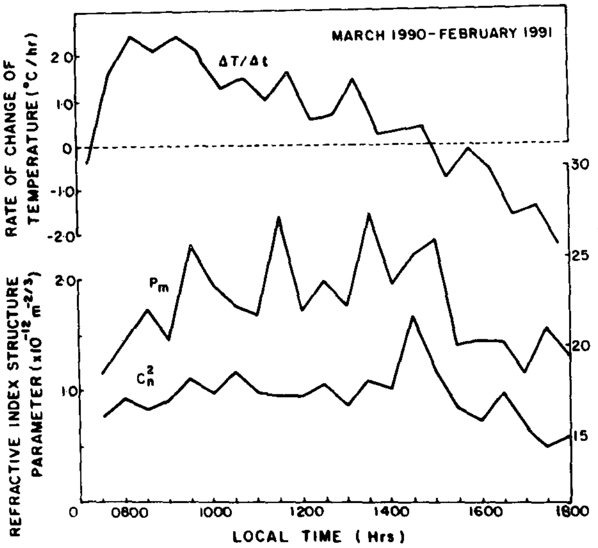

FIG. 1. Annual mean daytime temporal variation of P_m, C_n^2, and rate of change of temperature.

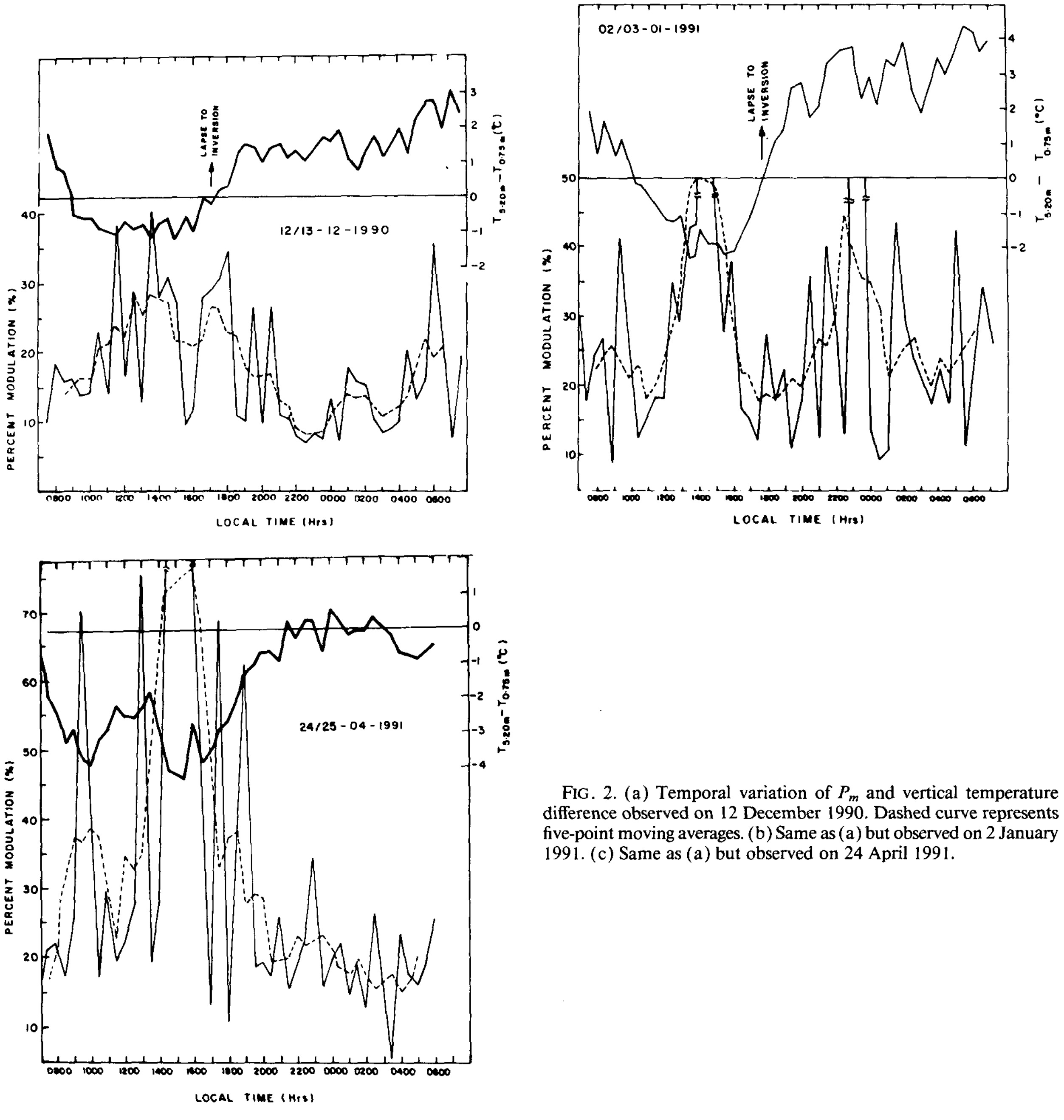

FIG. 2. (a) Temporal variation of P_m and vertical temperature difference observed on 12 December 1990. Dashed curve represents five-point moving averages. (b) Same as (a) but observed on 2 January 1991. (c) Same as (a) but observed on 24 April 1991.

mospheric conditions at the surface changed from lapse to inversion; however, P_m is not minimum at lapse-inversion changeover time on this day as might have been expected. It is possible that some inhomogeneity effects due to winds might have obscured the vertical temperature gradient effects on P_m. This aspect could not be examined here due to nonavailability of wind data at the experimental site during the period of observations. Around midnight, P_m was minimum, but in the postmidnight hours, there is an indication of a secondary peak. Such a nocturnal peak in temporal variation of P_m was found to be prominant in the data obtained on 2 January 1991 (Fig. 2b). On this day, the nocturnal peak is almost comparable to the daytime peak. On an examination of the temporal variation of vertical temperature difference, it is clear that the nocturnal inversion on 2 January is stronger than that observed on 12 December. Figure 2c shows temporal variation of P_m on another day (24 April 1991) when the nocturnal inversion was either weak or absent. It can be seen that the daytime P_m values are relatively higher and they closely follow the strong daytime lapse rate in the surface layer; the nighttime peak in P_m is completely absent. Thus, from a comparison of the variations in P_m and temperature on the above three days, it can be concluded that variations in the scintillation intensity are closely associated with those in vertical temperature gradients in the surface layer. It is also possible that during nighttime, even light winds would mix highly stratified layers close to the ground, causing an increase in scintillation intensity, which would result in a nighttime peak in P_m variations (Portman et al. 1962; Lawrence and Strohbehn 1970).

To quantify the features mentioned above and to compare the results with those obtained by earlier investigators, average P_m for lapse and inversion conditions are computed for four days and are shown in Table 2. For the sake of convenience and uniformity, P_m values between 0600 and 1730 LST are considered to represent the lapse conditions and those from 1800 to 0530 LST are taken to represent inversion conditions. Further, the ratio of P_m(lapse) to P_m(inversion) was computed and it is found to vary from 1.132 to 2.02. Portman et al. (1968) have shown that P_m for lapse could be almost twice that for inversion. The range of variation in the ratio [P_m(lapse)/P_m(inversion)] in the present study can be explained on the basis of vertical temperature difference ($|T_{5.20} - T_{0.75}|$) values (given in parentheses) as shown in Table 2. When the daytime vertical temperature gradient magnitude is more than the nighttime value (as on 24 April 1991), P_m for lapse is almost twice that for inversion. But when nighttime temperature gradient magnitude is more (as on 2 January 1991), P_m during inversion tends to become comparable in magnitude to the daytime value. Thus, the present study shows that a systematic relationship exists between scintillation intensity and temperature gradient in the air layers close to the ground.

c. C_n^2 during cloudy sky and clear sky conditions

In order to examine the nature of variation of C_n^2 during different sky conditions, scintillation data obtained on a typical cloudy-sky day (31 August 1990) and on a typical clear-sky day (21 November 1990) are shown with the corresponding C_n^2 variations in Fig. 3. The rate of change of temperature $\Delta T/\Delta t$ at the 0.75-m level on the above two days is also shown in the same figure. It is noticed that average C_n^2 values in the daytime on the cloudy-sky day are nearly one order of magnitude lower than those on the clear-sky day. In addition, on the cloudy day, the rate of change of temperature in the surface layer did not show any systematic diurnal variation and showed intermittent heating and cooling of the surface layer. These results corroborate the findings of other investigators (Lawrence and Strohbehn 1970; Clifford et al. 1974; Pearson 1975) who had observed reduction in scintillation strength during cloudy-sky conditions.

TABLE 2. Mean P_m and temperature difference for lapse and inversion conditions.

Date	Average P_m and temperature difference: Lapse	Inversion	P_m(lapse)/P_m(inversion)
7 November 1990	22.70 (NA)	11.21 (NA)	2.02
12 December 1990	21.78 (1.1)	13.70 (1.4)	1.59
2 January 1991	29.56 (1.7)	26.24 (2.7)	1.13
24 April 1991	41.60 (2.7)	21.02 (0.7)	1.98

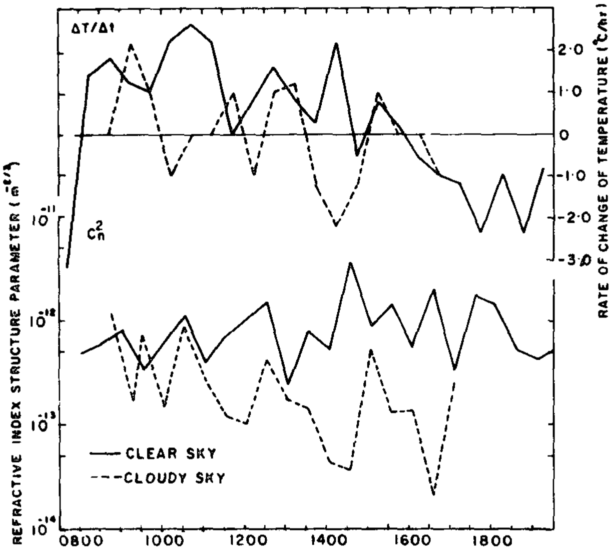

FIG. 3. Temporal variations of C_n^2 and $\Delta T/\Delta t$ on a typical clear-sky day and cloudy-sky day.

d. Pathlength dependence of P_m and C_n^2

Scintillation measurements were made simultaneously over two pathlengths, 30 and 60 m, in the same horizontal direction using a single laser source and two identical detectors. Temporal variations (24-h) of P_m and C_n^2 at these pathlengths observed on 2 January 1991 are shown plotted in Fig. 4. It is seen that both P_m and C_n^2 over longer pathlengths are higher in magnitude than those obtained over shorter pathlengths. Similar results have been reported in the literature (Portman et al. 1965; Clifford et al. 1974; Churnside 1991). Also, the temporal scintillation variations of both pathlengths are nearly identical. There were occasions, however, when both P_m and C_n^2 over the shorter pathlengths exceeded those over the longer pathlengths, particularly at noontime. This could be partly due to closeness in pathlengths and or due to saturation effects for longer pathlengths, which might have resulted in making the strength of scintillations at 30 m equal to or even more than that at 60 m during the periods of strong turbulence. The peak observed around midnight hours in both P_m and C_n^2 for 60 m as well as 30 m may be attributed to the temperature inversion condition as explained in the previous section.

From the scintillation data recorded on four different selected days, average P_m was computed for 30- and 60-m pathlengths. Tatarski (1961) has shown theoretically and also experimentally that the relationship between P_m and L is of the form $P_m \propto L^p$. The values of p inferred from the present experiments are shown in Table 3, which also shows the theoretical value of p obtained by Tatarski (1961). It is seen that except on 16 April 1991, the values of p are very close to the theoretical value of Tatarski and to the experimentally derived value of 0.98 by Gurvich et al. (1958) and Portman et al. (1962, 1965). According to Tatarski (1961) the theoretical relationship between σ_x^2 and L is of the form $\sigma_x^2 \propto L^n$. Averages of σ_x^2 for both pathlengths were computed and values of the pathlength exponent n are derived and shown in Table 3 along with the theoretical exponent value. The values of n obtained from the present experiment are comparable to the theoretical and experimentally deduced values (1.96 and 2.10) of Tatarski (1961). Thus, the dependence of P_m and σ_x^2 on pathlengths observed in the present study is satisfactorily in agreement with the theoretical and experimental results available in the literature.

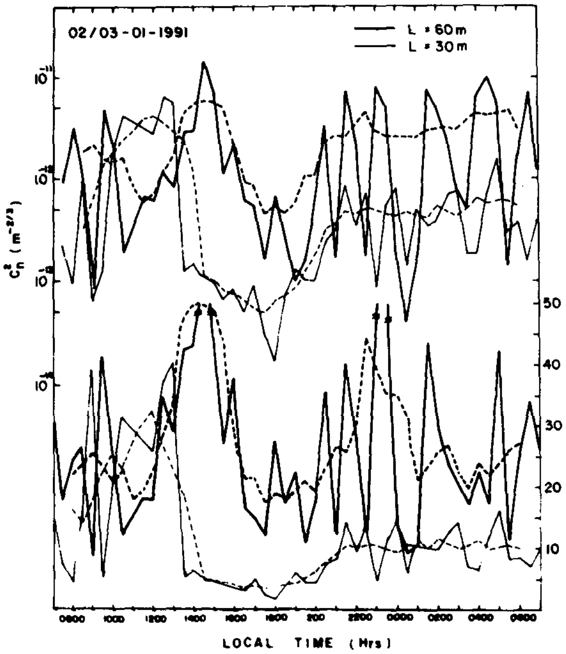

FIG. 4. Diurnal variation of P_m and C_n^2 at two pathlengths, as observed on 2–3 January 1991. Dashed curves represent corresponding five-point moving averages.

TABLE 3. Dependence of P_m and optical σ_x^2 on L.

Date	($P_m \propto L^p$) p	($\sigma_x^2 \propto L^n$) n
19 December 1990	1.20	1.88
2 January 1991	1.16	3.14
16 April 1991	0.38	1.94
24 April 1991	0.91	1.37
Tatarski (1961)	0.92	1.83

4. Summary and conclusions

Results of the analysis of laser beam scintillation observations over 30- and 60-m pathlengths in the air layer 1.1 m above a cement surface at a tropical station have indicated the following.

(i) Optical C_n^2 and P_m exhibit systematic diurnal variation with broad maximum during afternoon hours and smaller values in the early morning and evening hours under clear sky conditions. A secondary maximum also occurs around midnight on the nights when the nocturnal surface inversion is strong.

(ii) There is a conspicuous seasonal variation in both P_m and C_n^2, with higher values in winter and lower values in premonsoon months.

(iii) During lapse conditions, P_m was nearly double that during inversions. When strong nighttime surface inversion conditions prevail, however, P_m during lapse and inversion tends to be nearly equal in magnitude.

(iv) Cloudy conditions suppress the intensity of scintillations at ground level and result in diurnal variations different from those observed under clear conditions. Abundance of turbulence near the ground can be expected on a cloudy day as long as there is wind.

(v) Multipath scintillation measurements reveal pathlength dependance of P_m and C_n^2 that are in accordance with the theory and within the limits of experimental uncertainities.

(vi) As the parameters studied in this paper give a measure of atmospheric turbulence, such observations would be useful for correcting many of the atmospheric remote-sensing systems. As the measurements were made over an artificial surface, however, the above results do not necessarily represent other types of terrains. The results show that information on atmospheric turbulence structure could be obtained remotely over inaccessible regions by adopting the type of experimental method described in the paper.

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