MAUSAM, **64**, 2 (April 2013), 363-370

551.510.62

# Measurement and analysis of refractive index structure constant $C_n^2$ profile over Delhi on diurnal and seasonal basis

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(*Received 23 February 2011, Modified 23 April 2012*)

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**सार** – रेडियों तरंग के संचरण को प्रभावित करने में रेडियो अपवर्तकता एक महत्वपूर्ण कारक का कार्य करती है। रेडियो अपवर्तकता, वायुमंडल की भौतिक अवस्थाओं जैसे – तापमान, दाब और आर्द्रता पर निर्भर करती है। रेडार अत्यन्त छोटी आकृति के अपवर्तनांक भिन्नताओं जो रेडार के तरंग दैर्ध्य की आधी होती है, के प्रति संवेदी होते है। पश्च प्रकीर्णन शक्ति अपवर्तनांक नियतांक $C_n^2$ की आकृति के परिमाण पर निर्भर करती है। अतः मौसम रेडार, विशष रूप विंड प्रोफाइलर रेडार के ड़िजाइन के लिए किसी स्थान के $C_n^2$ के मान उपयोगी होते है। इस शोध पत्र में दिल्ली के ऊपर के उपरीतन वायुमंडल में वायुमंडलीय अपवर्तनांक नियतांक $C_n^2$ की रूपरेखा दैनिक एवं ऋतुओं के आधार पर तैयार करने की कोशिश की गई है।

**ABSTRACT** The radio refractivity is an important factor which effects radio wave propagation. Radio refractivity depends upon the physical states of atmosphere, *i.e.*, its temperature, pressure and humidity. Radars are sensitive to refractive index irregularities on scale size equal to half wavelength of Radar. Backscattered power is dependent on the magnitude of refractive index structure constant $C_n^2$. Hence $C_n^2$values of a place are useful for designing weather radar specially wind profiler radars. This paper is an attempt to map the profile of refractive index structure constant $C_n^2$ of atmosphere in the upper atmosphere, over Delhi on diurnal and seasonal basis.

**Key words** – Refractivity, Radiowave transmission, Atmospheric turbulence, Troposphere, Vapour pressure, Humidity, Radiosonde.

## 1. Introduction

Atmospheric turbulence is expected to impact astronomical imaging, aerial surveying and wireless communication. Major effects can be observed in beam broadening, irradiance fluctuations, *i.e.*, scintillation, and angle-of-arrival fluctuations (Rasouli *et al*., 2006). The effects of atmospheric turbulence for optical propagation studies are interesting in case of variation of refractive index in terms of its gradient and fluctuations. The corresponding refractive-index structure constant, $C_n^2$, is the parameter most commonly used to describe the strength of atmospheric turbulence. In past, standard meteorological radiosondes have been used to derive $C_n^2$, Warnock & VanZandt (1985), VanZandt *et al*., (1978) and Vasseur (1999). Under the co-ordination of World Meteorological Organization (WMO), as part of the global meteorological network, radiosonde measurement are generally carried out at synoptic times (0000, 0600, 1200 and 1800 UTC) across the globe. Radiosonde launches are carried out twice a day at more than 700 sites and four times a day at more than 300 sites across the world.

Radiosondes measure atmospheric variables like, pressure, humidity and temperature as well as wind speed and direction across the full vertical profile however only measurements at standard and significant pressure levels are stored and archived having typical resolutions from 100 to 1000 meters, which are much bigger than the typical outer scales of turbulence. Hence, these resolutions are not sufficient to characterize turbulence, which in general occurs in relatively thin layers, and as a consequence, assumptions on the occurrence of turbulent layers are necessary to derive $C_n^2$. Therefore, probability distributions for wind shear, buoyancy and the outer scale of turbulence have to be assumed.

## 2. Concept

The potential refractive index gradient, M, is required to calculate the refractive index structure constant $C_n^2$, because it is the only relevant gradient, or variation of the refractive index due to turbulence alone. Hence considering the refractive index variation in terms of

**TABLE 1**

**Log $C_n^2$ values at 0000 UTC during winter season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -7.4 | -7 | -9.1 | -11.4 | -10.2 | -11.5 | -13.2 | -14.3 | -14.6 | -14.7 | -17 | -15.3 |
| 2 | -7 | -7.6 | -9.2 | -10.5 | -11.3 | -11.4 | -12.8 | -14.1 | -14.5 | -15.6 | -16.4 | -15 |
| 3 | -6.9 | -7.8 | -10.6 | -10.1 | -10.4 | -11.8 | -13 | -14.2 | -15.2 | -15.4 | -16.5 | -17 |
| 4 | -7.1 | -8.2 | -9.3 | -12.3 | -11.3 | -11.8 | -12.9 | -14.9 | -14.6 | -15.7 | -16.7 | -15 |
| 5 | -6.7 | -10 | -9.3 | -12.9 | -11.5 | -11.2 | -12.5 | -14.8 | -14.6 | -17.7 | -17 | -16 |
| 6 | -7.3 | -7.5 | -9.5 | -11 | -11 | -11 | -13 | -14 | -14 | -15.7 | -16.1 | -16 |
| 7 | -6.9 | -7.6 | -10.2 | -10.2 | -10.3 | -11.3 | -12.5 | -15.3 | -14 | -17 | -17.2 | -15.6 |
| 8 | -6.8 | -8.1 | -11 | -9.6 | -11 | -11.4 | -13.5 | -14 | -13.6 | -15.7 | -16 | -16 |
| 9 | -6.9 | -8.3 | -10.2 | -9.8 | -11.6 | -11.3 | -13.6 | -13.8 | -13.2 | -15.8 | -15.7 | -14.4 |
| 10 | -7 | -8.4 | -11.1 | -9.6 | -10 | -11.4 | -13.3 | -13.8 | -14.6 | -16 | -15.9 | -16.9 |
| 11 | -7.4 | -7.4 | -9.6 | -11.1 | -11.7 | -11.1 | -12.8 | -13.7 | -14.5 | -14.4 | -16.5 | -15.7 |
| 12 | -7 | -8.8 | -10 | -9.7 | -11.5 | -10.8 | -13 | -12.8 | -14.5 | -14.9 | -17 | -16 |
| 13 | -6.7 | -8.7 | -10.8 | -9.5 | -12.3 | -10.7 | -13.5 | -12.7 | -15.6 | -15.4 | -17 | -17.2 |
| 14 | -6.5 | -8.8 | -8.5 | -12.9 | -10.7 | -10.8 | -12.3 | -13.5 | -11 | -16.2 | -17.5 | -15.6 |
| 15 | -6.7 | -7.3 | -10.3 | -9.8 | -12 | -11.2 | -12 | -16 | -14.9 | -15.7 | -15 | -15 |
| 16 | -7 | -7.8 | -11.2 | -11.9 | -10.6 | -12.3 | -12.5 | -13.1 | -14 | -16 | -17 | -18 |
| 17 | -7 | -7.8 | -10.8 | -11.2 | -11.5 | -11.6 | -12.9 | -13 | -14.9 | -15.5 | -15.8 | -16 |
| 18 | -6.9 | -7.9 | -10.9 | -9.3 | -10.6 | -11.8 | -12.4 | -13 | -17 | -15.5 | -15.7 | -16 |
| 19 | -7 | -8.1 | -9.3 | -11.2 | -10.2 | -11.2 | -12.6 | -14.2 | -11 | -16.3 | -15.2 | -16.8 |
| 20 | -7 | -8.3 | -14 | -11.1 | -10.8 | -11.1 | -14.2 | -13 | -14.8 | -14.4 | -17 | -16.4 |
| 21 | -7.1 | -7.6 | -13 | -9.3 | -12 | -11 | -13 | -13 | -14.8 | -17.3 | -15.7 | -15.8 |
| 22 | -7 | -8.2 | -8.9 | -14.6 | -12.4 | -11.4 | -11.9 | -14.7 | -14.6 | -16 | -18.2 | -15.7 |
| 23 | -7 | -8.4 | -9 | -10 | -11 | -11.6 | -12.8 | -14.3 | -14.8 | -16 | -16 | -15.7 |
| 24 | -6.7 | -8.5 | -9.3 | -10.2 | -11.4 | -11.7 | -13.4 | -14.2 | -14.9 | -18 | -16.3 | -15.7 |
| 25 | -6.7 | -8.3 | -9.1 | -11.7 | -10.6 | -11.8 | -13.2 | -13.8 | -15 | -15 | -17 | -15.4 |
| 26 | -6.8 | -8 | -9.8 | -10 | -11 | -11.7 | -13 | -14 | -15.4 | -15 | -15.8 | -15.8 |
| 27 | -6.8 | -7.8 | -9.6 | -11.5 | -10 | -12 | -13.2 | -14 | -14.8 | -15 | -17.8 | -15.3 |
| 28 | -6.8 | -8.4 | -11 | -9.6 | -11.8 | -11.5 | -12.4 | -14 | -14 | -18 | -16 | -16 |
| 29 | -6.8 | -7.5 | -9.6 | -10 | -11.2 | -11.7 | -12.5 | -14 | -15 | -17.2 | -16 | -16 |
| 30 | -7 | -7.6 | -9.5 | -12.5 | -10.7 | -11.8 | -12.9 | -14.1 | -15 | -15.1 | -15.8 | -1.5 |
| 31 | -7 | -7.4 | -11.1 | -10 | -11 | -12 | -12.8 | -14 | -15 | -15 | -17.1 | -17 |

conservative additives, for a layer of average pressure $p$ and thickness $\partial z$, a generalised approach for $M$ used by Warnock & VanZandt (1985) has the form:

$$M = -\frac{77.6\times10^{-6}}{T}\,p\,\frac{\partial \ln \theta}{\partial z}\,.\left[1+\frac{15500.q}{T}-\frac{15500}{2T}.\frac{dq/dz}{\partial \ln \theta/\partial z}\right] \qquad (1)$$

Where $T$ is absolute average temperature, $\theta$ is potential temperature, and $q$ is specific humidity.

With these expressions $C_n^2$ can be calculated using Tatarskii (1971):

$$C_n^2 = a^2\, A\, L_0^{4/3}\, M^2 \qquad (2)$$

{Where, $a^2$ is a dimensionless constant most commonly used at a value of 2.8 [Monin and Yaglo ([1971)]. A = is a numerical constant generally considered

**TABLE 2**

**Log $C_n^2$ values at 1200 UTC during winter season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -7.1 | -8.5 | -9 | -13.3 | -11.5 | -11 | -12.8 | -13.9 | -14.3 | -15.3 | -18 | -16.4 |
| 2 | -6.9 | -8 | -12.6 | -10.6 | -11 | -11.4 | -14 | -13 | -15 | -15 | -18 | -16.8 |
| 3 | -7 | -8.2 | -10.5 | -10 | -12.7 | -11.4 | -12.7 | -14.1 | -14 | -16 | -19.6 | -15.4 |
| 4 | -7.2 | -7.7 | -10.2 | -9.7 | -10.2 | -12.4 | -13 | -14 | -14 | -15.3 | -16.2 | -15.7 |
| 5 | -7 | -8 | -9.6 | -14 | -10.6 | -11.3 | -13.4 | -13.9 | -14.4 | -16 | -19.2 | -16.7 |
| 6 | -6.8 | -7.6 | -11 | -9.9 | -11.4 | -11.4 | -13.7 | -13.7 | -16.2 | -15 | -16.4 | -15 |
| 7 | -7.2 | -8 | -10 | -10 | -11.4 | -11.5 | -12.6 | -14.3 | -15.7 | -15.4 | -17.3 | -15.5 |
| 8 | -7 | -7.8 | -11.8 | -10.3 | -11.3 | -11.4 | -12.2 | -15 | -15.7 | -14.8 | -20 | -15.4 |
| 9 | -7 | -9 | -10.2 | -10 | -11 | -12 | -12.2 | -14.9 | -15 | -13.2 | -17 | -15.4 |
| 10 | -7 | -8 | -11 | -10 | -11 | -11.5 | -14 | -12.1 | -15.3 | -15.4 | -21.7 | -15.9 |
| 11 | -7 | -11.4 | -9.4 | -10 | -12 | -12 | -11 | -15 | -16 | -14.2 | -17 | -15.9 |
| 12 | -7 | -8.7 | -9 | -9.9 | -10.5 | -11.3 | -12.6 | -13.3 | -15 | -16.2 | -16.2 | -15.9 |
| 13 | -6.5 | -11.2 | -11 | -15 | -11 | -11 | -11.8 | -12.7 | -17 | -14.7 | -16.5 | -15.7 |
| 14 | -6.5 | -7.6 | -10.3 | -13 | -11.9 | -11 | -12.6 | -13.3 | -16 | -14.9 | -17 | -16.5 |
| 15 | -6.6 | -8.3 | -11.2 | -9.7 | -10.6 | -11.5 | -12.5 | -12.7 | -15 | -14.5 | -17.3 | -15.3 |
| 16 | -6.7 | -9.1 | -10.3 | -10 | -11.8 | -12.1 | -11.8 | -13 | -15.2 | -16.2 | -17.5 | -16.1 |
| 17 | -6.8 | -7.8 | -11.3 | -10 | -11.6 | -10.6 | -12 | -15 | -18 | -15.7 | -20.3 | -15.7 |
| 18 | -7 | -8.2 | -10 | -10 | -10.7 | -11.3 | -12.5 | -13.2 | -15 | -16.3 | -16 | -15.8 |
| 19 | -7 | -8.2 | -9.7 | -12 | -9.8 | -16 | -12.1 | -15 | -15 | -15.8 | -15.4 | -15 |
| 20 | -7 | -7.2 | -11 | -10.1 | -11.4 | -11.5 | -12.3 | -14 | -16 | -16.2 | -20 | -16 |
| 21 | -7 | -7.3 | -10.4 | -10.3 | -10.7 | -11 | -12.1 | -14.6 | -15.4 | -16 | -15.4 | -16 |
| 22 | -7 | -9.3 | -9 | -9.7 | -11 | -11.3 | -13.3 | -13.5 | -15 | -14.6 | -16.3 | -16 |
| 23 | -6.8 | -9.6 | -8.7 | -10 | -10.8 | -11.5 | -13 | -13.5 | -15 | -15.9 | -15.2 | -13.3 |
| 24 | -6.7 | -8.2 | -11 | -9.7 | -11.2 | -11 | -13.2 | -14.7 | -14.3 | -15 | -18.7 | -15.9 |
| 25 | -6.6 | -9 | -10 | -10.3 | -10.5 | -11.8 | -14 | -13.3 | -15.2 | -15.7 | -16.8 | -15.2 |
| 26 | -6.5 | -7.6 | -10.1 | -6.3 | -10.2 | -12 | -12.7 | -14 | -14.2 | -15.8 | -17.5 | -16 |
| 27 | -6.4 | -7 | -9.9 | -9.6 | -10.6 | -12.6 | -13.3 | -13.2 | -15 | -14.7 | -17 | -15.9 |
| 28 | -6.4 | -8 | -10.1 | -9 | -10.7 | -11.8 | -14.6 | -12.6 | -15 | -14.5 | -16 | -16 |
| 29 | -6.4 | -8.6 | -9.8 | -11 | -12 | -11.4 | -12.8 | -14.2 | -14.6 | -15.6 | -17.9 | -15.4 |
| 30 | -6.3 | -7 | -10.7 | -10.7 | -10.7 | -9 | -13.9 | -14.3 | -15.2 | -15.9 | -16.2 | -16 |
| 31 | -6.2 | -10.1 | -10 | -10.3 | -11.4 | -13 | -13.1 | -15 | -15 | -15.4 | -17.9 | -16.3 |

equal to unity. $L_0$ is the outer scale of turbulence, which has been set equal to the resolution of the radiosonde data = 10}.

Using equation 2 the refractive index structure constant can be calculated for every radiosonde measurement considered as turbulent.

## 3. Data and methodology

For model calculations of refractive index structure constant $C_n^2$ over Delhi, the temperature, altitudes and specific humidity at various atmospheric pressure levels are studied at 0000 UTC and 1200 UTC from radiosonde observations of IMD make radiosondes having accuracy of sensors for temperature 1.0 °C, pressure 1.5 hPa and humidity 7%, throughout the ten years study (2000 to 2009). The $C_n^2$ for twice a day is calculated for various layers of standard pressure levels, such as 925-850 hPa, 850-700 hPa, 700-600 hPa and so on, using Equations (1) & (2) above. In this study $C_n^2$ are examined from seasonal point of view. Data for 1st January for the years 2000 to 2009 have been studied and the average value is determined. Similarly the values have been calculated for

**TABLE 3**

**Log $C_n^2$ values at 0000 UTC during summer season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -8 | -8.4 | -8.4 | -9.7 | -10 | -11 | -11 | -13 | -14.3 | -14.7 | -16.4 | -15.7 |
| 2 | -8.2 | -8.3 | -8.6 | -10 | -9.6 | -11.3 | -13.3 | -12.7 | -15.2 | -15 | -17.1 | -15.4 |
| 3 | -9 | -8 | -9 | -9.3 | -10.4 | -10.7 | -12 | -13.3 | -14.2 | -15 | -17.8 | -15.6 |
| 4 | -7.9 | -9 | -9.1 | -9 | -11.1 | -10.2 | -11.4 | -14.4 | -13.4 | -14.4 | -19 | -17 |
| 5 | -8.1 | -8.5 | -8.1 | -10.2 | -10.2 | -10.3 | -13.2 | -11.8 | -15.4 | -13.6 | -17.2 | -18.3 |
| 6 | -8 | -9 | -8.2 | -9.6 | -9.8 | -11.2 | -11.7 | -15.1 | -13.3 | -15 | -16.8 | -15.1 |
| 7 | -7.7 | -8.3 | -9.5 | -8.3 | -10.8 | -10.1 | -12.3 | -13.8 | -14.4 | -14.4 | -16.7 | -15.6 |
| 8 | -8.5 | -8 | -9.1 | -8.8 | -11 | -10.2 | -12.4 | -13.9 | -13.6 | -15.7 | -16.1 | -18.3 |
| 9 | -8.2 | -9.1 | -8.2 | -10.1 | -9.8 | -10.3 | -12.2 | -13.5 | -14.2 | -15 | -18 | -15 |
| 10 | -7.9 | -9.3 | -8.4 | -9.6 | -10.4 | -10.4 | -12.5 | -14 | -14.1 | -14.3 | -16.3 | -15.8 |
| 11 | -8.2 | -8.9 | -9.4 | -8.9 | -11.2 | -11 | -12 | -12.7 | -14.3 | -15 | -17.6 | -15.2 |
| 12 | -8.3 | -8.2 | -9 | -8.5 | -10.3 | -11 | -13 | -13 | -13.6 | -15.5 | -16.3 | -15.7 |
| 13 | -8.8 | -8.4 | -9.6 | -8.2 | -11 | -10.4 | -10.9 | -12.3 | -15.2 | -13.3 | -16.9 | -16.1 |
| 14 | -7.7 | -9.5 | -7.9 | -9.8 | -9.7 | -10.3 | -14 | -11.9 | -14 | -14.3 | -16.9 | -16.8 |
| 15 | -7.5 | -9.4 | -8 | -9 | -10 | -10.3 | -11 | -12.8 | -13.2 | -15.3 | -16.7 | -17.3 |
| 16 | -7.3 | -9.4 | -8.1 | -9.1 | -9.2 | -11.4 | -12.3 | -12.8 | -13.6 | -15.3 | -17.1 | -16.3 |
| 17 | -7.6 | -8.5 | -7.7 | -10.2 | -10.3 | -10.4 | -11.8 | -14 | -13.2 | -15.3 | -16.6 | -15.7 |
| 18 | -8 | -9 | -8 | -10.9 | -9.7 | -10.2 | -11.9 | -12.7 | -13.7 | -14 | -15 | -17.6 |
| 19 | -8.2 | -8.3 | -8.3 | -9.6 | -9.5 | -10.8 | -12 | -13.7 | -13.7 | -15.3 | -15.6 | -16.2 |
| 20 | -8.3 | -8 | -8.3 | -8.4 | -9.9 | -10.6 | -12.6 | -13 | -14.3 | -15.6 | -16.4 | -17.9 |
| 21 | -8.3 | -8.5 | -8.7 | -8.7 | -11 | -10.4 | -12.2 | -12.8 | -14.7 | -15 | -16.8 | -17 |
| 22 | -8 | -8.5 | -7.9 | -9.7 | -9.6 | -11.1 | -11.6 | -13.2 | -14.1 | -15 | -18 | -17.3 |
| 23 | -7.8 | -8.3 | -8.3 | -10.8 | -9.8 | -10.3 | -12 | -14.1 | -15.8 | -14.3 | -16.8 | -15.9 |
| 24 | -7.8 | -10 | -7.8 | -9.5 | -9.8 | -11.6 | -12 | -12.9 | -14 | -14 | -18.3 | -15 |
| 25 | -7.6 | -9.6 | -8.4 | -8.4 | -9.8 | -10.8 | -12.9 | -12.9 | -14.4 | -15.6 | -18.2 | -15.3 |
| 26 | -8.3 | -9.1 | -8.5 | -8.5 | -10.3 | -10.7 | -12.7 | -13.2 | -13.3 | -16.4 | -16.3 | -16.3 |
| 27 | -7.3 | -9.1 | -8.6 | -8.6 | -10.1 | -10.6 | -11.6 | -13.1 | -14 | -16.2 | -16.2 | -16.7 |
| 28 | -7.2 | -8.4 | -10.2 | -8.71 | -9.2 | -11 | -13 | -13.3 | -13.3 | -17.3 | -17 | -15.3 |
| 29 | -7 | -10 | -8.2 | -8.3 | -10.8 | -10.7 | -11.6 | -11.8 | -16.1 | -15 | -17.5 | -16 |
| 30 | -7.6 | -9.5 | -9.6 | -9.6 | -10 | -11.7 | -11.6 | -13 | -13.7 | -15.6 | -15.7 | -16.9 |

each date of the month of January from the above mentioned ten year's period. Month of January has been taken as representative month of winter season. In this manner, exercise has been completed for the month of April to cover summer season and for July as representative month for monsoon.

## 4. Results and discussion

The log of $C_n^2$ values have been tabulated at various pressure level layers of atmosphere against various dates of the months pertaining to the related seasons (Table 1).

(*i*) *Season (Winter)* - Large variations have been observed in values of $C_n^2$ during winter season ranging from $10^{-6.5}$ to $10^{-21}$. The fluctuations in $C_n^2$ values in a particular layer are much larger in 1200 UTC in comparison to 0000 UTC during winter season. Also it is observed that larger variation of $C_n^2$ values in upper layers as compared to lower atmosphere.

(a) *0000 UTC* - The extreme values of $C_n^2$ at 0000 UTC vary from $10^{-6.5}$ to $10^{-18}$. The values of $C_n^2$ at 0000 UTC are decreasing with height and minimum at 100-70 hPa

**TABLE 4**

**Log $C_n^2$ values at 1200 UTC during summer season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -8.6 | -7.6 | -9 | -10.5 | -9 | -11 | -12.1 | -13.8 | -15.3 | -14.9 | -16.7 | -15 |
| 2 | -8.2 | -8.2 | -8.5 | -9.4 | -10 | -11 | -12 | -13.9 | -13.9 | -15.2 | -18 | -18 |
| 3 | -8 | -8.2 | -8.1 | -11.2 | -11 | -11.1 | -12.4 | -13.2 | -14.3 | -15.8 | -18 | -14.8 |
| 4 | -8.7 | -8.1 | -8.5 | -8.7 | -10.7 | -10.9 | -12.1 | -15 | -16 | -15.1 | -16.6 | -17.2 |
| 5 | -8 | -8 | -9.2 | -9.2 | -9.2 | -11 | -13.3 | -13.4 | -13.4 | -15.1 | -17.1 | -16.2 |
| 6 | -7.9 | -8 | -9.5 | -8.7 | -10.6 | -10.7 | -11.2 | -12.9 | -14.7 | -15 | -15.8 | -16.1 |
| 7 | -8.4 | -8.4 | -9 | -9 | -9.4 | -10.7 | -11.7 | -15.2 | -13.7 | -15.1 | -18 | -16 |
| 8 | -7.7 | -7.9 | -10.3 | -9.9 | -9.5 | -11.1 | -13.2 | -14 | -14 | -15.3 | -15.9 | -16.3 |
| 9 | -8 | -8 | -9.3 | -8.8 | -10.1 | -11 | -12 | -14.8 | -13.8 | -15.7 | -16.3 | -14.8 |
| 10 | -8.2 | -8.5 | -8.2 | -9 | -9.3 | -12 | -13.3 | -14.1 | -13.3 | -15.4 | -16.2 | -16 |
| 11 | -7.6 | -8.6 | -8.3 | -10 | -10.2 | -10.7 | -11.9 | -14.2 | -13.3 | -15 | -16.5 | -15.3 |
| 12 | -7.5 | -8.8 | -9.1 | -9.7 | -8.9 | -11 | -12.6 | -13.2 | -14.1 | -14.9 | -17.5 | -16.8 |
| 13 | -7.7 | -8.6 | -8.9 | -8.7 | -10 | -10.6 | -12.5 | -12.7 | -14 | -16 | -17 | -16 |
| 14 | -8.1 | -8.1 | -8 | -9.8 | -9.1 | -11 | -12 | -13 | -13.3 | -15 | -16 | -16 |
| 15 | -7.8 | -8.2 | -9 | -9.3 | -10 | -11 | -11.8 | -12.3 | -13.3 | -15.2 | -16.7 | -15.2 |
| 16 | -8.3 | -8 | -9.6 | -9 | -9.9 | -10.9 | -12.2 | -12.2 | -14.2 | -14.3 | -16.3 | -16 |
| 17 | -8.6 | -8 | -9 | -9.3 | -8.8 | -11.1 | -11.9 | -13.4 | -13.3 | -15 | -16 | -16.4 |
| 18 | -8.8 | -8 | -8.7 | -9 | -10.2 | -11 | -11.9 | -15 | -13 | -15.3 | -17.6 | -15.4 |
| 19 | -7.6 | -8.5 | -8.5 | -8.5 | -10.3 | -11.8 | -12.6 | -12.3 | -13.9 | -16.7 | -18.1 | -15.4 |
| 20 | -8.2 | -8.1 | -8.4 | -8.8 | -10.5 | -10.7 | -11.5 | -12.6 | -14.2 | -15.7 | -16.6 | -15.7 |
| 21 | -7.7 | -8.1 | -10 | -8.7 | -9.8 | -10.6 | -13.3 | -11.9 | -14.4 | -15.2 | -17 | -16.2 |
| 22 | -8.1 | -7.9 | -9 | -8.8 | -10.1 | -10.5 | -11.3 | -13.2 | -14.6 | -14.6 | -16.9 | -15.7 |
| 23 | -8.5 | -8.5 | -8.6 | -9.4 | -9.1 | -11.2 | -13.8 | -11.8 | -15.3 | -13.8 | -17 | -17.2 |
| 24 | -7.7 | -8 | -10.2 | -8.6 | -10 | -11.6 | -12.8 | -13.4 | -13.8 | -15.7 | -16.1 | -16 |
| 25 | -8.1 | -8 | -9 | -8.5 | -10.2 | -11.3 | -12.5 | -12 | -16.3 | -14.4 | -16.9 | -17.4 |
| 26 | -10 | -7.6 | -10.3 | -8 | -10.1 | -11 | -11.5 | -12.7 | -15.7 | -14.3 | -16 | -14.9 |
| 27 | -8.9 | -8 | -8.8 | -9.5 | -9.3 | -10.9 | -12.8 | -12.3 | -13.4 | -14.9 | -16.8 | -16.2 |
| 28 | -7.6 | -8.6 | -9.8 | -8.6 | -9.4 | -10.8 | -10.7 | -15.8 | -14.5 | -14.3 | -18.7 | -15 |
| 29 | -8.5 | -8.1 | -8.3 | -8.1 | -9.5 | -10.6 | -13.1 | -13.4 | -14 | -14.7 | -16.2 | -16.6 |
| 30 | -7.9 | -8 | -9.8 | -9.3 | -10.7 | -10.1 | -11.4 | -12.8 | -14.2 | -16 | -16.8 | -16 |

layer, and further increases beyond this layer (Table 1).

(b) *1200 UTC* - The extreme values of $C_n^2$ at 1200 UTC vary from $10^{-6.5}$ to $10^{-21.5}$. The values of $C_n^2$ at 1200 UTC are decreasing with height and minimum at 100-70 hPa layer, and further increases beyond this layer (Table 2).

(*ii*) *Season (Summer)* - The fluctuations in $C_n^2$ values in a particular layer are much larger in 0000 UTC in comparison to 1200 UTC during summer season.

(a) *0000 UTC* - The extreme values of $C_n^2$ at 0000 UTC vary from $10^{-7}$ to $10^{-19}$. The values of $C_n^2$ at 0000 UTC are decreasing with height and minimum at 100-70 hPa layer, and further increases beyond this layer (Table 3).

**TABLE 5**

**Log $C_n^2$ values at 0000 UTC during monsoon season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -7.6 | -7.4 | -8.3 | -8.4 | -9 | -10.4 | -11.3 | -11.5 | -12.8 | -15 | -15.7 | -15 |
| 2 | -7.3 | -7.8 | -7.6 | -9 | -9 | -10.2 | -11.8 | -13 | -13.5 | -13.5 | -15.6 | -14.8 |
| 3 | -7.2 | -7.8 | -7.8 | -8.3 | -9.4 | -10.3 | -10.8 | -11.6 | -11.8 | -15 | -15.7 | -16.7 |
| 4 | -7.3 | -7.3 | -7.9 | -10 | -8.9 | -9.6 | -11 | -11.1 | -12.2 | -15 | -16.3 | -16.9 |
| 5 | -7.3 | -7.4 | -7.8 | -9.6 | -9 | -9.7 | -10.9 | -11.4 | -12.4 | -15 | -14.3 | -14.3 |
| 6 | -7.3 | -7.6 | -8.2 | -8.4 | -9.6 | -10 | -10.7 | -11.7 | -12.7 | -14 | -15.3 | -17 |
| 7 | -7.7 | -7.5 | -8.3 | -8.4 | -8.8 | -9.9 | -11.2 | -11.6 | -12.8 | -14.1 | -15.3 | -16.1 |
| 8 | -8 | -7.7 | -7.8 | -8.2 | -10 | -9 | -10.8 | -11.8 | -11.8 | -14.7 | -15.2 | -15.1 |
| 9 | -7.5 | -7.9 | -7.9 | -8.3 | -9 | -9.8 | -11.6 | -13 | -11 | -14.3 | -15.3 | -16.3 |
| 10 | -7.6 | -7.6 | -8.3 | -8.2 | -9 | -9.6 | -11.1 | -11.7 | -12.9 | -15 | -15 | -15.7 |
| 11 | -7.5 | -7.5 | -9 | -8 | -9 | -10 | -11 | -11.1 | -13.3 | -14.3 | -15.5 | -16.4 |
| 12 | -7.9 | -7.7 | -8 | -8.9 | -8.7 | -9.3 | -11.5 | -11.5 | -12.1 | -14.4 | -15.4 | -16.3 |
| 13 | -7.8 | -7.3 | -7.8 | -9.2 | -9 | -8.8 | -11 | -11.4 | -12.8 | -14.5 | -15.1 | -16.2 |
| 14 | -7.9 | -7.6 | -7.9 | -9 | -9.8 | -9.6 | -11 | -11.3 | -12.3 | -15 | -15.5 | -16.5 |
| 15 | -7.7 | -7.7 | -8 | -8.9 | -8.8 | -9.4 | -10.7 | -11.3 | -12 | -15.7 | -15.4 | -16.3 |
| 16 | -7.6 | -7.8 | -8.2 | -9 | -8.3 | -10.4 | -10.6 | -10.9 | -13.4 | -15 | -15.6 | -15 |
| 17 | -7.7 | -7.4 | -8.3 | -8.3 | -8.6 | -9.8 | -10.7 | -11.8 | -13.5 | -14.2 | -15.3 | -16.4 |
| 18 | -7.8 | -7.7 | -7.7 | -8.7 | -9 | -9.7 | -10.1 | -11.6 | -12.2 | -14.2 | -15.1 | -17.6 |
| 19 | -7.4 | -7.4 | -7.6 | -9.1 | -9.3 | -9.6 | -10.7 | -10.9 | -14.3 | -13.8 | -15.6 | -15 |
| 20 | -7.8 | -7.7 | -7.6 | -8.3 | -9 | -9.5 | -10.8 | -11.6 | -12.6 | -15.2 | -15.7 | -16.8 |
| 21 | -7.6 | -7.7 | -8 | -8.6 | -8.7 | -9.4 | -10.9 | -11.8 | -12.9 | -15 | -15.7 | -15.3 |
| 22 | -7.7 | -7.7 | -7.7 | -9.1 | -8.3 | -9.6 | -11 | -12.8 | -12.4 | -14.7 | -15.1 | -16.6 |
| 23 | -8.8 | -7.4 | -8.2 | -8.3 | -9 | -9.6 | -10.4 | -12 | -12.2 | -15 | -16 | -16 |
| 24 | -8 | -7.6 | -8.8 | -8.1 | -8.7 | -9.8 | -11 | -13.1 | -12.2 | -15 | -15 | -15.7 |
| 25 | -7.6 | -7.6 | -8.6 | -8 | -8.9 | -9.6 | -10.6 | -11.7 | -12.4 | -15 | -16.1 | -16 |
| 26 | -7.5 | -7.7 | -7.8 | -8.4 | -9.1 | -9.4 | -10.3 | -11 | -13.3 | -15 | -15.3 | -15.7 |
| 27 | -7.4 | -7.6 | -7.7 | -9.2 | -8.7 | -9.4 | -10.7 | -11.8 | -12.7 | -15.9 | -15.2 | -17.6 |
| 28 | -7.4 | -7.6 | -7.7 | -8.3 | -8.8 | -9 | -10.3 | -11.2 | -12.7 | -14.8 | -15.8 | -15 |
| 29 | -7.3 | -7.6 | -7.7 | -8.9 | -8.3 | -9.6 | -11.6 | -12.2 | -12.7 | -15.2 | -16 | -17 |
| 30 | -7.4 | -7.5 | -7.6 | -8.3 | -9 | -9.5 | -10.4 | -12.4 | -12.6 | -14.8 | -15 | -17 |
| 31 | -7.6 | -7.4 | -7.6 | -9.1 | -8.8 | -10.4 | -11 | -11.3 | -13.7 | -14.2 | -15.4 | -16.1 |

(b) *1200 UTC* - The extreme values of $C_n^2$ at 1200 UTC vary from $10^{-7.5}$ to $10^{-19}$. The values of $C_n^2$ at 1200 UTC are decreasing with height and minimum at 100-70 hPa layer, and further increases beyond this layer (Table 4).

(*iii*) *Season (Monsoon)* - Higher values of $C_n^2$ are observed during monsoon season ranging from $10^{-7}$ to $10^{-18}$. Also the $C_n^2$ have minimum values in the layer 70-30 hPa, instead of 100-70 hPa layer as in other seasons.

(a) *0000 UTC* - The extreme values of $C_n^2$ at 1200 UTC vary from $10^{-7.5}$ to $10^{-18}$. The values of $C_n^2$ at 1200 UTC are decreasing with height and minimum at 70-30 hPa layer, and further increases beyond this layer (Table 5).

**TABLE 6**

**Log $C_n^2$ values at 1200 UTC during monsoon season**

| Day | Layer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 925-850 | 850-700 | 700-600 | 600-500 | 500-400 | 400-300 | 300-250 | 250-200 | 200-150 | 150-100 | 100-70 | 70-50 |
| 1 | -7.7 | -7.4 | -8.6 | -8.5 | -9.3 | -9.9 | -11.3 | -11.8 | -13.2 | -14.7 | -15.5 | -15.9 |
| 2 | -7.5 | -7.9 | -7.7 | -8.5 | -9.2 | -10.6 | -10.8 | -11.6 | -12.8 | -14.2 | -16.2 | -15.1 |
| 3 | -8.6 | -7.5 | -7.9 | -8.7 | -8.7 | -10.5 | -10.8 | -11.1 | -12.4 | -14.7 | -17.1 | -15.3 |
| 4 | -8.1 | -7.6 | -8 | -9 | -9 | -9.4 | -10.6 | -11.3 | -12.6 | -14.7 | -16.4 | -15.9 |
| 5 | -8 | -7.7 | -7.6 | -9.1 | -9.1 | -10.1 | -10.7 | -11.5 | -12 | -15.2 | -15.8 | -16.2 |
| 6 | -7.9 | -7.7 | -7.5 | -9 | -9 | -10 | -10.7 | -11.2 | -13.3 | -14.5 | -15.8 | -14 |
| 7 | -7.6 | -7.5 | -9.3 | -8 | -9.1 | -9.8 | -10.2 | -11 | -12.7 | -14.6 | -15.7 | -15.2 |
| 8 | -8 | -7.6 | -8 | -8.7 | -8.7 | -10.2 | -10.7 | -11.2 | -12.4 | -15 | -16 | -15.3 |
| 9 | -8 | -7.7 | -8 | -8.2 | -8.7 | -9.3 | -12 | -10.9 | -13.1 | -14.7 | -15.4 | -14.7 |
| 10 | -8 | -7.9 | -8 | -8.6 | -9.2 | -9.2 | -10.7 | -11.3 | -12.9 | -14.1 | -15.8 | -14.1 |
| 11 | -7.8 | -8 | -7.7 | -8.7 | -9 | -9.4 | -10.6 | -11.3 | -12.8 | -14 | -15.6 | -15 |
| 12 | -7.7 | -7.6 | -7.9 | -8.8 | -9.2 | -9.4 | -10 | -11.1 | -12.7 | -14.4 | -15.6 | -17.4 |
| 13 | -7.5 | -7.7 | -8.6 | -8.3 | -9.3 | -9.4 | -10.8 | -12 | -12.8 | -14.7 | -15.3 | -16.6 |
| 14 | -7.8 | -7.3 | -8.5 | -9.3 | -8.6 | -10 | -11.1 | -11.7 | -12.1 | -14.8 | -15.9 | -16.5 |
| 15 | -8 | -7.7 | -7.8 | -8.6 | -9.2 | -9.3 | -10.7 | -13.1 | -11.9 | -14.8 | -15.6 | -15.4 |
| 16 | -7.7 | -8.1 | -7.6 | -9.9 | -8.2 | -9.7 | -10.6 | -11.8 | -13.1 | -15 | -15 | -15.8 |
| 17 | -7.6 | -8 | -8 | -8.7 | -8.7 | -10 | -10.6 | -10.9 | -12.6 | -15 | -15.7 | -16.8 |
| 18 | -7.9 | -7.9 | -8.1 | -8.7 | -9.2 | -9.5 | -10.7 | -10.8 | -12 | -15.3 | -15.7 | -15.7 |
| 19 | -7.5 | -8 | -8 | -8.3 | -9.1 | -9.4 | -10 | -11.9 | -12.8 | -14.8 | -15.7 | -17.3 |
| 20 | -7.9 | -7.7 | -8.6 | -8.3 | -8.6 | -9.5 | -10.7 | -12.1 | -12.7 | -14.7 | -15.8 | -15.4 |
| 21 | -7.6 | -7.5 | -8.5 | -8.3 | -8.6 | -9.6 | -10.7 | -11.5 | -14.1 | -14 | -15.9 | -15 |
| 22 | -7.5 | -7.8 | -8.4 | -8.4 | -8.6 | -10.5 | -9.3 | -11.1 | -13.4 | -15.1 | -17 | -15.2 |
| 23 | -7.7 | -7.8 | -8 | -9 | -9 | -9.5 | -10.6 | -10.6 | -14 | -16 | -16.8 | -14.7 |
| 24 | -8 | -7.7 | -8 | -8.3 | -9.1 | -9.4 | -11 | -10.9 | -13 | -14.6 | -17.8 | -14.2 |
| 25 | -7.2 | -8.1 | -7.6 | -10.6 | -8.4 | -9.2 | -10.6 | -10.9 | -12.9 | -15.3 | -15.8 | -15.7 |
| 26 | -7.5 | -7.5 | -8.4 | -8.8 | -9 | -9.3 | -11 | -11.3 | -12.6 | -15.4 | -15.9 | -15.4 |
| 27 | -7.6 | -7.9 | -8.3 | -8.8 | -8.9 | -9.1 | -10.7 | -11.8 | -12.6 | -15.4 | -16.5 | -14.5 |
| 28 | -8.4 | -7.8 | -8 | -9.9 | -8.5 | -9.8 | -10.7 | -11 | -13.7 | -13.5 | -15.8 | -15.1 |
| 29 | -7.6 | -7.9 | -7.9 | -8.7 | -8.8 | -9.6 | -10.7 | -11.8 | -13.3 | -15 | -15.7 | -16 |
| 30 | -7.4 | -7.5 | -8 | -9.8 | -8.6 | -10.3 | -10.6 | -11.7 | -12.6 | -14.9 | -15.9 | -16.8 |
| 31 | -7.6 | -7.9 | -7.9 | -9.9 | -9.2 | -10 | -10.7 | -12.4 | -12.7 | -14.6 | -15.3 | -15.8 |

(b) *1200 UTC* - The extreme values of $C_n^2$ at 1200 UTC vary from $10^{-7}$ to $10^{-18}$. The values of $C_n^2$ at 1200 UTC are decreasing with height and minimum at 70-30 hPa layer, and further increases beyond this layer UTC (Table 6).

The standard deviations and Root Mean Square values of Log $C_n^2$ have also been calculated and summarized in Table 7. From this Table 7, it is observed that that variability of $C_n^2$ in winter is more than one Standard Deviation (SD) or around one SD for layers

**TABLE 7**

**Standard Deviations (SD) and Root Mean Square (RMS) values of Log $C_n^2$**

| Layers of atmosphere in hPa ranges | Standard Deviations (SD) and Root Mean Square (RMS) values of Log $Cn^2$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Winter season | | | | Summer season | | | | Monsoon season | | | |
| | 0000 UTC | | 1200 UTC | | 0000 UTC | | 1200 UTC | | 0000 UTC | | 1200 UTC | |
| | SD | RMS | SD | RMS | SD | RMS | SD | RMS | SD | RMS | SD | RMS |
| 925-850 | 0.20 | -6.9 | 0.28 | -6.8 | 0.45 | -7.8 | 0.52 | -8.0 | 0.31 | -7.6 | 0.29 | -7.8 |
| 850-700 | 0.59 | -8.1 | 1.06 | -8.5 | 0.59 | -8.7 | 0.29 | -8.0 | 0.16 | -7.6 | 0.21 | -7.7 |
| 700-600 | 1.19 | -10.2 | 1.59 | -10.6 | 0.63 | -8.5 | 0.66 | -8.9 | 0.36 | -8.0 | 0.39 | -8.1 |
| 600-500 | 1.28 | -10.9 | 0.86 | -10.3 | 0.75 | -9.1 | 0.68 | -9.0 | 0.49 | -8.7 | 0.60 | -8.9 |
| 500-400 | 0.66 | -11.1 | 0.62 | -11.1 | 0.56 | -10.0 | 0.59 | -9.7 | 0.38 | -9.0 | 0.29 | -8.9 |
| 400-300 | 0.39 | -11.5 | 1.06 | -11.7 | 0.44 | -10.5 | 0.38 | -10.8 | 0.40 | -9.7 | 0.42 | -9.7 |
| 300-250 | 0.49 | -12.9 | 0.79 | -12.9 | 0.72 | -12.0 | 0.74 | -12.1 | 0.40 | -10.9 | 0.43 | -10.7 |
| 250-200 | 0.74 | -14 | 0.82 | -13.9 | 0.75 | -13.0 | 1.05 | -13.2 | 0.60 | -11.7 | 0.53 | -11.5 |
| 200-150 | 1.13 | -14.5 | 0.85 | -15.2 | 0.76 | -13.9 | 0.84 | -14.0 | 0.66 | -12.7 | 0.53 | -12.8 |
| 150-100 | 0.98 | -15.9 | 0.71 | -15.3 | 0.83 | -14.8 | 0.60 | -14.9 | 0.53 | -14.7 | 0.49 | -14.8 |
| 100-70 | 0.75 | -16.5 | 1.60 | -17.5 | 0.87 | -16.7 | 0.76 | -16.6 | 0.40 | -15.4 | 0.58 | -15.9 |
| 70-50 | 0.76 | -15.9 | 0.64 | -15.8 | 0.97 | -16.0 | 0.80 | -15.8 | 0.84 | -16.1 | 0.88 | -15.6 |

700-500 hPa and 200-50 hPa and in Summer same is observed for layers 200-50 hPa. However during Monsoon variability of $C^2n$ values is less than one SD.

## 5. Conclusion

It has been observed that the values of refractive index structure constant $C_n^2$ in the evening hours are comparable to those of morning hours in all seasons. Only the extreme values are changing with the season. The values have decreasing trend in troposphere with height and start increasing in stratosphere. Although $C_n^2$ values during winter and summer are more than or around one SD for some of the layers but in Monsoon the $C_n^2$ values are less than one SD for all layers of atmosphere up to 70 hPa. As the backscattered signal depends upon the values of $C_n^2$ the extreme values in various seasons may be helpful in designing of wind profilers for mapping of wind profiles over Delhi and its surroundings for various seasons. This work has been undertaken with the data of one station (Delhi) only. The study can be extended by taking a number of stations representing the whole country.

### *Acknowledgement*

The authors are thankful to AVM (Dr.) Ajit Tyagi, DGM, New Delhi for constant encouragement, invaluable suggestions and guidance.

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