VHF SCINTILLATIONS AS A DIAGNOSTIC TOOL FOR THE STUDY OF IONOSPHERIC IRREGULARITIES

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(Received 8 March 1993)

Abstract. In this paper we present the results of observations of the scintillations of radio beacon on 250.351 MHz from geostationary satellite FLEETSAT (73° E) recorded at Bombay on April 9–10, 1992 during night hours. The scintillation index, S_4, is used to describe the strength of the scintillations. The variation of scintillation index with local time shows a maxima of 0.589 at 02:55 IST. This scintillation activity is linked with the spread F-irregularities. A brief description of the scintillation theories like phase screen theory and theory for weak scintillations – Rytov solution is given. These theories provide an integral measure of the fluctuations in terms of phase and amplitude fluctuations imposed on VHF signals while traversing through the ionosphere. Power spectrum analysis for the log-amplitude and phase departure and cross spectrum between them have also been carried out. Using spectral index $p = 1$, we have shown that the scale sizes for the ionospheric irregularities are greater than 1 km.

1. Introduction

The word "Scintillation" refers to the amplitude and phase changes of HF, VHF or UHF signals transmitted by sources like radio stars or artificial geostationary satellites. The scintillation studies involving transionospheric prepogation is of considerable interest in understanding the physical processes controlling high latitude ionospheric plasma density like generation mechanism and transport of ionospheric irregularities, soft particle precipitations with energies $\sim$100 eV, penetration of magnetospheric electric fields and auroral current systems (Kelley *et al.*, 1982; Anderson *et al.*, 1987; Kersley *et al.*, 1988). First measurement of scintillations was performed by Hey *et al.*, in 1946 from the radio source Cygnus. Ryle and Hewish (1950) have predicted the origin of scintillations to be due to the presence of ionsopheric irregularities at E and F regions of the ionosphere. With the aid of first man-made satellite Sputnik-1 launched in 1957 by Russian Scientists and other satellites like explorer 22 and 27, BE-B, BE-C, S-66, AE-C, AE-E, NNSS etc. it became possible to measure scintillations of transionospheric signals in order to understand the basic physics and dynamics of the ionospheric irregularities (Kent, 1959; Yeh and Swenson, 1959; Aarons *et al.*, 1963; Basu and Dasgupta, 1969; Koster, 1972; Chandra and Rastogi, 1974; Chatterjee *et al.*, 1974; Rastogi and Iyer, 1976; Iyer and Rastogi, 1978; Basu *et al.*, 1980, 1983; Valladares *et al.*, 1983; Kersley *et al.*, 1988). After the introduction of geostationary satellites, continuous observations were possible for recording scintillations at low latitudes. In India, the first work on scintillations was reported by Subbo and Somayajulu (1949) and later on by Bhargava (1964) using radio stars and a

Earth, Moon and Planets **65:** 247–268, 1994.

good correlation between spread F and scintillations was noted. The scintillation recording was started in India during the period August 1975–July 1976 when ATS-6 satellite was positioned at 34° E (Rastogi *et al.*, 1977, 1978; Chandra *et al.*, 1979; Krishna Moorthy *et al.*, 1979).

The scintillations arise for the most part from irregularities in the F-layer and is associated mostly with the nighttime phenomena whereas very rarely in the E-layer particularly sporadic E and auroral E and is associated with the day time scintillations. The correlation between nighttime scintillations and spread F was reported by many workers (Ryle and Hewish, 1950; Wright *et al.*, 1956; Bhargava, 1964; McClure, 1964; Frihagen, 1968; Bandopadhyoy and Aarons, 1970; Paul *et al.*, 1970; Koster, 1972; Weber *et al.*, 1978; Basu *et al.*, 1980). Rastogi *et al.* (1990) have compared the scintillation results obtained during nighttime in the Indian zone with the corresponding data obtained from the American Sector. Also Rastogi (1980) compares in a similar manner the results taken during daytime in the Indian zone and American sector and found slow and weak fluctuations of about 1–2 dB in the American longitudes whereas 4–5 dB in the Indian zone and that these were associated with eastward electrojet currents. Many other workers (Lockwood and Petrie, 1963; McClure, 1964; Bramley and Browning, 1978; Rastogi *et al.*, 1991) have proposed daytime scintillations caused mainly by E-region irregularities.

The E-region (100–120 Km) and F-region (200–1000 Km) of the ionosphere contain irregularities with scale sizes of the order of several hundred meters to a few kilometers, extending from the plasmapause through the trough to the polar cap (Ossakow, 1981; Tsunoda, 1981; Kersley *et al.*, 1988, 1989). Several mechanisms have been proposed for the formation of irregularities of sub-kilometric size in the high latitude F-region which are responsible for the phase and amplitude scintillations (Kersley, 1989). The morphology of the medium scale irregularities is now well documented (Shimikazi, 1959; Singleton, 1960, 1968; Tao, 1965; Rodger and Aarons, 1988). The existence of ionospheric irregularities over a wide spectral range is well summarized by Booker (1979) as reproduced in Figure 1.

As the incoming signal traverses the ionosphere containing free electrons, a phase change occurs in relation to free space propagation along the same path. If, in addition, the ionosphere contains irregularities of plasma density, phase fluctuations build up across the wavefront. As the wave traverses away from the ionosphere, phase mixing occurs and fluctuations in amplitude develop. This concept can be used to study the observed phase and amplitude scintillations (Fejer and Kelley, 1980). The source of the wave appears to scintillate if it has very small angular size and that the bandwidth of the receiver is sufficiently narrow, otherwise its apparent angular size is broadened by the scattering phenomena. Booker (1956) and Ratcliffe (1956) were the first to put the theoretical aspects of ionospheric scintillations in terms of thin phase screen theory. The global morphology of ionospheric scintillations have been discussed by Aarons (1982) in

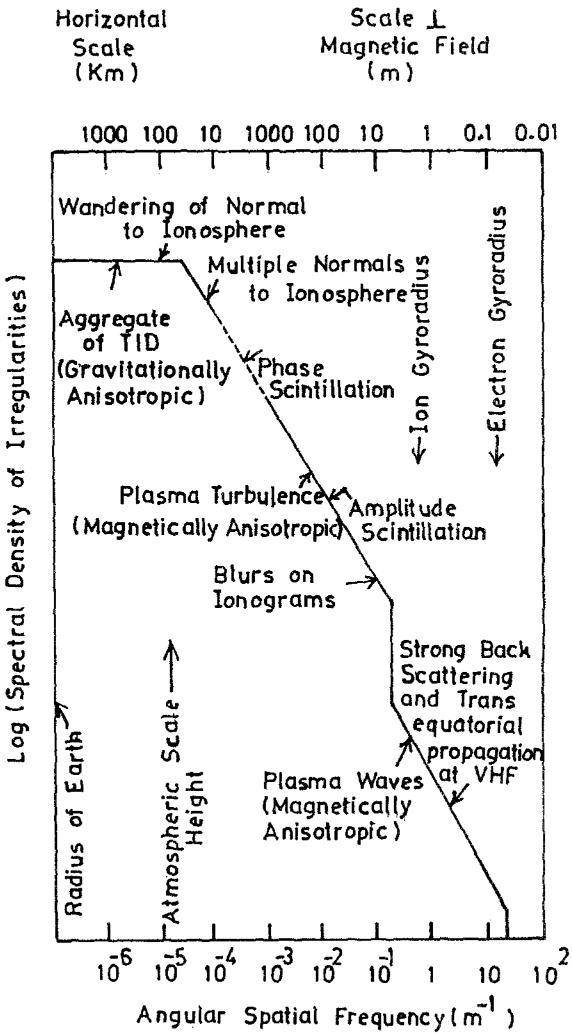

Fig. 1. A composite spectrum of plasma fluctuations versus angular frequency. (After Booker, 1979).

his review paper and the phenomenon of scintillations of radio wave propagating through the ionosphere is given by Yeh and Liu (1982). Advances in the study of wave propagation in random media have helped in the effort to develop a unified scintillation theory (Barabenenkov *et al.*, 1971). The single scatter theory is well established for weak scintillation. The multiple scatter theory for strong scintillation has also made much progress in recent years.

In this paper, we have reported the VHF ionospheric scintillations observed at Bombay (geomag. lat., 13.4° N) on April 9–10, 1992 from geostationary satellite FLEETSAT (73° E). In Section 2 an experimental recording of VHF

TABLE I

Geographic coordinates of Bombay		Sub ionospheric coordinates at 420 km height		Angle of elevation	Angle of elevation	Range of satellite
Lat.	Long.	Lat.	Long.			
19° N	73° E	17.6° N	73° E	67° E	Almost due south	36475.8 km

scintillations is given and an attempt has been made to analyse the data in order to find the strength of scintillation activity. The daily variation of scintillation index shows one peak around 02:55 IST. In Section 3 the phase screen theory and theory for weak scintillations – Rytov solution are discussed in detail to explain the VHF scintillation observations at Bombay. These theories provide an integrated measure imposed on VHF signals while traversing through the ionosphere. Lastly, in Section 4 the parameters of the signals such as power spectra for the log-amplitude and phase departure and their cross spectrum are computed. Our results clearly show greater than one kilometric scale sizes of ionospheric irregularities with spectral index $p = 1$.

2. Observations and Data Analysis

To study the generation and measurement of ionospheric irregularities at low latitudes, a network of stations in India for recording amplitude fluctuations of 250.351 MHz radio beacons from FLEETSAT (73° E) satellite has been established. The scintillation data used in this study have been recorded at I.I.G. Bombay during the night hours of April 9–10, 1992. The geographic coordinates and the subionospheric points with respect to FLEETSAT (73° E) positioned for Bombay are listed in Table I. Measurements of scintillation activity have been undertaken at a VHF frequency of 250.351 MHz transmitted by a geostationary satellite FLEETSAT at 73° E. As viewed from Bombay, FLEETSAT has been at an elevation of 67° and almost due south. Almost 5 h scintillation activity have been observed during nighttime hours on April 9 and 10, 1992. We have reconstructed the data and the same is shown in Figure 2a and 2b. The scintillations are generally found to start abruptly and may rise to the value of even 8 dB peak to peak within a minute or so. Some times brief periods of inactivity are also observed in between strong scintillations. The scintillations are found to be very rapid during the premidnight hours and fading rate slows down with the advance of nighttime.

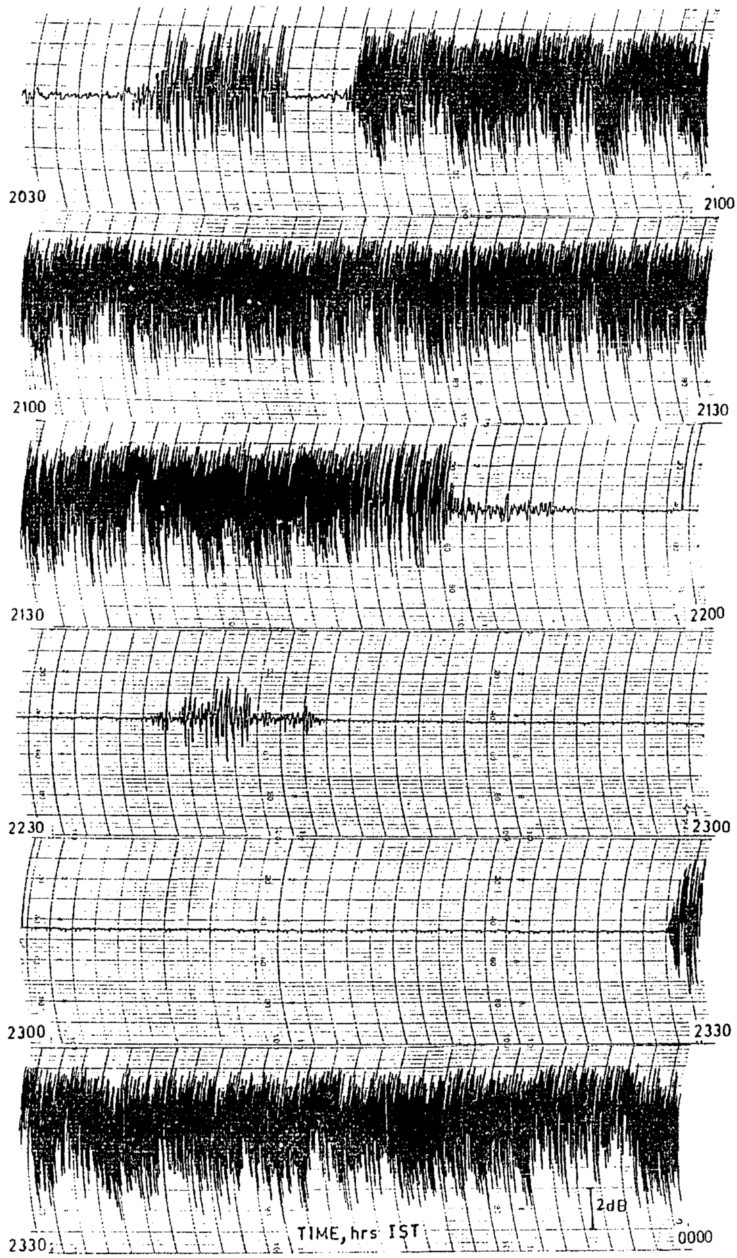

Fig. 2a. VHF scintillations recorded at Bombay on 250.351 MHz transmission of FLEETSAT (73° E) on April 9, 1992.

The essential features of scintillations recorded at Bombay are that it occured around midnight in discrete patches of varied duration ranging from about (45 to 60) minutes activity. The available data, with a data interval of one minute

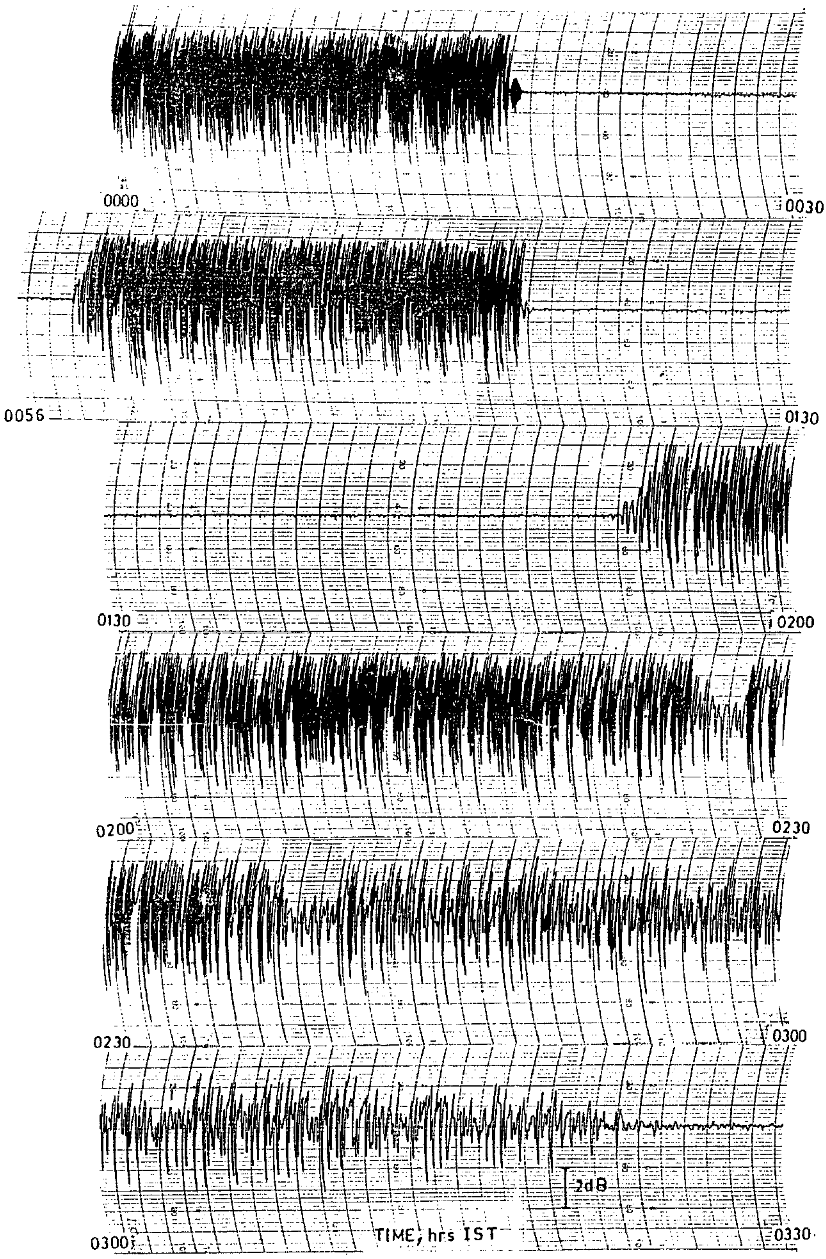

Fig. 2b. VHF scintillations recorded at Bombay on 250.351 MHz transmission of FLEETSAT (73° E) on April 10, 1992.

has been used to obtain the mean data for every 5 minute interval. It is this data which is analysed to compute the strength of scintillations as characterized by

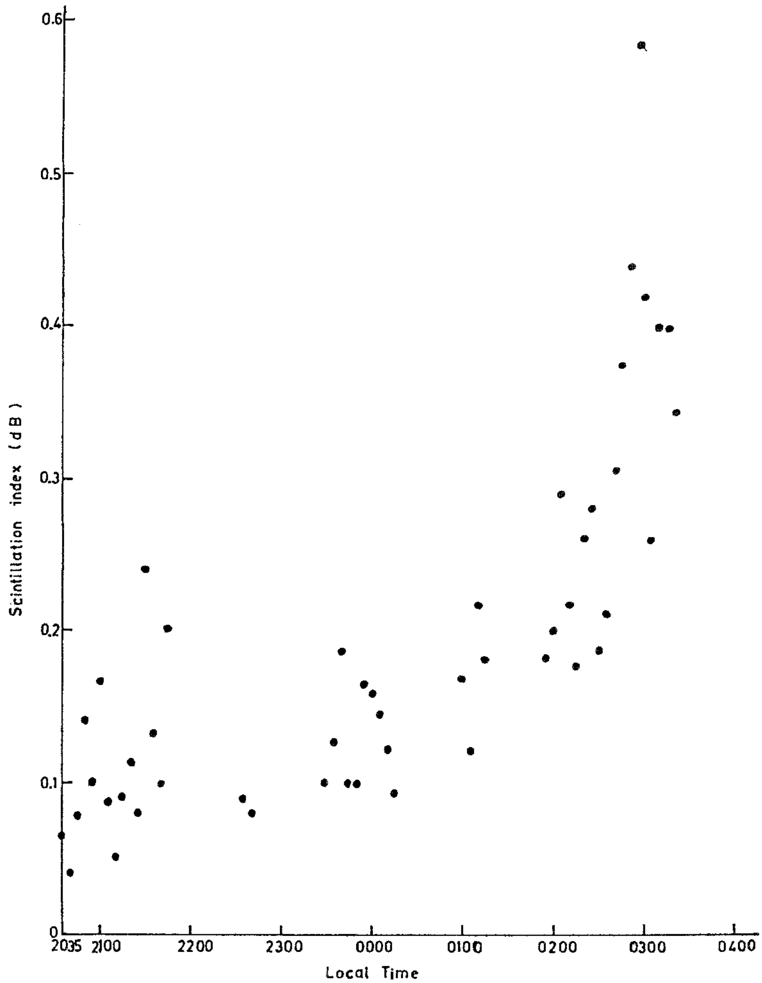

Fig. 3. Variation of scintillation index with local time during 9–10 April, 1992.

the index S_4. A less rigorous but simple measure of scintillation index (Whitney *et al.*, 1969) for scaling long-term chart records, is defined by

$$SI = (P_{max} - P_{min})/(P_{max} + P_{min}),$$

where P_{max} is the power level of the third peak down from the maximum excursion of the scintillations and P_{min} is the level of the third peak up from the minimum excursion measured in decibles. The scintillation index for the observations of April 9–10, 1992 at Bombay has been computed and is shown in Figure 3.

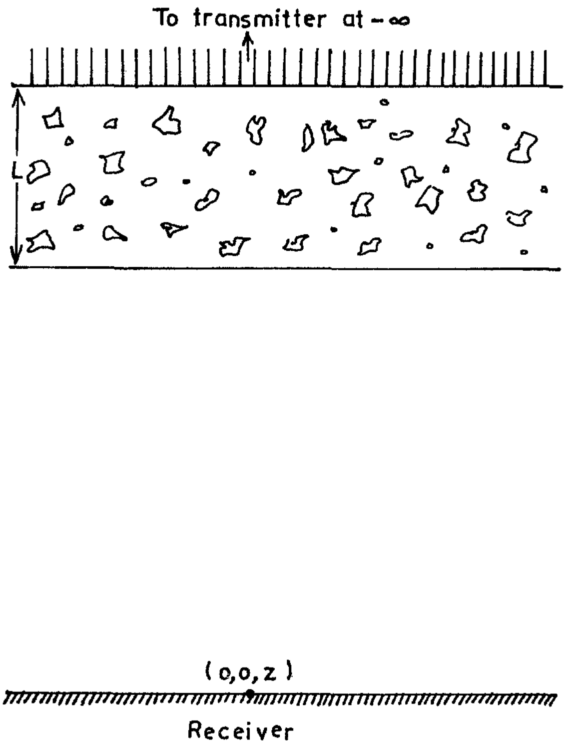

Fig. 4. Geometry of the ionospheric scintillation problem. (After Yeh and Liu, 1982).

3. Theoretical Considerations

In order to explain the ionospheric irregularities with the help of our scintillation data, we have selected the theoretical model given by Yeh and Liu (1982). Figure 4 depicts the conceptual geometry of the ionospheric scintillation phenomena in which a region of random irregular electron density patches is located from $z = 0$ to $z = L$, where L is the thickness of the irregular slab. A time-harmonic electromagnetic wave incident is supposed to be on this irregular slab situated at $z = 0$ and is received on the ground at $(\vec{\rho}, z)$. The irregularity slab can be characterized by a dielectric permitivity (Yeh and Liu, 1982)

$$\epsilon = \langle\epsilon\rangle[1 + \epsilon_1(\vec{r}, t)], \tag{1}$$

where $\langle\epsilon\rangle$ is the background average dielectric permitivity which for ionosphere

$$\langle\epsilon\rangle = (1 - f_{p0}^2/f^2)\epsilon_0, \tag{2}$$

and $\epsilon_1(\overrightarrow{r}, t)$ denotes the fluctuating part characterizing the medium caused by the irregularities, and is given by

$$\epsilon_1(\overrightarrow{r}, t) = -\frac{(f_{p0}^2/f^2)[\Delta N(\overrightarrow{r}, t)/N_0]}{(1 - f_{p0}^2/f^2)}, \tag{3}$$

where ΔN is the electron density fluctuation, f_{p0} is the plasma frequency corresponding to the background electron density N_0 and f is the incident wave frequency. In the percentage fluctuation, $\Delta N/N_o = \xi$, the temporal variations, caused by either the motion of irregularities as in a frozen flow or the turbulence evolution as in a non-frozen flow, or both, are considered to be much slower than the period of the incident wave.

As the wave propagates through the irregular slab, the phase is affected first by the random fluctuations in refractive index. This phase deviation is equal to $k_0(\Delta\phi)$, where k_0 is the free space wave number and $\Delta\phi$ is the deviation of the optical path from the mean and is expressed as

$$\begin{aligned} \Delta\phi(\overrightarrow{\rho}) &= -\frac{e^2}{2m\epsilon_0\omega^2}\Delta N_T(\overrightarrow{\rho}) \\ &= -\frac{\lambda^2}{2\pi}r_e\Delta N_T(\overrightarrow{\rho}) \end{aligned} \tag{4}$$

where $\overrightarrow{\rho} = (x, y)$ is the transverse coordinate, e is the electronic charge, m the mass of electron, ϵ_0 is the free space permitivity, w the circular radio frequency, λ is the wavelength of the plane wave and r_e is the classical electron radius. The quantity ΔN_T is the deviation in the total electron content through the irregular slab and is given as

$$\Delta N_T(\overrightarrow{\rho}) = \int \Delta N(\overrightarrow{\rho}, z)\,\mathrm{d}z. \tag{5}$$

After the wave has emerged from the slab, its phase front is randomly modulated. As this wave propagates to the ground, the distorted wave front will be diffracted. The random deviation of the curvature of the phase front is determined by the size and strength and distribution of the irregularities. It is found that the major contribution to the amplitude fluctuations on the ground comes from the phase front deviations caused by irregularities of the size of the order $\mathrm{d}F = [\lambda(z - L/2)]^{1/2}$ which is the size of the first Fresnel zone (Briggs, 1975). This describes the amplitude scintillation phenomenon qualitatively when the phase deviations are small. The wave front remains coherent across each irregularity which acts to focus or defocus the ray. However, when the irregularities are strong enough, the phase deviations may become so high that the phase front remains no longer coherent across the irregularities larger than certain size. These irregularities then lose their ability to focus or defocus the rays. The interference scenario for the amplitude fluctuations therefore is no longer valid. Qualitatively, one would expect the saturation of the amplitude fluctuation to occur. Further, in the case of a sufficiently thick slab of irregularity, one can also expect the amplitude fluctuations to develop inside the slab such that as wave emerges from the slab it has suffered both phase and amplitude perturbations. Hence, the development of the diffraction pattern on the ground is affected by both factors (Yeh and Liu, 1982).

Using electrodynamics wave equation under the assumption (Tatarskii, 1971)

(i) the temporal variations of the irregularities are much slower than the wave period,

(ii) the characteristic size of the irregularities is much greater than the wavelength,

the vector wave equation for the electric field vector inside the slab can be replaced by a scalar wave equation

$$\nabla^2 E + k^2[1 + \epsilon_1(\vec{r})]E = 0, \quad 0 < z < L, \tag{6}$$

where E is a component of the electric field in phasor notation and $k^2 = k_0^2\langle\epsilon\rangle$.

Equation (6) is a partial differential equation with random coefficient. The general solution of this equations is rather difficult. One has therefore to rely on some approximate solutions depending upon the nature of applications. Considering the case of normal incidence and introducing the complex amplitude for the wave field $u(\vec{r})$ given by

$$\vec{E} = u(\vec{r})\exp(-jkz), \tag{7}$$

where j is the unit vector in the quadrature direction in the complex plane we can write the complex amplitude equation as

$$-2jk\frac{\partial u}{\partial z} + \nabla^2 u = -k^2\epsilon_1(\vec{r})u, \quad 0 < z < L. \tag{8}$$

On the basis of Equation (8), Parabolic Equation Method (PEM) has been developed to deal with the problems regarding wave propagation in randomly inhomogeneous medium by Barabenenkov *et al.* (1971) with the following more assumptions:

(iii) the Fresnel approximation in computing the phase of the scattered field is valid, corresponding to $z \gg l \gg \lambda$.

(iv) Forward scattering: The wave is scattered mainly into a small angular cone. Let l represent the characteristic scale of the irregularities which can be taken as mean scale size of the irregularities (Barabenenkov *et al.*, 1971; Scrafim, 1981). The backscattered power is negligible corresponding to $\langle\epsilon_1^2\rangle kz \ll 1$.

(v) The attenuation of the coherent wave field per unit wavelength is small corresponding to $\langle\epsilon_1^2\rangle kl \ll 1$.

Making use of assumption (iii) above we can rewrite Equation (8) as

$$-2jk\frac{\partial u}{\partial z} + \nabla_\perp^2 u = -k^2\epsilon_1(\overrightarrow{r})u, \quad 0 < z < L, \tag{9}$$

where $\nabla_\perp^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is the transverse Laplacian. This equation is a parabolic type whose solution is found by the "initial" condition at $z = 0$ and has been used in quasi-optics and other propagation problems (Castel, 1966). Using Equation (9) with assumptions (iv) and (v), a series of equations for the moments of the complex amplitude can be derived that constitute the basis for the scintillation theory. With the assumption (ii), the complex amplitude below the slab satisfies the equation

$$-2jk\frac{\partial u}{\partial z} + \nabla_\perp^2 u = 0, \quad z > L. \tag{10}$$

The "initial" condition for Equation (10) is given by the solution of Equation (9) evaluated at $z = L$.

Therefore, Equations (9) and (10) form the basis upon which the ionospheric scintillation theories are developed.

(1) Phase Screen Theory: Many workers (Booker *et al.*, 1950; Hewish, 1951; Fejer, 1953; Bramley, 1954; Ratcliffe, 1956; Bowhill, 1960; Mercier, 1962; Briggs and Parkin, 1963; Salpeter, 1967; Buckley, 1971 and Rufenach, 1975) put forward an idea of wave diffraction from a phase-changing screen. Considering an incident wave passing through the irregular slab, the ionosphere acts as a phase-changing screen that modifies only the phase of the wave. Therefore, upon emerging from the ionosphere, the wave has the form

$$u_0(\overrightarrow{\rho}) = A_0 \exp[-j\phi(\overrightarrow{\rho})], \tag{11}$$

where A_0 is the constant amplitude of the incident wave. The irregular slab is considered to act as a thin screen located at $z = 0$ that contributes to changing the phase of the incident wave by the amount

$$\phi(\overrightarrow{\rho}) = k_0(\Delta\phi) = -\lambda r_e \Delta N_T(\overrightarrow{\rho}). \tag{12}$$

As the wave $u_0(\vec{\rho})$ propagates to the ground, the field can be found by using the Kirchhoff's diffraction formula (Ratcliffe, 1956). Under the forward scattering assumption, the Fresnel diffraction results in (Ratcliffe, 1956)

$$u(\vec{\rho}, z) = \frac{jkA_0}{2\pi z} \int\int \mathrm{e}^{-j[\phi(\vec{\rho}\,')+(k/2z)|\vec{\rho} - \vec{\rho}\,'|^2]} \cdot \mathrm{d}^2\rho'. \tag{13}$$

It is interesting to note that Equation (13) satisfies Equation (10).

In order to develop phase screen theory, one assumes that the phase perturbation introduced by the screen is a Gaussian random field with zero mean. The central limit theorem then predicts the Gaussian distribution for the phase. Utilizing the property

$$\langle \exp(-j\phi) \rangle = \exp[-\langle \phi^2 \rangle /2], \tag{14}$$

for the homogeneous Gaussian field ϕ, we obtain from Equation (13) the expression for the mean field on the ground

$$\langle u(\vec{\rho}, z) \rangle = A_0 \exp[-\phi_0^2/2], \tag{15}$$

where

$$\begin{aligned} \phi_0^2 &= \langle \phi^2 \rangle = \lambda^2 r_e^2 B_{\Delta N_T}(0) \\ &= 2\pi\lambda^2 r_e^2 \int\int_{-\infty}^{\infty} \Phi_{\Delta N}(\vec{k}_\perp, 0)\, \mathrm{d}^2 k_\perp. \end{aligned} \tag{16}$$

In Equation (16) above $B_{\Delta N_T}(\vec{\rho})$ is the correlation of electron content deviation $\Delta N_T(\vec{\rho})$ and is given by

$$\begin{aligned} B_{\Delta N_T}(\vec{\rho}) &= z \int_{-\infty}^{\infty} B_{\Delta N}(\vec{\rho}, z)\, \mathrm{d}z \\ &= 2\pi z \int\int_{-\infty}^{\infty} \Phi_{\Delta N}(\vec{k}_\perp, 0) \mathrm{e}^{j\vec{k}_\perp \cdot \vec{\rho}} \cdot \mathrm{d}^2 k_\perp, \end{aligned} \tag{17}$$

where $\vec{k}_\perp = (k_x, k_y)$.

Equation (16) has been derived by using Equation (17). Here $\Phi_{\Delta N}(\vec{k}_\perp, 0)$ is the three dimensional spectrum of the density fluctuation ΔN with $k_z = 0$. For a power-law irregularity spectrum

$$\Phi_{\Delta N}(\vec{k}_\perp) = C_N^2 |\vec{k}_\perp|^{-p}, \tag{18}$$

where

$$C_N^2 = 8\pi l_0^3 r_e^2 \lambda \langle (\Delta N)^2 \rangle,$$

and l_0 is some characteristic size for the irregularities.

The average field is attenuated according to Equation (15) because of the fact that part of the energy has gone to the incoherent part of the total field which is generated by the random phase front.

The average intensity on the ground can also be computed from Equation (13).

$$\langle u(\vec{\rho}, z) u^*(\vec{\rho}, z) \rangle = A_0^2, \tag{19}$$

which is a constant equal to the incident intensity, consistent with the assumption (iv).

In the experimental observation of the scintillation phenomenon, fluctuations of the amplitude (intensity) of the received signal is measured and with the introduction of satellite beacon experiments (Davies *et al.*, 1975; Fremouw *et al.*, 1978), the phase fluctuations of the signal can also be measured. To derive useful formulae for these observed quantities, let the field u $(\vec{\rho}, z)$ in Equation (13) be written in the form

$$\begin{aligned} u(\vec{\rho}, z) &= A_0 \exp[\chi(\vec{\rho}, z) - jS(\vec{\rho}, z)] \\ &= A_0 \exp[\psi(\vec{\rho}, z)], \end{aligned} \tag{20}$$

where $\chi(\vec{\rho}, z)$ is the log-amplitude, $S(\vec{\rho}, z)$ is the phase departure of the wave and ψ denote the Fourier domain.

For a "Shallow screen" such that $\phi_0^2 \ll 1$, it is easy to show from Equation (13) that

$$\chi(\vec{\rho}, z) = \frac{k}{2\pi z} \int \int_{-\infty}^{\infty} \phi(\vec{\rho}') \cos[k|\vec{\rho} - \vec{\rho}'|^2/2z] \, \mathrm{d}^2\rho', \tag{21}$$

$$S(\vec{\rho}, z) = \frac{k}{2\pi z} \int \int_{-\infty}^{\infty} \phi(\vec{\rho}') \sin[k|\vec{\rho} - \vec{\rho}'|^2/2z] \, \mathrm{d}^2\rho'. \tag{22}$$

From Equations (21) and (22) we can get the following results for the moments of χ and S.

The mean

$$\langle \chi \rangle = \langle S \rangle = 0. \tag{23}$$

The correlation functions

$$B_\chi(\vec{\rho}) = \int \int_{-\infty}^{\infty} \Phi_\phi(\vec{k}_\perp) \sin^2(k_\perp^2 z/2k) \cos \vec{k}_\perp \cdot \vec{\rho} \, \mathrm{d}^2 k_\perp, \tag{24}$$

$$B_S(\vec{\rho}) = \int\int_{-\infty}^{\infty} \Phi_\phi(\vec{k}_\perp)\cos^2(k_\perp^2 z/2k)\cos\vec{k}_\perp\cdot\vec{\rho}\,\mathrm{d}^2k_\perp, \tag{25}$$

where $\Phi_\phi(\vec{k}_\perp)$ is the power spectrum for the phase $\phi(\vec{\rho})$ given by

$$\Phi_\phi(\vec{k}_\perp) = \lambda^2 r_e^2 \Phi_{\Delta N_T}(\vec{k}_\perp) = 2\pi L\lambda^2 r_e^2 \Phi_{\Delta N}(\vec{k}_\perp, 0). \tag{26}$$

From Equations (24), (25) and (26), we obtain the mean-square fluctuations for χ and S.

$$\langle\chi^2\rangle = 2\pi L\lambda^2 r_e^2 \int\int_{-\infty}^{\infty} \Phi_{\Delta N}(\vec{k}_\perp, 0)\sin^2(k_\perp^2 z/2k)\,\mathrm{d}^2k_\perp, \tag{27}$$

$$\langle S^2\rangle = 2\pi L\lambda^2 r_e^2 \int\int_{-\infty}^{\infty} \Phi_{\Delta N}(\vec{k}_\perp, 0)\cos^2(k_\perp^2 z/2k)\,\mathrm{d}^2k_\perp, \tag{28}$$

and the power spectra for the log-amplitude and the phase departure

$$\begin{aligned} \Phi_\chi(\vec{k}_\perp) &= \sin^2(\vec{k}_\perp^2 z/2k)\Phi_\phi(\vec{k}_\perp) \\ &= 2\pi L\lambda^2 r_e^2 \sin^2(k_\perp^2 z/2k)\Phi_{\Delta N}(\vec{k}_\perp, 0), \end{aligned} \tag{29}$$

$$\begin{aligned} \Phi_S(\vec{k}_\perp) &= \cos^2(\vec{k}_\perp^2 z/2k)\Phi_\phi(\vec{k}_\perp) \\ &= 2\pi L\lambda^2 r_e^2 \cos^2(k_\perp^2 z/2k)\Phi_{\Delta N}(\vec{k}_\perp, 0). \end{aligned} \tag{30}$$

These expressions are no longer valid if one considers a “deep screen” where ϕ_0^2 is no longer small.

(2) Theory for Weak Scintillation – Rytov Solution: In order to include the effects of scattering on the amplitude of the wave inside the irregular slab in the scintillation phenomenon, one has to go back to Equations (9) and (10). With the substitution of Equation (20), Equation (9) therefore becomes

$$-2jk\frac{\partial\psi}{\partial z} + \nabla_\perp^2\psi + (\nabla_\perp\psi)^2 = -k^2\epsilon_1(\vec{r}), \tag{31}$$

Under the assumption of weak scintillation, the higher order term like $(\nabla_\perp\psi)^2$ can be neglected, we obtain the equation for the Rytov solution (Barabenenkov *et al.*, 1971; Tatarskii, 1971) as

$$-2jk\frac{\partial\psi}{\partial z} + \nabla_\perp^2\psi = -k^2\epsilon_1(\vec{r}). \tag{32}$$

The range of validity of this solution has been discussed by many workers (Brown, 1967; Fried, 1967 and Keller, 1969). This solution can well be applied to ionospheric scintillation data even for moderately strong scintillations (Crane, 1966).

Let us restrict ourselves to a plane incident wave with unity amplitude. Then the mean values $\langle\chi\rangle = \langle S\rangle = 0$. The power spectra for χ, S and the cross spectrum between χ and S for the field on the ground are given respectively by Wernick and Liu (1975) as

$$\Phi_{\chi S}(\overrightarrow{k}_{\perp}) = \frac{\pi k^2 L}{4}\left[1 \mp \frac{2k}{k_{\perp}^2 L}\sin\left(\frac{k_{\perp}^2 L}{2k}\right)\cdot\cos\frac{k_{\perp}^2}{k}(z - L/2)\right]\Phi_{\epsilon}(\overrightarrow{k}_{\perp}, 0),$$

$$\Phi_{\chi S}(\overrightarrow{k}_{\perp}) = \frac{\pi k^3}{k_{\perp}^2}\sin\frac{k_{\perp}^2 L}{2k}\sin\frac{k_{\perp}^2}{2k}(z - L/2)\Phi_{\epsilon}(\overrightarrow{k}_{\perp}, 0). \tag{33}$$

The correlation functions can be obtained from Equation (33). By letting $L \to 0$ in the expression for Φ_{χ} and Φ_S, we obtain the phase screen results (29) and (30) if the substitution $\Phi_{\epsilon} = (r_e^2\lambda^4/\pi^2)\Phi_{\Delta N}$ is made.

4. Results and Discussion

In the preceding pages of this paper we have made an attempt to relate the scintillation phenomenon to the structure and dynamics of the ionospheric irregularities. However, with an isolated effort like that of ours it is not possible to know the irregularity patch, its height, thickness, the variance of fractional electron density fluctuations and the irregularity spectrum unless a global scintillation mode is not framed (Basu *et al.*, 1976). In this direction, Aarons (1982) has attempted to produce the global morphology of the ionospheric scintillation. Further, Yeh and Liu (1982) have reviewed the phenomenon of scintillation of radio waves propagating through the ionosphere and have compared the experimental results with the theoretical predictions. At present, no satisfactory theory is presented to predict the probability distribution function of scintillations. During the periods of irregularities producing scintillations, the amplitude and phase and also the angle of arrival of the wave will fluctuate. We have therefore undertaken power spectra analysis for log-amplitude and phase-departure and their cross spectrum have been computed. For this purpose, we have chosen different thickness of irregular slabs of 50, 100, 150, 200 and 250 km with outer scale size l_0 =500 m; z =350 km and $\Delta N_T = 10^{12}$ el/m^3 (Koparkar, 1985). We have also shown that the irregularity spectra can well be described by taking spectral index $p = 1$. The power spectra for log-amplitude versus normalized wave number $(k_{\perp}^2 z/k)$ corresponding to the phase screen model is depicted in Figure 5. It is clear from Figure 5 that power spectra for log-amplitude increases with the increase in the thickness of the irregularity slab 'L'. A plot of power spectra for log-phase departure

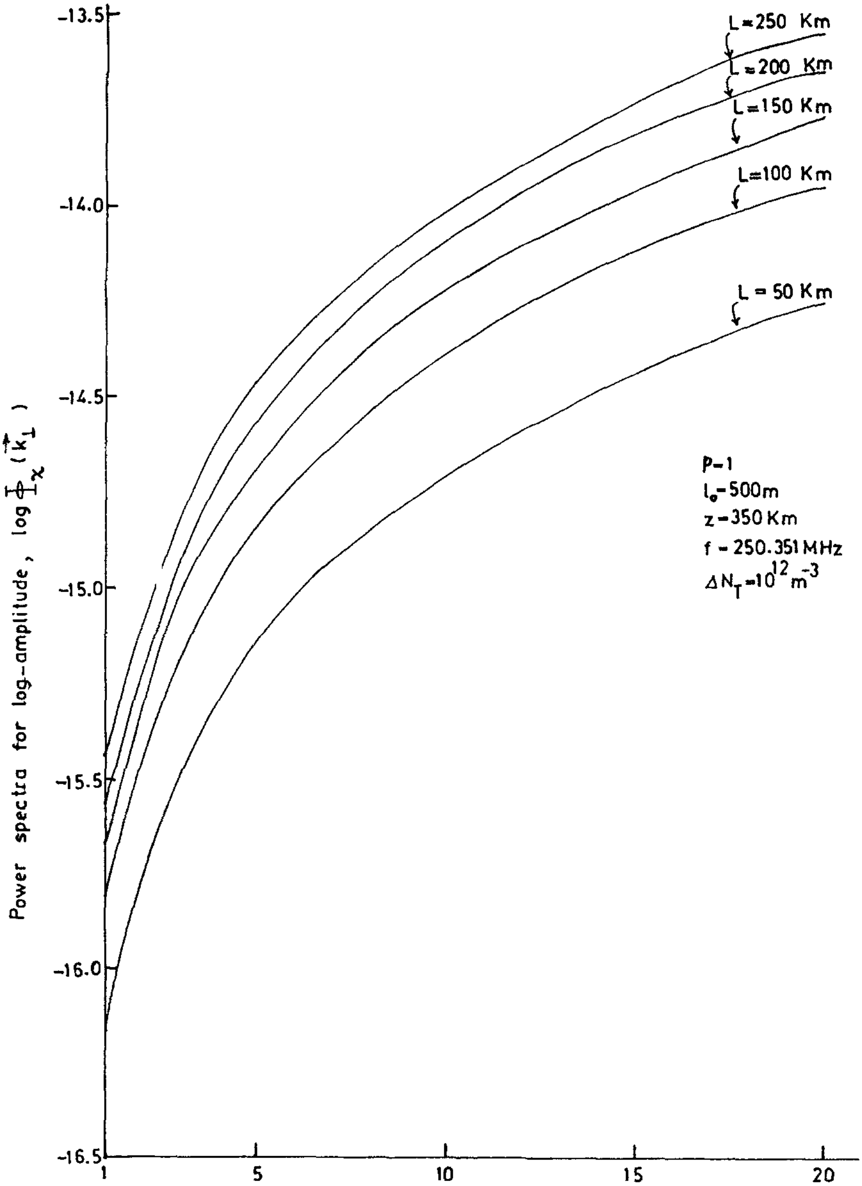

Fig. 5. Power spectra for log-amplitude against normalized wave number for different scale sizes of irregular patches.

versus normalized wave number ($k_\perp^2 z/k$) is shown in Figure 6 corresponding to phase screen model. The decreasing trend for different thicknesses of irregularity slab L is noted here. Figure 7 shows the variation of power cross spectra between log-amplitude and phase departure with normalized wave number ($K_\perp^2 z/k$) for

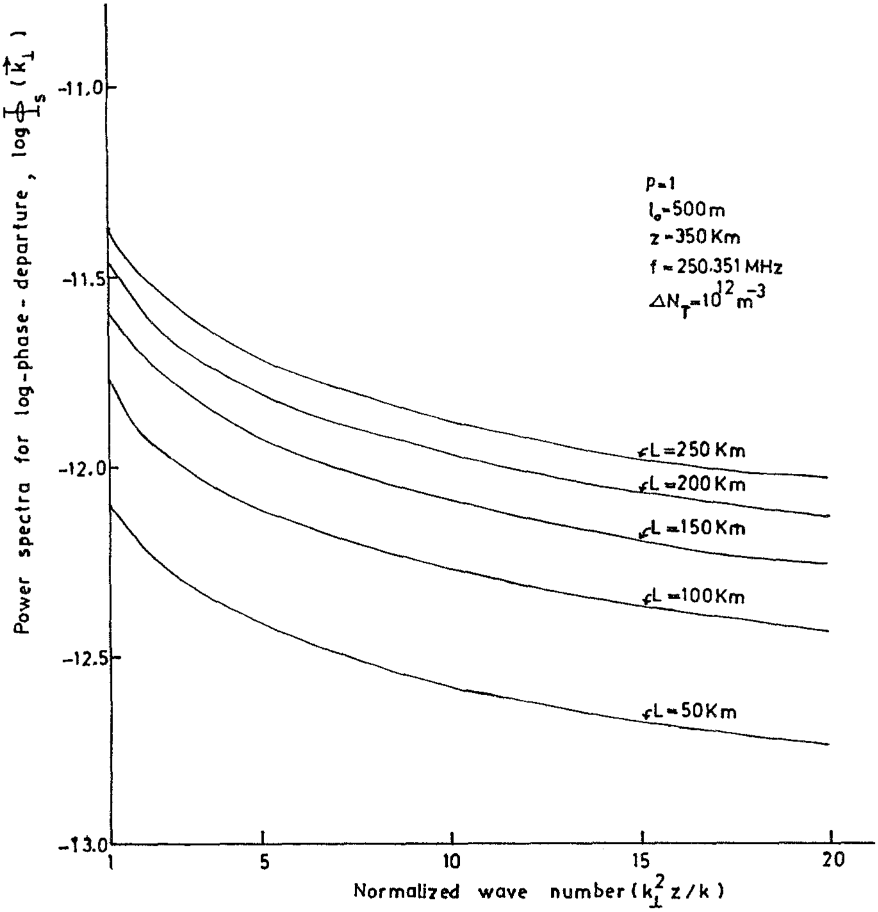

Fig. 6. Power spectra for log-phase departure against normalized wave number for different scale sizes of irregular patches.

different values of 'L' corresponding to theory for weak scintillation – Rytov solution and it increases with the increase of L.

The results shown in Figures 5, 6 and 7 are in good agreement with those of other workers (Basu and Basu, 1981; Rino and Owen, 1984). Employment of an equivalent phase screen theory and the theory for weak scintillation – Rytov solution have been found to be satisfactory for explaining the ionospheric and radio astronomical scintillation observations. The results presented in this paper, confirm the fact that power spectra for $p = 1$ may be satisfactorily described with the aid of an equivalent phase screen. The results are strongly dependent on power spectral index 'p', as power increases the spectra for log-amplitude increases. The calculations presented here are adequate to illustrate the considerable similarity that exists between the results of a fluctuating medium and those for a centrally

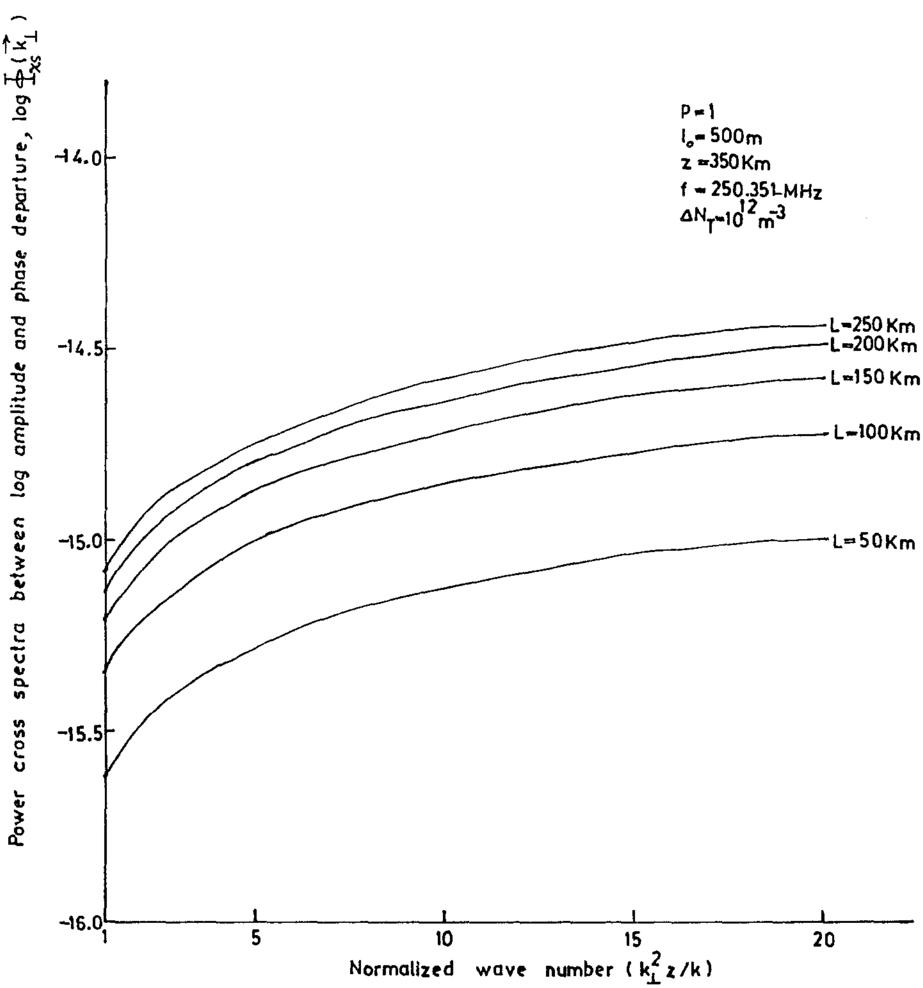

Fig. 7. Power cross spectra between log-amplitude and phase departure against normalized wave number for different scale sizes of irregular patches.

located phase screen having the same type of fluctuation spectrum and the same value for the mean square fluctuations of the phase.

These results reflect a significant progress in predicting the scale sizes of ionospheric irregularities. Irregularity spectra are inferred from the scintillation data. If the irregularities produce weak scattering, phase screen model tells us that the irregularities with a power law spectrum will produce a signal phase spectrum with a spectral index $p = 1$ that is steeper by unity than p, the one dimensional, in situ, spectral index (Cronyn, 1970; Rino, 1979). Basu and Basu (1981) reported a spectral index value of 2.8 for scale sizes less than 1 km and 1.5 for scale sizes greater than 1 km. Our results with $p = 1$, clearly indicate scale sizes for ionospheric irregularities greater than 1 km and are inconsistent with the results obtained earlier by Rino and Owen (1984). These authors considered a phase spectrum equivalent to an irregularity spectrum with power index of 1 at the large scale end.

Generally, the daily variation of scintillation index show two maxima, one during the night and the other during the day around noon period while for low latitude stations, only one peak during nighttime is observed. The variation of scintillation index with time shown in Figure 3 has the lowest value around 20:40 IST and is about 0.043. Further scintillation index increases with time and reaches a peak value of 0.589 at around 02:55 IST. this increase in scintillation index is associated to the spread F-irregularities. Our results are in agreement with the earlier observations (Pathan *et al.,* 1992).

Recently, Vats (1989) has computed the scale sizes of irregularities and has shown that for the scintillation index $\sim$0.6, the irregularity scale will be around 2 km which directly confirms our results.

Acknowledgement

The authors gratefully acknowledge Professor A. M. Bhat, Principal of the Regional Engineering Collage, Srinagar for his keen interest in reporting this communication.

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