250 MHz/GHz Scintillation Parameters in the Equatorial, Polar, and Auroral Environments

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Abstract—Ionospheric scintillation effects encountered in the equatorial anomaly crest, polar cap, and auroral regions have been contrasted to provide information for the design and evaluation of the performance of multifrequency satellite communication links in these regions. The equatorial anomaly region is identified as the most disturbed irregularity environment where the amplitude and phase structures of 250 MHz and *L*-band scintillations are primarily dictated by the strength of scattering rather than ionospheric motion. In the anomaly region, the spectra of intense amplitude scintillations at these frequencies are characterized by uniform power spectral density from the lowest frequency (10 MHz) to 4 Hz at 257 MHz and to 1 Hz at *L*-band (1541 MHz) and steep rolloff at higher fluctuation frequencies with power law indexes of -5 to -7 . Such structures are compatible with intensity decorrelation times of 0.1 and 0.3 s at 257 and 1541 MHz, respectively. The phase spectra at 244 MHz are described by power law variation of psd with frequency with typical spectral indexes of -2.4 . The strong scattering at VHF induces extreme phase rates of 200° in 0.1 s. The 90th percentile values of rms phase deviation at 244 MHz with 100 s detrend are found to be 16 rad in the early evening hours, whereas amplitude scintillation can cover the entire dynamic range of 30 dB not only in the 250 MHz band but at *L*-band as well. In the polar cap, the 50th and 90th percentile values of rms phase deviation at 250 MHz for 82 s detrend are 3 and 12 rad, respectively, with comparable values being obtained in the auroral oval. The corresponding values for the S_4 index of scintillation are 0.5 and 0.8 in the polar cap, which are slightly higher than those recorded in the auroral oval. The power law index of phase scintillation at high latitudes is in the vicinity of -2.3 , which is not a result of very strong turbulence as in the equatorial region but is considered to be a consequence of shallow irregularity spectral indexes. The phase rates at auroral locations are an order of magnitude smaller than in the equatorial region and attain values of 100° in 0.5 s. The extreme variability of ionospheric motion in the auroral oval sensitively controls the structure of scintillations.

The long-term morphology (period 1979–1984) of intensity scintillations at 250 MHz in the polar cap shows that, in addition to the absence of diurnal variation of scintillations, and the presence of an annual variation with a pronounced minimum during local summer, there exists a marked solar control of scintillation activity such that it abruptly decreases when the solar activity falls below a threshold level.

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I. INTRODUCTION

SATELLITE communication links in the 250 MHz/GHz range can be subjected to the effects of ionospheric scintillations which are caused by the irregularities of electron density in the *F*-region of the ionosphere. These irregularities impose random phase perturbations on the wavefront of a satellite signal during its passage through the ionosphere. As the wavefront with perturbed phase travels toward the ground, intensity and phase fluctuations develop across the wavefront due to phase mixing. In the case of an orbiting satellite, these intensity and phase fluctuations sweep past a receiver because of the satellite motion and the receiver output registers time variations of intensity and phase known as intensity or phase scintillations. On the other hand, in the case of a geostationary satellite, the motion of the ionospheric irregularities carries the intensity and phase variations across a fixed ray path and causes scintillations on a communication link. It should be remembered that the ray path from a satellite orbiting, at an altitude of 1000 km, sweeps past the ionospheric irregularities assumed to be at 350 km at a speed of $\sim 3 \text{ km s}^{-1}$. On the other hand, the speed of *F*-region irregularities relative to a receiver on the ground is typically on the order of 100 m s^{-1} . As a result, the scintillation rate of orbiting satellite signals is generally an order of magnitude faster than in the case of geostationary satellites.

Scintillations cause both enhancements and fadings about the median level of the signal as the radio signals sweep across the irregular ionosphere. When these fadings exceed the specified fade margin of a link, its performance is degraded. The degree of degradation will depend on the magnitude of fadings relative to the margin, the duration of the fade, the rate of fading, the type of modulation, and the criteria of acceptability. On a global scale, the degradations are most serious for propagation paths which transit the low latitude irregularity belt around the magnetic equator and the high latitude environment encompassing the auroral oval and polar cap regions (cf. Fig. 1 given in [1]).

The morphology of scintillations has been studied for several years and documented for the equatorial, midlatitude, auroral, and polar cap regions. Intensity scintilla-

tion measurements with orbiting and geostationary satellites provided the major database for such long-term studies [1]. The morphology of phase scintillations was developed by the use of multifrequency phase coherent DNA wide-band satellite transmissions in the equatorial [2] and auroral regions [3], [4]. More recently, near-stationary polar beacon satellites, which can be viewed at high elevation angles from high latitude stations, have been used to develop the morphology of phase and intensity scintillations in the auroral oval and polar cap regions [5]. In addition, case studies of ionospheric scintillations have been made in conjunction with rocket, radar, satellite *in situ*, and optical measurements [6]–[8]. These investigations have provided much insight into the mechanisms of irregularity formation and are expected to be helpful in developing predictive systems of scintillations based on geophysics [9].

In this paper, we first isolate very disturbed irregularity environments at both high and low latitudes, provide quantitative measures for the level of disturbance encountered by communication links in these regions, and analyze further the results in a form that can be used to evaluate communication system performance. We shall emphasize the difference between the structures of scintillation at high and low latitudes and isolate the appropriate parameters of concern to communication links operating in these two distinct disturbed regions of the globe.

II. DATA AND METHOD OF ANALYSIS

We have used both intensity and phase scintillation data from Thule, Greenland (76.5°N, 68.7°W), a polar cap station; Goose Bay, Labrador (53.3°N, 60.3°W), located in the nighttime auroral oval; and Ascension Island (7.9°S, 14.4°W), an equatorial anomaly station where the critical frequency of the *F*2 layer attains high values in the postsunset period when the ionospheric irregularities become most pronounced.

At Ascension Island, 244 MHz signals from the geostationary satellite, Fleetsatcom, were recorded digitally by a computer-controlled phase-lock receiver. The processing of the phase and intensity scintillation data using the phase-lock system has been described earlier [10], [11]. This system was operated over a limited period of time, namely, Jan.–Feb. 1981 and Jan.–Feb. 1982, corresponding to periods of strong scintillation activity at this location. In addition to the above, total power receiving systems are employed to make routine recordings of signal intensity from Fleetsatcom at 244 MHz and from the geostationary satellite, Marisat, at a variety of frequencies, namely, 257, 1541, and 3954 MHz. Round-the-clock observations by this total power system are recorded on chart recorders and manually analyzed to determine intensity scintillation magnitude over 15-min intervals [12]. During special campaign periods, however, the signals were recorded on magnetic tapes to perform spectral analysis and to evaluate both the first- and second-order parameters related to scintillation statistics.

Fig. 1. A 3-min data segment of scintillations observed at 3954, 1541, and 257 MHz at Ascension Island and their respective spectra.

At the high latitude stations, Thule and Goose Bay, 250 MHz signals from near-stationary polar beacon satellites were received at high elevation angles by both the computer-controlled phase-locked receiver and the total power system. In view of the periodic frequency updating of this satellite at 168-s intervals, the phase and intensity scintillation data could be processed over 82-s intervals spaced 168 s apart [5]. The total power system acquired intensity scintillation data on chart recorders on a round-the-clock mode which were analyzed manually as mentioned earlier.

III. RESULTS

A. Ascension Island

During the last sunspot maximum period, the most severe scintillation activity was encountered at this equatorial station [13], [14]. Fig. 1 shows a sample of such an extreme case of scintillation activity which was recorded on multifrequency transmissions from Marisat. The left-hand panel shows, from the top, intensity scintillations at 3954, 1541, and 257 MHz over a 3-min period in the early evening hours. The right-hand panel shows the corresponding power spectra for the samples with the power law index (slope) of the best fit straight line to the linear rolloff portions indicated on the diagram. On the left-hand panel, the second central moment of signal intensity,

namely, the S_4 index of intensity scintillations defined in [15], is labeled to provide a quantitative measure of intensity fluctuations. At the lowest frequency, 257 MHz shown in the bottom panel, the S_4 index of scintillations attains a value of 0.88 approaching the saturation condition of $S_4 \sim 1$. The rate of fading is extremely fast and approaches the receiver response time of 0.1 s. A receiver with larger dynamic range and faster response time would have recorded fading depths much larger than the 15 dB level registered in the figure. At higher frequencies, the phase perturbations are reduced so that scintillation magnitudes are expected to be less. In general, when scintillations are not very intense ($S_4 < 0.6$), intensity scintillation magnitudes (S_4) follow a frequency (f) dependence of $f^{-1.5}$ shown in [16]. The middle panel, however, shows that at 1541 MHz in the L-band, the S_4 index remains at the saturated level somewhat exceeding unity. This signifies that the irregularity environment is so intense that saturated scintillations are obtained at 1541 MHz, and 257 MHz scintillations are driven far into saturation. The level of activity can be gauged from the top panel which shows that even in the C-band (3954 MHz), scintillation with $S_4 = 0.31$ is obtained. From an engineering standpoint, this corresponds to a fluctuation of 6 dB [17].

The power spectra of scintillations obtained by the use of the fast Fourier transform (FFT) algorithm are shown in the right-hand panel of Fig. 1 [18]. The spectrum of weak scintillations at 3954 MHz is shown in the top panel. It is characterized by maximum power spectral density (psd) at a frequency (f_m) of about 0.4 Hz. This frequency can be expressed as $f_m = u/\sqrt{2}\lambda z$ where u is the drift speed of irregularities orthogonal to the propagation path, λ is the radio wavelength, and z is the slant range from the observing site to the irregularities [19]. For these observations, $\lambda = 0.076$ m, $z = 450$ km, and $f_m = 0.4$ Hz, so that the value of u is derived as 104 m s $^{-1}$. This is in agreement with the observed values in the equatorial region where, during the early evening hours, the drift speed of F-layer irregularities with respect to the ground generally varies between 100–200 m s $^{-1}$ [20]. In contrast to only a factor of 2 variation of drift speed in the equatorial region, the speed in the auroral oval can vary by a factor of 10 or more. This causes a considerable shift of f_m even for a given geometry and a specified frequency as will be shown later in the paper. The other features to be noted are the slopes of the spectra on either side of the maximum psd. Since both psd and frequency are plotted on a logarithmic scale, a linear slope indicates a power law variation of psd with frequency. The spectrum of 3954 MHz scintillations indicates that at the low-frequency end, the variation can be approximated by f^{+1} and the variation of psd at the high-frequency end can be expressed by $f^{-4.2}$. These spectral slopes are typically observed and have been related to the spectra of ionospheric irregularities [18] based on which the scintillation spectra have been successfully modeled [19].

The middle right-hand panel shows the spectrum of

1541 MHz signals which represents the case of saturated scintillations. In contrast to the 3954 MHz spectrum discussed above, the spectral maximum in this case is broad and covers a frequency range of 0.1 Hz–1 Hz. The high-frequency slope is also steeper indicating a power law index of -5.5 . The broad spectral width and steep spectral slopes are characteristics of strong intensity scintillations [21], [22], [19]. In fact, on the basis of the expression for f_m given in the previous paragraph, which is valid for weak scintillations, one expects that at 1541 MHz, a lower value of f_m will be obtained. Instead, f_m extends to much higher values due to strong scattering [23]. Since the autocorrelation function and power spectra are Fourier transform pairs, the increased spectral width signifies a shorter autocorrelation interval. Henceforth, the time interval for 50 percent decorrelation will be referred to as the decorrelation time (τ). For practical purposes, it is found that the inverse of the frequency $f = 2$ Hz, namely, 0.5 s, where the psd falls to a level of 20 dB below the maximum, corresponds quite well to the decorrelation time.

The lowest panel in Fig. 1 shows the scintillation spectrum of 257 MHz transmissions which is driven far into saturation. The spectral broadening is extreme in this case and extends to 4 Hz. The spectral slope is steepest and corresponds to a power law index of -7 . The decorrelation time is found to be 0.13 s signifying an extreme fading rate. It should be noted that although the S_4 indexes for both 1541 and 257 MHz are approximately unity indicating saturation, the decorrelation interval still varies, becoming shorter at the lower frequency which suffers stronger scattering.

Fig. 2(a) and (b) shows the cumulative distribution function (cdf) of signal amplitude for the C- and L-band frequencies illustrated in Fig. 1. The cdf is a first-order statistic and is useful for defining the minimum margin requirements for communication links in nondiversity systems. The diagrams indicate the cdf for the observations (solid line) as well as the theoretical Nakagami m -distribution discussed in [24] which is indicated by dotted lines at the m value ($m = 1/S_4^2$) appropriate for the data sample. It can be seen that the theoretical distributions represent the observations quite well over a wide range of activity levels, being weak at 3954 MHz and strong at 1541 MHz. For intense scintillations such as seen on 1541 MHz, the cdf approaches a Rayleigh distribution ($m = 1$). The Nakagami m -distribution has been earlier shown to be useful for describing the effects of scintillations on satellite communication links [25].

In addition to the cdf which describes the probability distribution of the depth of fading, a statistical description of the fading rate is necessary to fully characterize the effects of scintillations on communication links. The information on the fading rate is contained in the power spectra of scintillations which we have described earlier. Another way of obtaining this information is to employ a level crossing technique. This gives the distribution of fade duration across a set of specified fading levels. Often, this representation is simpler and easier to interpret in re-

Fig. 2. (a) The cumulative amplitude distribution of scintillations at 3954 MHz shown in Fig. 1. (b) Same as in Fig. 2(a) for scintillations at 1541 MHz.

lation to systems applications. The left- and right-hand panels in Fig. 3 show the distribution of fades obtained at 3954 and 1541 MHz, respectively, over the first 1.5 min of the 3-min signal segments illustrated in Fig. 1. The shortest fade duration that could be measured in conformity with the data digitization rate was 0.04 s. The left-hand panel shows the distribution of fade duration for the 3954 MHz scintillation sample. Four separate fade depth levels at 1 dB intervals are found to be appropriate for this sample of weak scintillation. At the -1 dB fade level, the flat top portion of the curve commences to slope

downwards at a fade duration of 0.2 s, which represents the longest fade duration at this fade level. The maximum number of fades encountered at the -1 dB level is 54. This number reduces with decrease in fade duration and attains a count of 27, i.e., 50 percent of the maximum count at a fade duration of 0.08 s. At the next lower fade level of -2 dB, the maximum number of fades reduces to 22. The -4 dB fade level lies on the abscissa indicating that fades do not reach this level. The right-hand panel shows the corresponding distribution for 1541 MHz scintillation which is much more intense and is, in fact, sat-

Fig. 3. Distribution of the fade durations for the period of weak scintillations at 3954 MHz and strong scintillations at 1541 MHz illustrated in Fig. 1.

urated at $S_4 = 1.12$. In this case, the fade levels are chosen at wider intervals. The distribution is interesting in the sense that the number of fades is drastically reduced at higher fade levels exceeding -16 dB. Thus, although the fade depth of strong 1541 MHz scintillations exceeds 20 dB, the number of fades at -16 dB level in one 1.5-min interval is only 7 and the maximum fade duration does not exceed 0.1 s.

We shall next concentrate on the results of both intensity and phase measurements at Ascension Island performed with the computer-controlled receiver discussed in Section II. These measurements were performed by the use of 244 MHz transmissions from Fleetsatcom. The intensity and phase scintillation data were analyzed over successive 150 s periods. Since the 257 MHz intensity scintillation data acquired from the Marisat satellite have been discussed in earlier publications [14], [19], we shall comment primarily on the phase scintillation data which are quite unique and are being reported here for the first time.

Fig. 4 shows the 50th and 90th percentiles of the S_4 index of intensity scintillation (defined earlier) and rms phase deviation (σ_ϕ) over 150-s periods (detrended with a 0.01 Hz filter) as a function of local time. The time interval corresponds to the postsunset to postmidnight period (20–04 LT) (local time) when equatorial F -region irregularities are most intense and abundant. The period Jan.–Feb. 1981 corresponds to a period of high scintillation occurrence as previously mentioned. The number of data points in each 2-h block is indicated along the abscissa. It may be noted that in the early evening hours between 20–22 LT, both the median and 90th percentile values of S_4 and σ_ϕ are highly elevated. The intensity scintillation data saturated at a level of approximately $S_4 = 0.8$ because of receiver constraints. With the Marisat sat-

Fig. 4. The median (50th percentile) and 90th percentile values of phase and intensity scintillations at 244 MHz in terms of four 2-h blocks of local time (LT) during Jan.–Feb. 1981 at Ascension Island.

ellite, we have shown that both the 257 MHz and L -band intensity scintillations at this station become saturated with $S_4 \approx 1.0$. The saturation of intensity scintillation data at about 0.8 did not, however, affect phase measurements. It may be noted that the 90th percentile of rms phase deviation in the 20–22-h block is as large as 16 rad with 100 s detrend. In a similar propagation geometry, the values of rms phase deviation may be scaled to shorter detrend intervals (T_d) by multiplying the given values by $[T_d/100]^{(p-1)/2}$, where p (~ 2.5) is the phase spectral index [26]. From Fig. 4, it may also be noted that the

Fig. 5. Phase scintillation data segments at 244 MHz over 88-s intervals and their spectra in alternate panels acquired at Ascension Island on Feb. 3, 1981.

50th and 90th percentile values of these scintillation parameters decrease sharply with increasing local time owing to the decay of irregularity strength.

We shall now discuss the 244 MHz phase scintillation data that were acquired from the Fleetsat satellite at Ascension Island on Feb. 3, 1981. Multifrequency intensity scintillation data from the Marisat satellite for this day have already been presented earlier. Fig. 5 shows a sequence of phase scintillation data over successive 88-s intervals and their spectra obtained by the maximum entropy method [27] in the adjacent panels. The signal segments and their spectra are numbered on the left-hand side of each panel for ease of comparison. The rms phase deviation in radians for each 88-s interval is indicated on the right-hand side of the data segments. The intervals between the tic marks on the data panel represent 50 rad and on the spectral panels psd of 80 dB. The initial data segments with no activity are not shown and the panels start from the 34th data segment, which commences at 222430 universal time (UT). The first two data segments (34 and 35) show very little phase variation. The corresponding phase spectra show that the noise floor extends from the Nyquist frequency of 25 Hz to about 0.2 Hz. Phase power spectral densities (psd) are noticeable only

at lower frequencies. A sudden onset of scintillations may be noted in the third panel. The corresponding spectra indicates an abrupt increase of psd at all frequencies up to 25 Hz. The numbers alongside the spectra indicate the magnitude of maximum instantaneous spectral slopes. The spectral slopes attain values ranging between -2 to -2.5 during the period of scintillations, but remain much higher before the onset of scintillations as may be noted from the first two spectra. It is worthwhile to recall that the spectral slope of intensity scintillations at a similar frequency (cf. Fig. 1) and a similar period of intense activity is very steep. This is caused by the refractive effects of large scale irregularities of electron density on the structure of intensity scintillations [21], [22]. Until recently, one expected that the spectra of weak intensity scintillations and phase scintillations of any magnitude would reflect the slope of irregularity spectra in the ionosphere. In fact, the slope of -4.2 in the weak scintillation spectrum at 3954 MHz as shown in Fig. 1 reflects very well the average one-dimensional irregularity spectral slope of -3.5 at small scales [18]. The spectral slopes of strong phase scintillations at 244 MHz, however, indicate shallow spectral slopes in the vicinity of -2.5 . The apparent discrepancy has been resolved by Rino and Owen [28]. They simulated an

ASCENSION ISLAND JAN-FEB 1981 $S_4 > .6$

Fig. 6. A scatter plot of the phase spectral slope against phase spectral strength (dB) at Ascension Island at 244 MHz. The slope approaches a value of -2 at high phase spectral strengths.

ASCENSION ISLAND JAN-FEB 1981 $S_4 > .6$

Fig. 7. A scatter plot of intensity decorrelation time against the phase spectral strength of 244 MHz scintillations recorded at Ascension Island. The theoretical dependence of the two parameters in the strong scatter regime for a phase spectral index $p_\phi = -2.4$ is indicated by the straight line.

ionospheric phase screen, allowed a radio wave to propagate through it, and computed numerically the phase structure and phase spectra at various distances from the screen. They showed that due to the diffractive effects of phase in a strong scattering medium, the phase structure develops large, near-discontinuous phase changes (termed "cycle slips") and yields phase spectra with slopes approaching -2 .

Fig. 6 shows a scatter plot of phase spectral slope versus phase spectral strength in decibels which is defined as the phase psd at 1 Hz when the S_4 index exceeds 0.6, i.e., for strong scintillations. The data were acquired at Ascension Island during Jan.-Feb. 1981. At low values of phase spectral strengths or high decibel numbers, phase spectral slopes show a wide scatter between -2 and -2.9 in Fig. 6; but at high values of phase psd, the slopes approach a value of -2 . This provides observational support to the "cycle slip" argument presented in the previous paragraph.

In Fig. 7, we show an interesting plot of intensity decorrelation time at 244 MHz on a logarithmic scale against phase spectral strength (decibels) for strong scintillations ($S_4 > 0.6$). It may be noted that with increased phase spectral strengths in this regime, the intensity scintillations systematically develop finer structures on the ground so that the decorrelation time decreases from about 1 to 0.05 s. By using the method outlined in [26], it is possible to derive the average spectral slope from the slope of the best fit straight line to the scatter plot of Fig. 7. The scatter diagram indicates a spectral slope of -2.4 . This is in very good agreement with the phase spectral slopes of the data segments illustrated in Fig. 5.

The results shown in Figs. 6 and 7 imply that in the disturbed equatorial ionosphere, the structures of inten-

sity and phase scintillations are controlled by the strength of scattering. The decorrelation time is a function of the spatial structure of intensity variation on the ground as well as the ionospheric drift which controls the motion of the spatial structure past a receiving antenna. The fact that the decorrelation time is so well ordered in terms of the phase spectral strength indicates that the drift velocity does not vary much between the postsunset and the midnight period, and it is the strength of the irregularities which control primarily the fading pattern of scintillations. This is, however, not true at high latitudes where the phase spectral strength of the integrated strength of irregularities is not as intense as in the equatorial region, but the drift velocity can vary by an order of magnitude within a short interval of time. At high latitudes, therefore, the fading pattern is primarily controlled by the irregularity drift.

From Fig. 5 it was evident that in intense equatorial phase scintillation events, considerable power resides in the regime of high fluctuation frequencies. This is equivalent to stating that the probability of having a high rate of change of phase is considerable. The phase rate, on the other hand, is a measure of the Doppler spread the signal undergoes in traversing the irregularities of the ionosphere. In Fig. 8, the probability distribution of the phase rate in phase scintillations has been computed over 0.1-s intervals during a 30-min period of intense scintillations at Ascension Island. Since the Nyquist frequency is 25 Hz, the phase rate could have been computed over a much shorter time interval. However, at small sampling intervals, the noise becomes comparable to the signal and the derived phase rates would have been contaminated by the phase rate of noise signals. In Fig. 8(a), the occurrence

Fig. 8. (a) The distribution of phase rate of 244 MHz scintillations at Ascension Island. The high values at the two ends indicate percent occurrence of values $> 500^\circ \text{ s}^{-1}$.

of phase rate between $\pm 500^\circ \text{ s}^{-1}$ has been plotted. It is found that nearly 20 percent of the total population (10^5 points) contains phase rates in excess of $\pm 500^\circ \text{ s}^{-1}$. The distribution of population with extreme phase rates has been plotted in Fig. 8(b) over a wider range extending from ± 500 to $\pm 2300^\circ \text{ s}^{-1}$. It may be noted that phase rates as high as $2000^\circ \text{ s}^{-1}$ or 2° ms^{-1} occur in 0.1 percent of the population with extreme phase rates which, in turn, represents 20 percent of the total number of observations during approximately a half-hour period. Such extreme phase rates have considerable deleterious effects on radar systems. Since the phase scintillation magnitude varies inversely as frequency [29], the above phase rate may be scaled from the 244 MHz observations to 2.4 GHz as $0.2^\circ \text{ ms}^{-1}$.

B. Thule, Greenland

At Thule, a polar cap station, the phase and intensity scintillation data were acquired by receiving 250 MHz transmissions from the near-stationary Air Force satellites at high elevation angles. The ionospheric intersection of

the ray path covered a corrected geomagnetic latitude range of $85^\circ\text{--}89^\circ\text{N}$. Since scintillations are better ordered in terms of corrected geomagnetic latitude (CGLAT) and magnetic local time (MLT) at high latitudes, we shall use this system of coordinates as described in [30]. The phase and intensity measurements were made with the computer-controlled phase-lock receiver during specified intervals as mentioned in Section II.

The morphology of intensity scintillations [31] and that of both phase and intensity scintillations [5] from Thule have been discussed earlier. In this paper, we shall present phase and intensity scintillation data during Jan.-Feb. 1982 not previously published, and use it to contrast its behavior against the Ascension Island observations. We have also extended the intensity scintillation morphology further through the years of low sunspot number to illustrate the control of solar activity on polar cap scintillations.

Fig. 9 shows the variation of 250 MHz intensity scintillation index (S_4) and rms phase deviation (σ_ϕ) over 82-s intervals with magnetic local time as observed at Thule

Fig. 8. (Continued) (b) The distribution of the population with extreme phase rates which corresponded to the two ends of the diagram in Fig. 8(a).

Fig. 9. The median (50th percentile) and the 90th percentile values of phase and intensity scintillation at 250 MHz in terms of four 6-h MLT blocks observed at Thule.

during Jan.-Feb. 1982. It may be noted that at Thule, the scintillation activity during years of high sunspot numbers persists at all hours, the median value of phase ranging between 3 and 5 rad over the entire diurnal period. This

behavior is in sharp contrast to that at Ascension Island, an equatorial station, where strong scintillations are, in general, confined between the postsunset to midnight hours. In view of this, the scintillation statistics in Fig. 4 were derived between 20-04 LT. At auroral locations, such as Goose Bay, scintillations on magnetically quiet days are again confined to nighttime periods as discussed in [5]. Thus, an absence of diurnal variation of scintillations during periods of high solar activity is a feature confined only to the polar cap. The level of 250 MHz scintillations is also high, the 90th percentiles of rms phase attaining values as high as 12 rad and intensity scintillations remaining near saturation with $S_4 \sim 0.9$.

The long-term statistics of 250 MHz intensity scintillations derived with total power receiving systems are shown in Fig. 10. The figure shows the variation of scintillation occurrence at various fade depths for 1979-1984. The highest fade level of ≥ 20 dB represents a peak-to-peak fluctuation level of ≥ 28 dB. The scintillations minimize during the summer months so that the annual variation becomes most conspicuous. During the sunlit period, the high conductivity at E-region heights (~ 100 km) is not favorable for the maintenance of irregularities in the overlying F-region of the ionosphere [32]. In other periods, particularly during the autumnal equinox, fade depths as large as 20 dB with 20 percent occurrence could

Fig. 10. Thule intensity scintillation statistics at 250 MHz during 1979–1984.

be obtained up to 1982. The scintillation activity did not vary much during the period 1979–1982 when sunspot numbers varied between 200 and 100. With further reduction of sunspot numbers, scintillations showed an abrupt decline during 1983 and 1984. Thus, there seems to be a lower threshold of solar activity below which irregularities of sufficient integrated strength are not encountered.

Fig. 11 shows the occurrence contours of fade levels at 250 MHz that exceed 10 dB on both a monthly and diurnal basis. As pointed out in the previous paragraphs, the annual variation of scintillations is the more prominent feature and the diurnal variation is virtually absent at Thule. However, there emerges a diurnal pattern in the Oct.–Nov. period which becomes most conspicuous during the low sunspot years of 1983 and 1984. The maximum activity during these months seems to be confined to the afternoon period around 15 MLT.

The strong scintillation events with S_4 exceeding 0.6, that could be recorded by the phase-lock receiving system at 250 MHz, were sorted. The intensity decorrelation time and phase spectral strengths were determined and their mutual dependence is plotted in Fig. 12. The best fit straight line through the scatter plots corresponded to the theoretical dependence [26] expected for the case of strong scattering with phase spectral slope of -2.2 . It signifies that during strong scintillations at Thule, the intensity scintillation structure is largely governed by the phase spectral strength. Increased scatter around the best fit line signifies that the drift speed may vary by a factor of 3–4.

On the other hand, the scatter in Fig. 7 is much less, indicating that the variation of drift speed is small in the equatorial region. At the auroral station of Goose Bay, a similar plot (not shown here) indicates considerable scatter as well due to the high variability of drift speeds.

C. Goose Bay, Labrador

We shall not discuss in great detail the features of scintillations at Goose Bay, an auroral station, but refer to [5] which compared the characteristics of polar cap and auroral scintillations. In short, the auroral station shows a well-ordered diurnal variation of scintillations with a nighttime maximum and daytime minimum, whereas we have shown the absence of such ordering in the polar cap region, such as Thule. The auroral scintillation magnitudes are, on the average, similar to that in the polar cap although, on occasions, more active conditions prevail in the polar cap. The polar cap scintillation pattern exhibits the presence of discrete structures, whereas in the auroral oval, intense scintillation events continue for hours without showing much variation in magnitude. The major feature of an auroral station is the extreme variability of drift speed. It is not uncommon to observe a change in speed from 100 m s^{-1} to 1000 m s^{-1} within a 30-min period. This variability in speed affects greatly the temporal structure parameters of scintillations such as the decorrelation time or the rate of change of phase and intensity. Fig. 13 shows the rate of change of intensity at 250 MHz encountered on two successive nights, Mar. 7 and 8, 1982. The scheme of the plot is similar to the phase rate plot in Fig.

Fig. 11. Intensity scintillations at Thule at 250 MHz on a seasonal and local time basis. The contour levels represent percent occurrence.

8(a) for Ascension Island, except for the longer data interval (0.5 s) used to compute the rates at the auroral location. Shorter time intervals could not be used here because of possible noise contamination. At the equatorial station, intervals as short as 0.1 s could be used to compute phase rates as high levels of ionospheric turbulence developed high-frequency structures much above the noise floor. Fig. 13 shows that at Goose Bay, on Mar. 7, 1982, the intensity rate of 3 dB s^{-1} occurs in 0.1 percent of the total population, whereas it increases to about 7 dB s^{-1} at the same 0.1 percent level on Mar. 8, 1982. Intensity spectral studies revealed that the irregularity drift speed was 65 m s^{-1} on Mar. 7, 1982, and increased to 390 m s^{-1} on Mar. 8, 1982 [5]. The sixfold increase in drift

THULE JAN-FEB 1982 $S_4 > .6$

Fig. 12. A scatter plot of the intensity decorrelation time against phase spectral strength observed at Thule at 250 MHz. The theoretical dependence of the two parameters for a phase spectral index of -2.2 is indicated by the straight line.

Fig. 13. The distribution of intensity rate of scintillations at 250 MHz at Goose Bay on two successive nights with different ionospheric drifts. The drift was lower on Mar. 7 by a factor of 6 as compared to Mar. 8.

speed is reflected in increased intensity rates. Fig. 14 shows the phase rate plots at the same frequency for the two days. It may be noted that at 0.1 percent level, the phase rate may attain values as high as 250° s^{-1} at an

Fig. 14. Same as for Fig. 13, except here the distribution of phase rate of scintillations at 250 MHz is shown.

auroral location when drift speed is high. If the change can be linearly extrapolated to smaller time intervals, the above value translates to $0.25^\circ \text{ ms}^{-1}$. This is an order of magnitude smaller than the phase rate encountered at Ascension Island and illustrated in Fig. 8(b).

IV. SUMMARY

The results on the structure of multifrequency amplitude scintillations covering the 250 MHz–4 GHz band of frequencies at the crest of the equatorial anomaly and the structure of approximately 250 MHz phase and amplitude scintillations in the equatorial anomaly, auroral, and polar cap regions can be summarized as follows.

At Ascension Island, located at the crest of the equatorial anomaly, the most disturbed irregularity environment on a global basis was encountered during the last sunspot maximum period. At this location, the disturbance level was so intense that not only the 250 MHz but also the 1541 MHz transmissions from geostationary satellites exhibited saturated intensity scintillations which covered the 30 dB dynamic range of receivers that were used to record the satellite transmissions. Even the transmissions at 4 GHz registered fluctuations as large as 6 dB. The median and the 90th percentile values of rms phase deviation at 244 MHz with 100 s detrend are 6 and 16 rad, respectively, during the early evening hours. The

phase spectral strengths (phase psd at 1 Hz) which indicate the strength of turbulence are found to attain values as high as -2 dB. This is at least 10 dB above the most intense levels that are obtained at the polar cap or auroral stations. The extreme levels of turbulence at Ascension Island induce strong scattering of 257 and 1541 MHz signals and thereby dictate the structures of amplitude and phase scintillations at both frequencies. The amplitude scintillation spectra at these frequencies under such situations show uniform psd up to fluctuation frequencies as high as a few hertz, and give rise to steep power law spectral indexes of -5 to -7 . The intensity decorrelation times are consequently reduced to values as low as 0.06 s at 257 MHz. The phase spectral slopes at 244 MHz approach a value of -2.5 which is much shallower than is expected from either the *in situ* irregularity spectra or weak amplitude scintillations spectra at 4 GHz. This probably arises from sharp discontinuous phase changes or “cycle slips” [28] that develop due to phase diffraction effects under strong scatter conditions. In view of these discontinuous phase changes, extreme phase rates of 2 – 3° ms^{-1} were observed. This is rather significant for UHF radar applications.

In the polar cap (Thule), the median and 90th percentile values of rms phase deviation at 250 MHz for 82-s detrend are observed to be 3 and 12 rad, respectively. The corresponding values for the S_4 index of scintillations are 0.5 and 0.8. These values are in reasonable agreement with those published in [5] for another period of observations. The point of interest is the absence of any diurnal variation of polar cap scintillations, its annual variation with a pronounced minimum during local summer, and rather abrupt decrease of scintillations when the solar activity decreases below a threshold level. The irregularity spectral strengths in the polar cap or auroral stations are shown to be not as intense as in the equatorial region. At high latitudes, the phase spectral indexes of about -2.2 cannot be attributed to strong scattering effects, but are probably a result of shallow irregularity spectral indexes in the ionosphere. At auroral locations, the variability of ionospheric motion greatly controls the temporal structure of scintillations. The phase rates at 250 MHz are typically of the order of 0.2 – $0.3^\circ \text{ ms}^{-1}$, but may show considerable changes due to the variability of ionospheric motion.

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Herbert E. Whitney, photograph and biography not available at the time of publication.