Scintillation modeling using in situ data

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Abstract

Satellite in situ measurements of plasma (electron) density fluctuations provide a direct information about the structure and morphology of irregularities that are responsible for scintillation of radio waves on transionospheric links. When supplemented with the ionosphere model and irregularity anisotropy model they can be applied to model morphology of scintillation provided a suitable propagation model is used. In this paper we present a scintillation climatological model for the Northern Hemisphere high-latitude ionosphere, which makes use of the DE2 RPA plasma density data, IRI ionosphere model and the phase screen propagation model. An important aspect
of our work is that we derived from the satellite data not just the turbulence strength parameter $C_s$ but also the spectral index $p$, which influences the scintillation level as well. We discuss the magnetic activity, seasonal, magnetic time, and latitude dependence of these parameters. We were able to reproduce successfully the observed scintillation intensity diurnal and seasonal variations. Model satisfactorily describes the expansion of the scintillation zone under magnetically disturbed conditions and reproduces the down-dusk asymmetry in the scintillation intensity. The results demonstrate the usefulness of the proposed approach.

INDEX TERMS: 2439 Ionosphere: Ionospheric irregularities; 2447 Ionosphere: Modeling and forecasting; 6979 Radio science: Space and satellite communication; 7944 Space weather: Ionospheric effects on radio waves

KEYWORDS: phase screen, scintillation, high-latitude ionosphere

1. Introduction

Rapid, random variations of the amplitude and phase of radio waves passing through the ionosphere are called scintillations. These scintillations may have a considerable effect on the performance of the satellite communication and navigation. In the case of GPS, scintillation may reduce the accuracy of the pseudorange and phase measurements. At times the amplitude scintillation may be so intense that the signal power drops below the threshold limit, the receiver loses lock to the signal, and the GPS positioning is not possible. Loss of lock may also be caused by strong phase scintillation, when resulting the Doppler shift exceeds the phase lock loop bandwidth.
Scintillation is characterized by considerable spatial and temporal variability, which depends on many factors, such as the signal frequency, local time, season, solar and magnetic activity; it depends also on the satellite zenith angle and on the angle between the ray path and the Earth’s magnetic field. Scintillation is most intense in the band around 20 degrees on either side of the magnetic equator, and in the auroral region. The region of auroral scintillation expands equatorward during periods of increased magnetic activity. Morphology of scintillations has been studied for many years and has been discussed in a number of articles [cf. Aarons, 1982, 1993; Basu et al., 1985b; Kersley et al., 1988; MacDougall, 1990a,b].

Recently we observe a considerable interest in modeling of the scintillation effects on the satellite radio systems. One can distinguish two kinds of modeling: (a) modeling of the wave propagation in the irregular ionosphere, and (b) modeling of the climatology of scintillation.

In the first kind of modeling one makes use of the theory of wave propagation in random media [cf. Tatarskii, 1971; Yeh and Liu, 1982; Yeh and Wernik, 1990; Bhattacharyya et al., 1992]. There is no doubt that scintillation of satellite radio signals is a consequence of the existence of random refractive index fluctuations associated with electron density irregularities within the ionosphere. As the wave propagates through the irregular ionosphere it is safe to assume, at frequencies of interest, that only the wave’s phase is distorted – the wave is randomly phase-modulated. This phase modulation is equal to \( k_0 \Delta \phi \), where \( k_0 = \frac{2\pi}{\lambda} \) is the free-space wavenumber for a radio wave of length \( \lambda \), and \( \Delta \phi \) is the variation of the optical path length within the layer with irregularities. \( \Delta \phi \) is
dependent on the fluctuations of the ionospheric total electron content $\Delta N_T$ caused by irregularities [Yeh and Liu, 1982]:

$$\Delta \varphi = -2\pi r_e \Delta N_T / k_0^2,$$

where $r_e$ is the classical electron radius.

As the wave propagates toward the receiver, phase mixing occurs inside the irregularity layer and in free space below the layer changing the modulation of the wave and eventually producing a complicated diffraction pattern on the ground. If the satellite and/or the ionosphere move relative to the receiver, temporal variations of intensity and phase are recorded. In the phase screen theory of scintillation, it is assumed that the irregularity layer is so thin that it can be considered as a screen, which modifies only the phase of the wave. The phase screen approach has been introduced to ionospheric scintillation by Booker et al. [1950] and later developed by Rino [1979a,b, 1980, 1982]. Knepp [1983] proposed a multiple phase screen model of scintillation, which is appropriate when dealing with a thick irregularity layer. Because of its simplicity and at the same time effectiveness, the phase screen approach is frequently used to model propagation effects caused by the irregular ionosphere.

Large database of scintillation measurements is used to construct climatological models of scintillation. The most popular WBMOD ionospheric scintillation model [Fremouw and Secan, 1984] and its upgrades [Secan et al., 1995, 1997] contain the worldwide climatology of the ionospheric plasma-density irregularities that cause scintillation (environment model), coupled to a model for the effects of these
irregularities on transionospheric radio signals (propagation model). The propagation model is a phase-screen model [Rino, 1979a, b] in which the ionospheric irregularities are characterized by a power-law electron density spectrum. The model for the propagation effects is based on a three-dimensional description of the plasma density irregularities with the following parametrization: axial ratio of the irregularities along and across the local magnetic field direction; the orientation of sheet-like irregularities with respect to the magnetic $L$ shells; the logarithmic slope and outer scale of the in situ spatial spectrum of the irregularities; the height-integrated strength of the spatial spectrum, defined at a scale size of 1 km ($C_kL$); the height of the phase screen; and the in situ velocity of irregularities. WBMOD includes models for each of these parameters, some derived from analysis of scintillation data, and others (the in situ drift velocity, for example) based on analysis of a variety of other data sets.

In this paper we will present a preliminary climatological model of the high-latitude scintillation based not on the scintillation measurements but instead deduced from the in situ measured plasma density fluctuations. Satellite in situ plasma density measurements offer an excellent database to map the global morphology of irregularity parameters, which define the scintillation. The main advantage of using satellite in situ data is the temporal and spatial coverage, much better than in the case of scintillation measurements made at sparsely distributed receiving stations.

The credit for a first attempt of using in situ data in scintillation modeling should be given to Basu et al. [1976] who used the OGO-6 measurements over the equatorial region. The phase screen model of propagation was applied with the electron density fluctuations derived from measurements and other model parameters assumed. In
particular, the three-dimensional spectral index for the irregularity spectrum was taken to be equal to 4. The irregularity layer height and thickness was assumed to be 450 km and 200 km, respectively. Modeling was performed for three values of the outer scale: 2, 6.7, and 20 km. The axial ratio of the field-aligned irregularities was taken to be larger than 5. The marked longitudinal variation of the occurrence of scintillation and the varying width of the equatorial scintillation belt have been found. Later, Basu et al. [1981] used the Atmospheric Explorer D data to model scintillation at high latitudes. Rino’s [1979a,b, 1980, 1982] formulation of the phase screen theory of scintillation was applied with only density variance computed from the satellite measurements. The spectral index of the irregularities was assumed to be 4, the outer scale equals 20 km. The ambient electron density and irregularity layer thickness were derived from the model of the ionosphere. Scintillation index and rms phase were calculated for three different types of the irregularity anisotropy, E-W sheets, N-S sheets, and field aligned rods. Contour maps of the overhead scintillation were produced. Basu et al. [1988b] combined the average spectral index derived from the Dynamics Explorer 2 (DE2) ionospheric electron density irregularity data with additional information regarding maximum ionization density, irregularity anisotropy, and layer thickness to model intensity and phase scintillation caused by polar cap patches. They conclude that the irregularity in situ measurements may serve as a valuable input to the scintillation model.

Our scintillation model makes use of the DE2 retarding potential analyzer plasma density data [Hanson et al., 1981] covering the period from August 1981 to February 1983, near to the solar maximum activity. From in situ measurements we derived the turbulence strength parameter $C_s$ and spectral index. With IRI model [Bilitza, 1997] the
\( C_s \) parameter was rescaled to get its value at the height of the maximum electron density. The IRI model was also used to estimate the irregularity layer thickness. To convert the parameters derived from in situ measurements to the equivalent scintillation index one should rely on the scintillation theory. We used the simplest phase screen approach as described by Rino. The limitations of this approach are discussed. Our final result are maps of the overhead scintillation index \( S_4 \) in the geomagnetic time (MLT)-invariant geomagnetic latitude (IGL) coordinates sorted according to the \( K_p \) geomagnetic activity index and season. For ease of comparison with scintillation observations we also present maps of \( S_4 \) in MLT-IGL coordinates of subionospheric points as seen from selected observation sites, and the UT and seasonal variations of \( S_4 \).

2. Scintillation model

The input data to our scintillation model are DE2 retarding potential analyzer (RPA) measurements of the ion density, equivalent by the charge neutrality to the electron density \( N_e \). The satellite was on a nearly polar orbit. The sampling frequency of RPA was 64 Hz, corresponding to every 120 m along the satellite orbit. These measurements were grouped over 8 s (512 samples) long segments. The data gaps not longer than 3 samples were filled using linear interpolation. Segments with longer gaps were rejected. Bad data defined as that falling outside the interval \( \pm 4\sigma_N \) around the mean electron density for the segment were corrected using linear interpolation. Only segments for which the invariant magnetic latitude was larger than 50º are considered. For each segment we calculated the maximum entropy power spectrum (MEM) using 30 filter
weights. Altogether we analyzed over 211 thousands segments. In Figure 1 we present an arbitrary chosen data segment and its spectrum.

Following Rino [1979a], the one-dimensional temporal spectrum of the in situ measured electron density is assumed to be of the form

\[ P_s(f) = \frac{C_s \Gamma(p/2)}{4\pi^2 \Gamma(p/2 + 1)} \frac{1}{V_e q_0^2 + (2\pi f / V_e)^2}^{p/2} \]  

(2)

where \( p \) is the one-dimensional spectral index, \( q_0 \) is the outer-scale wave number, \( V_e \) is the effective satellite velocity, and \( C_s \) is called the turbulence strength parameter. Note that Rino is using the index \( \nu \) for which the spectral index of the three-dimensional spectrum of density fluctuations is equal to \( 2\nu + 1 \) and the one-dimensional spectral index \( p = 2\nu - 1 \).

The effective velocity is a measure of the rate with which the satellite cuts across the contours of equal correlation of the electron density fluctuations, and accounts for the effect of irregularities anisotropy on conversion from the spatial to temporal fluctuations. The effective velocity \( V_e \) is a quadratic form in the \( x, y, \) and \( z \) components of the true satellite velocity \( V_s \). The \( x \) axis is horizontal in the magnetic meridian plane, \( z \) axis is oriented vertically downward, and \( y \) axis completes the right-handed coordinate system. The effective velocity can be calculated from the relationship \( V_e^2 = V_s^T C V_s \), where \( C \) is the matrix defined in the work of Rino and Fremouw [1977]. The matrix \( C \) depends on the irregularity elongation parameters in the magnetic field direction \( a \) and transverse to the magnetic field \( b \), magnetic dip angle, and inclination angle of the transverse irregularity axis. Figure 2 presents the dependence of the effective velocity on the dip
angle for several assumed irregularity anisotropies: isotropic irregularities \((a=b=1)\),
magnetic field aligned rods \((a=2\text{ and }10, b=1)\), and tilted sheets \((a=10, \delta=10^\circ)\). To
construct this plot it was assumed that the satellite moves along the \(x\) axis with the
velocity 7.6 km/s. One can see that the irregularity anisotropy causes \(V_e\) to be smaller
than the true velocity \(V_s\) with larger effect at smaller dip angles. At the dip angle 60\(^\circ\) \(V_e\)
deviates from the true velocity by 15%.

The turbulence strength parameter \(C_s\) appearing in (2) is given by:

\[
C_s = 8\pi^{3/2} \langle \Delta N_e^2 \rangle > q_0^{p-1} \Gamma(p/2 + 1)/\Gamma(p/2 - 1/2) \quad p>1
\]  

(3)

where \(\Delta N_e = N_e - \langle N_e \rangle\) is the electron density perturbation at the satellite location, and
the angle brackets denote ensemble averaging.

This parameter can be unambiguously measured from the spectra of in situ
measured electron density fluctuations [Livingston et al., 1981]. Indeed, if we assume that
\(2\pi f / V_e >> q_0\) then (2) can be written as:

\[
P_s(f) = \frac{C_s \Gamma(p/2)}{4\pi^2 \Gamma(p/2 + 1) V_e (2\pi / V_e)^p} f^{-p}
\]  

(4)

Thus if the spectral index \(p\) is derived from the measured spectrum and the
effective velocity \(V_e\) is known, the turbulence strength parameter \(C_s\) can be deduced from
the spectral power \(P_s(f_i)\) at a given frequency \(f_i\). To estimate \(C_s\) we assumed that
irregularities are isotropic and the satellite moves in the magnetic meridian plane along
the x axis. With this assumption \( V_e = V_s \), and since in fact \( V_e \leq V_s \), the \( C_s \) parameter is overestimated by a factor \( (V_s / V_e)^{(p+1)} \). If we take \( p = 2 \) and refer to Fig. 2 for values of \( V_e \) then we find that this factor is maximally equal to 1.6 at the dip angle 60°. Livingston et al. [1981] denote a factor by which \( f^{-p} \) is multiplied as \( T_1 \).

The one-dimensional spectral index \( p \) has been calculated using log-log least squares fit to the spectrum over the frequency band 1-20 Hz, which corresponds to the spatial scales approximately from 380 m to 7.6 km. The \( C_s \) parameter was estimated using the procedure just described at three frequencies 1, 6, and 20 Hz, corresponding approximately to the spatial scales 7.6, 1.3, and 0.4 km, respectively. In further calculations we took the mean \( C_s \).

The amplitude scintillation index \( S_4 \) was calculated using Rino’s [1979a] weak scatter phase screen formula, for \( p<4\):

\[
S_4^2 = (r_e \lambda)^2 L \sec \theta C_{s\theta} Z^{p/2} \frac{\Gamma(1 - p/4)}{\pi^{1/2} \Gamma(p/4 + 0.5) p} F
\]

in which \( r_e \) is the classical electron radius, \( \lambda \) is the wavelength, \( L \) is the irregular layer thickness, \( \theta \) is the zenith angle, \( Z \) is the Fresnel zone parameter

\[
Z = \frac{\lambda z_R \sec \theta}{4\pi}
\]
where \( z_R = \frac{z z_s}{z + z_s} \) is the effective distance in which \( z \) is the distance to the phase screen and \( z_s \) is the distance to the satellite. This modification takes into account the fact that for the satellite at the finite distance the wavefront is spherical, not plane.

The parameter \( C_{sr} \) is the turbulence strength parameter at the height of the phase screen, which we will locate at the peak electron density height. \( F \) is the geometry-dependent Fresnel filter factor defined in equation (34) of Rino [1979a]. For isotropic irregularities \( F=1 \).

With the assumption that the spectral index \( p \) and the outer scale wavenumber \( q_0 \) are independent of height, \( C_{sr} \) is defined by (3) with \( <\Delta N_s^2> \) replaced by \( <\Delta N_m^2> \), the variance of electron density fluctuations at the peak height. The parameter \( C_{sr} \) can be calculated from \( C_s \) assuming that the relative density fluctuations \( \Delta N/N \) are height independent, thus \( \Delta N_m = N_m \Delta N_s / N_s \). To verify the assumption about the height independence of \( p \) and \( \Delta N/N \) we averaged \( p \) and \( \sqrt{<\Delta N_s^2>/<N_s^2>} \) over the height bins 50 km wide and plotted the result in Figure 3 as a function of the satellite height. The vertical lines mark the rms spread of values. One can see that both parameters do not show any trend and indeed can be considered as height independent. Note that so calculated \( C_{sr} \) does not require any assumptions about the value of the outer scale \( r_0=2\pi/q_0 \), except that it is height-independent. This assumption is strong and difficult to verify.

It should be mentioned that Basu et al. [1981] have found that in the nighttime auroral oval the relative density fluctuations \( \Delta N/N \) are slightly, but evidently, larger at high altitudes and only in the polar cap they are height-invariant. DE2 data do not confirm this finding. Indeed, at magnetic latitudes less than 70° the \( \Delta N/N \) averaged over
MLT= 21-03 and altitudes less than 400 km is equal to 0.060±0.095. Exactly the same value is obtained if averaging is performed over altitudes above 400 km.

The peak electron density and its height have been derived from the IRI-95 model [Bilitza, 1997] for the actual sub-satellite geographic coordinates, date, time and geophysical conditions. It should be noted, however, that the IRI model does not provide sufficiently reliable electron density profiles at high latitudes, especially in the topside ionosphere. We have found that often the electron density above the peak is not decreasing, but even increasing with height. Whenever the profile was evidently wrong we used the closest most reliable profile. In our future work on the scintillation modeling we will use a model which better describes the high-latitude ionosphere.

The electron density profile is also required to estimate the irregularity layer thickness $L$. In the phase screen approach it is assumed that $L$ is so small that on the exit from the layer amplitude fluctuations are negligible and the background electron density is constant within the layer. It is also required that $L$ is much larger than the outer scale. In our model we have taken as the layer thickness the difference between heights at which the electron density falls to 0.95 of its peak value (Fig. 4). So defined layer thickness $L$ calculated from the IRI model ranges from 60 to 80 km. It satisfies the phase screen model conditions better than the commonly assumed value ranging from 200 to 250 km [e.g. Basu et al., 1981, 1988b]. Since, according to (5), the only dependence of the scintillation index on the layer thickness is through its proportionality to $L^{1/2}$ it is not difficult to rescale the modeled $S_4$ to an arbitrary layer thickness.

When rescaling the turbulence strength parameter to the peak density we assumed that the main contribution to scintillation comes from irregularities located near the peak
height. Although this is a common practice (e.g. Basu et al., 1981; 1988b) one should be aware that this simplification may lead to overestimated scintillation levels, especially when the assumed irregularity layer thickness is large.

We should note that, according to Rino [1982], the weak scatter formula (5) overestimates the scintillation index when \( C_{sr} \geq 10^{20} \). The turbulence strength parameter derived from the DE2 in-situ measurements exceeds this limiting value in 16% of cases. Nevertheless, for completeness, the cases with larger \( C_{sr} \) were included into our analysis.

In Figure 5 we present an example of calculations for a single DE-2 satellite path. The top panel shows the log of the electron density averaged over data segments 8 s long. The second panel shows the irregularity amplitude \(<(\Delta N)_{s}^{2}>^{1/2}/<N>\). In the third panel we plotted the log of turbulence strength parameter \( C_{sr} \) at the peak height. In the fourth panel the spectral index \( p \) is given, and in the bottom panel we show the scintillation index \( S_4 \) at the signal frequency 1200 MHz. High signal frequency was chosen to assure that the scintillation is weak enough to comply with the weak scatter assumption of (5). In total 2132 satellite passes were analyzed providing a large database of over 211 thousands of data points. This database is used to derive various statistically significant relationships and maps.

3. In situ results and discussion

3.1 Spectral index

As evidenced by (3) and (5), the spectral index \( p \) is an important parameter determining the scintillation level. Thus the relationship of the spectral index to the ionosphere conditions is of great practical importance for studying the scintillation effect.
on satellite communication links. Our database provides a sufficient information for analysis of statistical dependencies between the spectral index and various parameters defining ionospheric and helio-geophysical conditions. We note that Kivanç and Heelis [1998] used the spatial distribution of the density and velocity spectral indices derived from DE 2 measurements to draw conclusions regarding electric fields and instability mechanisms generating ionospheric irregularities. Electric field fluctuations measured with the AC electric field spectrometers onboard DE2 have been analyzed and extensively discussed by Heppner et al. [1993].

Figure 6 shows histograms of the spectral index $p$ for summer and winter. The continuous and dotted lines correspond to the invariant latitudes greater and smaller than 70, respectively. The statistical parameters of distributions are summarized in Table 1. The largest mean value of $p$ is observed in summer at high latitudes. At low latitudes, in summer, the mean spectral index is smaller but larger than in winter. In winter the spectral index is much less dependent on the latitude. These results agree with those given by Kivanç and Heelis [1998]. As the main cause of the increase of spectral index in summer they consider a high $E$ region conductivity and enhanced perpendicular diffusion effectively removing smaller scale irregularities. Except in summer at low latitudes the distributions are highly skewed towards smaller $p$ values. Mounir et al. [1991] reported a broad, skewed distribution of $p$ in the high-latitude regions of gradient-drift instability. Using DE 2 data, Kivanç and Heelis [1997] have shown that the distribution of spectral slopes of $\Delta N/N$ is skewed within polar cap ionization patches. It seems that the distribution of spectral index skewed towards small values is a common feature in the turbulent high-latitude ionosphere, with the exception of summer conditions and latitudes.
below 70°. We note also that, according to our data, kurtosis is negative in summer meaning that the distribution is flatter than the Gaussian distribution. The kurtosis in winter at low latitudes is small.

To verify the dependence of the spectral index on magnetic activity we plotted in the upper panel of Figure 7 the values of $p$ averaged over one $K_p$ unit bins for summer (dotted lines) and winter (continuous lines), and for two ranges of the invariant latitude: $< 70°$ (filled circles) and $> 70°$ (open circles). One can immediately note that at high latitudes the spectral index does not depend on the magnetic activity, in both summer and winter. However, spectra are much steeper in summer than in winter, as has been discussed in the previous paragraph. At low latitudes the spectral index increases with $K_p$ with the rate independent on season until it levels off for $K_p > 4$. Insufficient data for summer and $K_p > 6$ prevents us from a firm conclusion, but it seems that the saturation level is independent on season and close to the average $p$ for winter and high latitudes.

The physical interpretation of variations of the spectral index with magnetic activity is beyond the scope of this paper. We believe, however, that they should be related to the variations in the convection pattern which depends on $K_p$ and the direction of IMF, and plays an important role in the decay and transport of $F$ region irregularities [Kelley et al., 1982; Kivanç and Heelis, 1998].

The magnetic local time (MLT) variations of the spectral index are shown in Figure 8, separately for summer and winter, for high and low magnetic activity. In each panel we plotted the spectral index for latitudes less than 70° (filled circles) and higher than 70° (open circles). The spectral index and magnetic local time were averaged within 2 hr time bins. Only bins with more than 100 data points were considered. Roughly
speaking, low latitudes and MLT between 20 and 4 correspond to the auroral zone, while high latitudes and MLT between 11 and 13 to the cusp and noon sector of the polar cap. The steepest spectra are observed in summer at high latitudes with minimum around noon, i.e. in the cusp, both for low and high magnetic activity. High latitude summer spectra are consistently shallower. Due to insufficient data, it is difficult to reveal any systematic magnetic time variations at low latitudes but an increase of $p$ after noon seems to be apparent. This increase continues until midnight for low and high magnetic activity.

Spectral index in winter shows clear magnetic time dependence. At low latitudes the spectra are evidently steepest around noon and midnight, and shallowest around 6 and 18 MLT. This pattern is independent on the magnetic activity. Opposite behavior is seen at high latitudes and low activity but the amplitude of variations is much smaller. The spectrum is shallowest at noon and around midnight. For magnetically active periods the high-latitude spectral index does not depend on time.

### 3.2 Turbulence strength

According to (3) the turbulence strength parameter $C_s$ depends on both the electron density variance $\langle \Delta N_e^2 \rangle$ and the spectral index $p$. As a measure of the turbulence strength independent on the spectral index we used the irregularity amplitude $\langle \Delta N_e^2 \rangle^{1/2} / \langle N_e \rangle$. As it has been shown in the previous section, the irregularity amplitude, unlike density variance $\langle \Delta N_e^2 \rangle$ or the spectral power $P_s(f)$ at selected frequency, is practically independent on the satellite height and is more suitable for the statistical analysis of turbulence strength dependencies based on measurements taken at different heights.
The $K_p$ dependence of $<\Delta N_i^2>^{1/2}/<N_i>$ is shown in the middle panel of Figure 7. In general, one can see that this parameter increases with $K_p$ both in summer (dotted lines) and winter (continuous lines), and at low (filled circles) and high latitudes (open circles). A departure from this trend may be noted in winter at high latitudes when the irregularity amplitudes are practically independent on the magnetic activity up to $K_p \approx 6$. Because of a high plasma density in the entire sunlit summer high-latitude ionosphere with the exception of the midnight auroral zone, the turbulence strength measured in terms of the irregularity amplitude is weaker than that in winter. At low latitudes the turbulence strength is smaller than that at high latitudes but in winter it increases with magnetic activity $K_p$ fast enough to reach the high-latitude level for $K_p > 6$.

In Figure 9 we plotted the MLT dependence of $<\Delta N_i^2>^{1/2}/<N_i>$. One can observe that the irregularity amplitudes at high latitudes (open circles) are almost independent on the magnetic time. At latitudes less than $70^\circ$ (filled circles) the turbulence strength shows evident magnetic time variation. They are weakest equatorward of the cusp where, according to the commonly accepted scenario, originates the plasma which at high magnetic activity is convected in the antisunward direction and, restructured to form polar cap patches [Buchau et al. 1983]. In winter this is also a region with the steepest spectra (c.f. Figure 8). Highly turbulent plasma is observed in the nighttime with maximum around midnight.

Due to the data gaps it is difficult to follow MLT variations of $<\Delta N_i^2>^{1/2}/<N_i>$ in the summer low-latitude ionosphere. It seems, however, that the premidnight turbulence is weaker than that after midnight. Kivanç and Heelis [1998] have found the postmidnight-premidnight asymmetry in the amplitude of 1-km scale size irregularities
measured at invariant latitudes between 65° and 75°. They attribute higher turbulence level in the post-midnight sector to the difference in the velocity structure and operating $E \times B$ instability.

It is interesting to notice that Heppner et al. [1993] have found a prominent zone of maximum power spectral densities of electric field between 4 and 512 Hz at high latitudes between 5 and 13 MLT. The density data analyzed here do not show this maximum.

From the scintillation modeling point of view, the turbulence strength parameter reduced to the peak density $C_{sr}$ is important. According to (3) $C_{sr}$ depends on both variance of the electron density at the peak height $<\Delta N_m^2> = N_m<\Delta N_s^2>/N_s$ and the spectral index $p$.

Magnetic activity variations of log($C_{sr}$) are shown in the bottom panel of Figure 7. At low latitudes (filled circles) and low magnetic activity the $C_{sr}$ parameter in summer (dotted line) is considerably smaller than that in winter (continuous line). Both in summer and winter low-latitude $C_{sr}$ increases with $K_p$. In winter, at high latitudes (open circles) $C_{sr}$ increases slightly with magnetic activity up to $K_p = 4$ and then decreases with increasing $K_p$. In summer, in the high-latitude ionosphere $C_{sr}$ is almost constant for $1 < K_p < 6$. Sorry to say, lack of data does not allow us to conclude if the decrease observed at $K_p = 6$ continues for larger $K_p$.

Magnetic local time variations of log($C_{sr}$) are shown in Figure 10. In the summer ionosphere, at latitudes > 70° (open circles), a small maximum around noon is visible, for both high and weak magnetic activity. This maximum coincides with the minimum of the spectral index in the cusp region and noon sector of the polar cap (cf. Figure 8). In winter,
$C_{sr}$ is independent on MLT but its value is always considerably higher, by an order of magnitude, than that in summer. At latitudes $< 70^\circ$ (filled circles) the turbulence strength parameter varies considerably with MLT, except in summer during disturbed magnetic conditions. Characteristic features of the low-latitude $C_{sr}$ are minima around noon occurring in both the summer and winter ionosphere. In winter maxima are observed in the dawn and dusk sectors. This pattern shows a clear anti-correlation with the corresponding pattern of the spectral index with shallow spectra (small $p$) in the dawn and dusk sectors, and steep spectra (large $p$) around noon and midnight. In winter the low-latitude $C_{sr}$ is always smaller than that at high latitudes.

Rino et al. [1981] and Livingston et al. [1981] have found that in the equatorial $F$ region the spectral index systematically linearly decreases with increasing $\log(T_1)$ and $\log(C_s)$, where $T_1$ is the spectral power at 1 km spatial size. To confirm the dependence of the spectral index on the turbulence strength we plotted in Figure 11 the values of $p$ averaged over 0.5 wide intervals of $\log[P_s(6Hz)]$ for summer (dotted lines) and winter (continuous lines) and for two latitude ranges, below (closed circles) and above (open circles) $70^\circ$. A striking feature is a growth of the spectral slope for turbulence strength increasing from its minimum observed value up to $\log[P_s(6Hz)] \approx 15.5-17$ followed by a decline. At high latitudes the $p$ dependence on $\log[P_s(6Hz)]$ is very close to the convex parabola. In summer, the parabola has higher maximum spectrum slope and is narrower than that in winter. At low latitudes, the value of $\log[P_s(6Hz)]$ at which $p$ maximizes seems to be slightly larger compared to that at high latitudes. This behavior is very much different from that found by Rino et al. and Livingston et al.. Apparently their measurements correspond to a strong turbulence and miss the increasing part of the $p$
versus log\(P_s(6\text{Hz})\) dependence. Indeed, Rino et al. defined \(T_1\) as the spectral power at 1 km spatial size, very close to 1.3 km corresponding to our chosen frequency = 6 Hz, thus log\(P_s(6\text{Hz})\) \(\approx\) log\((T_1)\). They have found the linear decrease of the spectral slope for log\((T_1)\) between 18 and 20. As Figure 11 shows, within this range of log\((T_1)\) the spectral index decreases with increasing turbulence strength. We should mention that early investigations based on in situ density measurements [Phelps and Sagalyn, 1976] showed that the spectral index is insensitive to the irregularity amplitude. However, Kintner [1976] who used Hawkeye 1 electric field measurements has observed that spectra steepen with increase of the turbulence strength. This result has been later confirmed by Heppner et al. [1993]. To our knowledge, numerical simulations of plasma instability mechanisms operating in the high-latitude ionosphere do not explain the variability of the density and electric field spectral index with the turbulence strength.

The dependence between the spectral index and turbulence strength parameter \(C_{sr}\) that we have derived experimentally is shown in Figure 12. The construction of this plot is similar to that in Figure 11 except \(p\) is averaged over log\((C_{sr})\) bins. At latitudes above 70° \(p\) decreases with log\((C_{sr})\) linearly over wide range of \(C_{sr}\) with the rate of change of \(p\) per decade change in \(C_{sr}\) approximately equal to 0.3. This value is slightly larger than \(\sim 0.25\) estimated from Figure 8 in the work of Livingston et al. [1981] for 16.5< log\((C_{sr})< 22.5.\) At low latitudes the \(p\) vs. log\((C_{sr})\) dependence is nonlinear but also independent on season. However, for log\((C_{sr}) > 17\) this dependence is well approximated by a line with the rate of change of \(p\) \(\sim 0.07\), considerably smaller than that at high latitudes. Presumably the outer scale value and possible outer scale dependence on the turbulence strength cause the difference between low- and high-latitude dependence of the spectral
index on the turbulence strength parameter. If this interpretation is accepted then, according to (3), a larger rate of change of $p$ means smaller outer scale $r_0=2\pi/q_0$. Referring to Figure 12 we may say that for strong turbulence ($\log(C_{sr}) > 17$) the outer scale at low latitudes is larger than that at high latitudes.

Summarizing the in situ part, we observe that both spectral index and turbulence strength parameter vary with season, magnetic local time, magnetic latitude, and magnetic activity. These variations should be mirrored in the corresponding scintillation intensity variations. We also have found that the spectral index is a non-monotonic function of the turbulence strength.

4. Intensity scintillation modeling: results and discussion

As described in section 2, the intensity scintillation can be modeled if the spectral index $p$ and turbulence strength parameter $C_s$ are known from observations, and the ionosphere model is used to get the height of the peak electron density, irregularity layer thickness $L$, and $C_s$ rescaled to the peak electron density. The Fresnel filter factor $F$ in (5) depends on the anisotropy of irregularities, which in general is a function of magnetic time and geomagnetic latitude. For isotropic irregularities $F = 1$. For anisotropic irregularities $F$ is a function of the elongation parameters along $(a)$ and transverse $(b)$ to the magnetic field, the magnetic dip angle $I$, inclination angle of the transverse irregularity axis $\delta$, the zenith angle $\theta$ and magnetic azimuth $\phi$ of the satellite. A full set of equations used to calculate $F$ can be found in the works by Rino and Fremouw [1977] and Rino [1982].
Livingston et al. [1982] have performed a morphological study of anisotropy of high-latitude nighttime F region irregularities. So far, this is the only complete enough study of use for modeling of the scintillation morphology. Sorry to say, it is limited to the nighttime auroral zone. Livingston et al. distinguish three generic types of irregularities: field-aligned rods with the axial ratio (parallel to transverse dimensions) of \( a : 1 : 1 \), sheets elongated both along the magnetic field and in the transverse plane coinciding with the local \( L \)-shell and characterized by the axial ratio \( a : a : 1 \), wings for which the axial ratio is \( a : b : 1 \) where \( a > b \). A systematic dependence of irregularity anisotropy with local time and magnetic latitude is observed. Sheet-like irregularities are confined to the invariant latitudes less than 65° corresponding to the equatorward boundary of the auroral zone. The axial ratio varies between 5:5:1 and 10:10:1. Under moderate magnetic activity certain admixture of wings is observed in this region. At higher latitudes rod-like irregularities are dominant with the axial ratio decreasing with latitude. Gola et al. [1992] analyzed plots of the scintillation index as a function of angles between the ray path and the direction of irregularity axes and found that \( 6 < a < 15 \) and \( 1.8 < b < 3 \), with \( a \) slightly smaller during magnetic daytime than that in the nighttime. Data for the analysis were taken at Hornsund (invariant latitude \( \Lambda = 73.4^\circ \)). Additional complication arises from the dependence of the anisotropy on the scale of irregularities. Wernik et al. [1990] have found that smaller irregularities are more anisotropic than large irregularities.

Due to the scarcity of information we assumed the time independent composite model of irregularity anisotropy. Sheet-like irregularities with the axial ratio 10:10:1 are located at invariant geomagnetic latitudes (IGML) less than 65°, rod-like irregularities with the axial ratio 10:1 populate latitudes between 65° and 70°, and latitudes above 70°
are filled with rods with the axial ratio 3:1. It should be realized, however, that the assumed model of irregularity anisotropy influences both the distribution of scintillation in IGML-MLT coordinates and the scintillation intensity.

4.1 Overhead propagation geometry

In Figure 13 we show the variations of the average scintillation index with magnetic local time and invariant latitude for the composite anisotropy model and overhead propagation geometry. The signal frequency is 1200 MHz. Maps were constructed by sorting \( S_4 \) in bins of 10° invariant latitude and 3 hour magnetic time and averaging \( S_4 \) within each bin. Bins containing less than 100 points were not taken into account and are shown in white. Maps were built separately for summer and winter, and for \( K_p \leq 3 \) and \( K_p > 3 \). Below each map, the magnetic time variations of the mean scintillation index are shown for invariant latitudes less than 70° (filled circles) and greater than 70° (open circles). Note the difference in the scintillation index scale for summer and winter.

Both maps and plots show that in summer the scintillation is much weaker than that in winter. This agrees with the seasonal variations of the turbulence strength parameter \( C_{sr} \), which is by an order of magnitude larger in winter. In summer and low magnetic activity, the strongest scintillation is noted around magnetic noon and midnight at latitudes corresponding to the polar cusp and auroral zone, respectively. In winter and low magnetic activity, the strongest scintillation is observed in the polar cap. The maps show that with increasing magnetic activity the regions of the most intense scintillation expand equatorward. In winter the expansion of the scintillation zone is less defined in
the midnight sector and the polar cap scintillation intensity weakens. These model magnetic activity variations of the high-latitude scintillation zone are consistent with those found in the scintillation and other ionospheric irregularity sensitive measurements [see Tsunoda, 1988, and references therein].

One can observe that the mean scintillation index generally follows MLT variations of the turbulence strength parameter $C_{sr}$ shown in Figure 10. The dependence of the scintillation index on the spectral index is visualized in Figure 14 where we plotted the mean (filled circles) and rms value (open circles) of $S_4$ within 0.25 wide bins of $p$. All available data points were used. In spite of large rms values, a clear tendency towards decreasing scintillation intensity for $p$ exceeding 2 is observed. This result is important for the scintillation modeling since it means that one should not use a single, universal spectral index not caring about its seasonal, magnetic local time, magnetic latitude and magnetic activity variability.

Figure 15 shows the magnetic activity variations of the scintillation index for summer (dotted lines) and winter (continuous lines). Different symbols are used to denote magnetic latitudes higher than $70^\circ$ (open circles) and lower than $70^\circ$ (closed circles). One can observe a close correspondence between magnetic activity variations of $S_4$ and of the turbulence strength parameter $C_{sr}$ shown in the bottom plot of Figure 7.

Due to the multitude of affecting physical processes the irregular structure of the high-latitude ionosphere is highly variable and dynamic. This is apparently reflected in experimental data used to construct the scintillation model. Besides, any empirical model relies on a limited number of experimental data. Only models that give not just the average scintillation intensity but also its confidence limits have practical importance.
The maps and plots of the 95% confidence limit of the mean scintillation index are shown in Figure 16. The confidence limit has been calculated using the standard formula [cf. Bendat and Piersol, 1986]:

\[ t_{(\alpha/2, n-1)} \frac{\sigma_s}{\sqrt{n}} \]  \hspace{1cm} (6)

where \( n \) is the sample size, \( \alpha \) is the desired significance level, \( \sigma_s \) is the sample standard deviation, and \( t_{(\alpha/2, n-1)} \) is the upper critical level of the Student \( t \)-distribution with \( n-1 \) degrees of freedom.

The format of presentation of the confidence limit in Figure 16 is the same as that used in Figure 13 for the mean \( S_4 \). Thanks to a large number of the data points used in averaging \( S_4 \) within each time-latitude bin the confidence limit is negligibly small except in summer, at low latitudes under weak magnetic activity conditions.

4.2 Slant propagation scintillation at selected locations

To compare the model with scintillation measurements we calculated the scintillation index for several locations using (5) and a composite anisotropy model. In order to correct roughly for the scintillation intensity dependence on the zenith angle, the calculated \( S_4 \) was multiplied by \((\cos \theta)^{1/2}\) which effectively takes into account only the propagation path length changes. Similar operation is usually performed on the measured \( S_4 \). In Figure 17 we show the maps of the scintillation index and its 95% confidence level for an observer located at Tromsø (69.7° N, 18.9° E, 66°Λ) and Sondre Strømfjord (67.0° N, 59.1° W, 74.3° Λ) for winter conditions and \( K_p \leq 3 \). The coordinates are
invariant geomagnetic latitude of the ionosphere (350 km) pierce point for a satellite at 1000-km altitude and magnetic local time at this point. The signal frequency is 400 MHz and the maps may be compared with those shown in Figure 6 of MacDougall [1990a]. Bins with less than 50 data points are in white. On both Tromsø maps the most intense scintillation is observed in the nighttime and a secondary, weaker maximum around noon. Both maps show the dawn-dusk asymmetry in the sense that in the dusk sector scintillation is more intense. Similar asymmetry may be seen on both MacDougall and our Sondre maps. On Sondre map scintillation is the weakest between 00-06 MLT, in agreement with observations. Attempts to compare model maps and observations for summer failed, mainly because insufficient data.

The UT variations of scintillation at a given station can be easily retrieved from our model. To compare the model with measurements we have chosen Thule, Greenland (76.5° N, 68.7° W, 86° Λ) for which there are published results based on long-term measurements [Aarons et al., 1981; Basu et al., 1985a]. In Figure 18 we show the mean \( S_4 \) calculated within 2 UT hour bins for summer (upper plot) and winter (lower plot). The diurnal variations are plotted for both low \( (K_p \leq 3, \text{closed circles}) \) and for high \( (K_p > 3, \text{open circles}) \) magnetic activity. The smallest number (159) of data points is found in magnetically active summer in the bin 18-19 UT. The data analyzed by Aarons et al. [1981] show that the diurnal variation is weak in summer and apparent in winter with minimum around 8 UT (LT=UT-4) and maximum around 18 UT. As can be seen in Figure 18 this diurnal behavior is reproduced by the model sufficiently well. In an attempt to compare the model and measured scintillation intensities we converted the peak-to-peak excursion of 250 MHz signal expressed in dB, as used by Aarons et al., into
assuming that the scintillating signal amplitude has a Nakagami probability distribution [Nakagami, 1960]. Bischoff and Chytil [1969] validated this assumption. Under weak scintillation conditions, the scintillation index \( S_4 \) has a \( f^{-n} \) dependence with \( n=(p+4)/4 \) [Yeh and Liu, 1982]. This dependence with \( p=2 \) was used to convert \( S_4 \) at 250 MHz to \( S_4 \) at 400 MHz. It turns out that in winter the scintillation index \( S_4 \) varies between \( \approx 0.23 \) and 0.38. The model extremal \( S_4 \) values are smaller. The difference is likely to be due to the fact that Thule measurements were taken during November 1978-March 1980, a period of high solar activity, while DE-2 data were collected during August 1981-February 1983, a period of declining solar activity. In summer the average measured \( S_4 \approx 0.15 \) which again is slightly larger than predicted by the model. However, the ratio between the average winter and summer scintillation intensities as estimated from Aarons et al. figures agrees with our model. The model shows that the diurnal variation of scintillation index does not change with the magnetic activity, in accord with observations.

To investigate the seasonal variation, the occurrence of different levels of scintillation intensity at each month was calculated over the whole period of DE2 operation. All data within field of view from Thule and all magnetic activity data are included. The resulting statistics is shown in Figure 19. The plot has to be compared with Figure 7 of Basu et al. [1988a] in which the occurrence of scintillation at 250 MHz observed at Thule over the same period of time is plotted for several fade levels. One should keep in mind that the levels 5, 10, 15, and 20 dB used by Basu et al. correspond to \( S_4 \) at our working frequency 400 MHz equal to 0.12, 0.22, 0.32, and 0.40, respectively. Those are the levels we have chosen in our analysis. One may notice a close similarity of
the model and observations when intensity fading in excess of 10 dB is considered. Both show maxima in fall 1981, 1982 and spring 1982, and a deep minimum in summer 1982. According to Basu et al. [1985] the reduction in scintillation during summer arises from a decrease in the irregularities strength, possibly due to the presence of a highly conducting $E$ region.

5. Summary

The satellite in-situ measurements of plasma (electron) density fluctuations provide a direct information about the structure and morphology of irregularities that are responsible for scintillation of radio waves on transionospheric links. When supplemented with the ionosphere model and irregularity anisotropy model they can be used to model morphology of scintillation provided a suitable propagation model is accepted. We described a scintillation model for the Northern Hemisphere high latitude ionosphere, which makes use of the DE2 retarding potential analyzer plasma density data, IRI ionosphere model and the phase screen propagation model. The important aspect of our work is that we derived from the satellite data not just the turbulence strength parameter $C_s$ but also the spectral index $p$, which influence the scintillation intensity as well. The results demonstrate the usefulness of the proposed approach. We were able to reproduce successfully the observed scintillation intensity diurnal and seasonal variations. As far as the magnetic activity dependence of scintillation is concerned there is a qualitative agreement between the model and measurements. Model satisfactorily describes the expansion of the scintillation zone under magnetically disturbed conditions. The model reproduces the dawn-dusk asymmetry in the scintillation intensity.
As any other model also our model shows some limitations. First of all, the model is limited by the data used in its construction. It is known [Basu et al., 1988a] that the scintillation is strongly controlled by the solar activity. The DE2 was operating during period of moderate solar activity therefore the model is expected to be valid only when the sunspot number is within the range 80 -140. Another limitation is the assumption that irregularities traversed by the probe are isotropic. This assumption leads to the overestimated turbulence strength parameter and consequently overestimated scintillation index. At the dip angle 60° the error in $S_4$ might be as large as 25% for highly anisotropic irregularities but decreases with the geomagnetic latitude.

A serious limitation is imposed by the use of IRI model, which, as mentioned earlier, often fails to give reasonable high-latitude $F$ region electron density profiles, and such important parameters as the peak density, peak height and irregularity layer thickness might be erroneously estimated. Another source of the disagreement between modeled $S_4$ and observations is inaccurate model of irregularity anisotropy. Paucity of information about the variability of the irregularity anisotropy with magnetic latitude, magnetic time, magnetic and solar activity, enforce the use of the anisotropy model that might be far from reality. The most reliable part of the scintillation modeling is the theory of signal propagation in the irregular ionosphere. It seems that the phase screen model in the Rino’s formulation is sufficiently accurate to describe weak scintillation. Strong scintillation would require solving the parabolic equation formulated for wave propagation below a ‘thick’ phase screen or, alternatively, computation of the Huygens-Fresnel integral with the phase variations on a screen calculated in the geometrical optics
approximation from the in-situ data. For the GPS L-band frequency, a ‘thin’ phase screen approach is adequate.

In spite of the limiting assumptions made when using the in-situ data to model scintillation we have shown that the model agrees with measurements sufficiently well to carry on further study.

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References


Figure captions

Fig. 1 Example of the 8 s long data segment of ion density obtained by RPA on DE2 satellite and its maximum entropy spectrum. The dashed line is the $f^{-p}$ dependence obtained by the least squares fit over 1-20 Hz.

Fig. 2 Effective velocity for several anisotropies of irregularities: isotropic irregularities ($a=b=1$), magnetic field aligned rods ($a=2$ and 10, $b=1$), and tilted sheets ($a=b=10$, $\delta=10^\circ$). It is assumed that the satellite moves along the $x$ axis with the speed 7.6 km/s.

Fig. 3 Dependence of the average spectral index $p$ (left) and irregularity amplitude (right) on the satellite height. Vertical lines show the rms spread of parameters.

Fig. 4 Definition of the irregularity layer thickness $L$ as the difference between heights $h_2$ and $h_1$ at which the density falls to 0.95 of its maximum value $N_{max}$.

Fig. 5 Modeling results for a single satellite path. (a) Segment of the measured density data. (b) Irregularity amplitude $\Delta N_s / N_s$. (c) Turbulence strength parameter at the peak density height $C_{sr}$. (d) Spectral index $p$. (e) Scintillation index $S_4$.

Fig. 6 Histograms of the spectral index. The continuous and dotted lines correspond to the invariant latitudes greater and smaller than $70^\circ$, respectively.
Fig. 7 Variation of the spectral index, $<\Delta N_s^2>^{1/2}/<N_s>$, and $C_{sr}$ with magnetic activity in summer (dotted line) and winter (continuous line) and for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°.

Fig. 8 Magnetic local time (MLT) variation of the spectral index for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°. The summer and winter seasons, $K_p \leq 3$ and $K_p > 3$ cases are plotted separately.

Fig. 9 Magnetic local time (MLT) variation of $<\Delta N_s^2>^{1/2}/<N_s>$ for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°. The summer and winter seasons, $K_p \leq 3$ and $K_p > 3$ cases are plotted separately.

Fig. 10 Magnetic local time (MLT) variation of $\log(C_{sr})$ for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°. The summer and winter seasons, $K_p \leq 3$ and $K_p > 3$ cases are plotted separately.

Fig. 11 Spectral index versus $\log[P_s(6\text{Hz})]$ for summer (dotted lines) and winter (continuous lines). Open and filled circles correspond, respectively, to the invariant latitudes greater and smaller than 70°.
Fig. 12 Dependence of the spectral index on the turbulence strength parameter for summer (dotted lines) and winter (continuous lines) and for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°.

Fig. 13 Distribution of the scintillation index $S_4$ at 1.2 GHz under overhead propagation geometry for the irregularity anisotropy model described in the text. The maps coordinate system are the invariant latitude and magnetic local time. Plots beneath maps show the MLT variations of $S_4$ averaged over 2 hr MLT bins for latitudes < 70° (closed circles) and > 70° (open circles).

Fig. 14 Dependence of the scintillation index on the spectral index (closed circles). Open circles show the rms spread of the scintillation index.

Fig. 15 Average $S_4$ versus $K_p$ in summer (dotted line) and winter (continuous line) and for the invariant latitudes greater (open circles) and smaller (filled circles) than 70°.

Fig. 16 Distribution of the 95% confidence level of $S_4$ shown in Figure 13. The maps coordinate system are the invariant latitude and magnetic local time. Plots beneath maps show the MLT variations of the confidence level averaged over 2 hr MLT bins for latitudes < 70° (closed circles) and > 70° (open circles).

Fig. 17 Invariant latitude-magnetic local time maps of the scintillation index $S_4$ at 400 MHz and its 95% confidence level for two receiving stations, winter season, and low magnetic activity. It is assumed that the satellite is at 1000 km altitude.
Fig. 18 UT scintillation variations at Thule for both quiet ($K_p<3$, closed circles) and disturbed ($K_p>3$, open circles) magnetic conditions, in summer and winter.

Fig. 19 Seasonal behavior of the occurrence of the scintillation index $S_4$ at 400 MHz greater than 0.12 (continuous line), 0.22 (dash-dotted line), 0.32 (dash line), 0.40 (dotted line).
Table 1. Statistical Parameters of the Spectral Index $p$ Probability Distribution Function

<table>
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<tr>
<th>Season</th>
<th>Invariant latitude</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
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<td>Summer</td>
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<td>1.82</td>
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<td>0.46</td>
<td>−0.14</td>
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<tr>
<td></td>
<td>$&gt; 70^\circ$</td>
<td>2.14</td>
<td>0.43</td>
<td>0.07</td>
<td>−0.32</td>
</tr>
<tr>
<td>Winter</td>
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<td>1.68</td>
<td>0.41</td>
<td>0.59</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>$&gt; 70^\circ$</td>
<td>1.70</td>
<td>0.34</td>
<td>0.42</td>
<td>0.20</td>
</tr>
</tbody>
</table>
1981 229  16:09:34.64 UT

Spectral Power Density $[\text{m}^2 / \text{Hz}]$

$p=1.66\pm0.08$

$N_e$ $[\text{m}^{-3}]$

Time [s]