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Worldwide behavior of average VHF-UHF scintillation

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A description of the latitudinal, diurnal, seasonal, and solar-cycle variations of *F*-layer–produced scintillations, based on a comprehensive review of the literature, is given. Three distinct latitudinal regimes are discussed in regard to scintillation behavior and the quantitative utility of observations reported in the literature. A semiquantitative empirical model is suggested to describe the strength of scintillation-producing irregularities of *F*-layer electron density. Recent work suggests that more quantitative modeling might now be fruitful, but gaps in fully quantitative data exist. The prime needs are for observations at very high latitudes and for calibration of scintillation indices used at very low latitudes.

INTRODUCTION

There is an extensive literature describing the scintillation of radio-star and satellite signals, including observations from many latitudes and during all solar-cycle epochs. Relatively little effort, however, has gone into collating these data into a systematic description of the worldwide behavior of scintillation and of the inospheric irregularities responsible for it. It is our intent in this paper to begin the latter job by reviewing the observed characteristics of scintillation and suggesting a rudimentary empirical model for irregularity strength.

Collation of scintillation data has been impeded by the variety of observing conditions and procedures and especially by differences between scintillation indices employed by various workers. Recent progress in relating different indices offers alleviation of the latter problem. It is with this in mind that we suggest, toward the end of this paper, an analytical framework for summarizing the vast amount of scintillation data available in the literature. It is our hope that an empirical model for scintillation-producing irregularities, when fully evaluated quantitatively, may prove useful for application to problems involving satellite-to-ground communication systems and for providing geophysical insight.

In the main, this paper is concerned, not with the analytical model, but rather with the scintillation characteristics reported in the literature, upon which the model is based. The data used were obtained from a comprehensive review of the literature; no new data are presented. The references cited are representative of the work pertinent to our objective, but they do not comprise an all-inclusive list.

BACKGROUND

The scintillation of extraterrestrial radio signals in the VHF-UHF band is due primarily to scattering by irregularities in the electron density of the ionosphere. Some scintillations are produced in the *E* layer, but most are produced in the *F* layer [*Basler and Dewitt*, 1962; *Hook and Owren*, 1962; *Jespersen and Kamas*, 1964; *Lawrence and Martin*, 1964; *Yeh and Swenson*, 1964; *Frihagen and Lizska*, 1965; *Jones*, 1968]. The discussion presented here is confined to *F*-layer scintillations.

Scintillations of signals passing through the ionosphere are of three types:-amplitude, phase, and angle-of-arrival. Since most of the work that has been reported in the literature deals with scintillations in signal amplitude, we are forced to limit this study primarily to amplitude scintillations. Phase and angle scintillation data are important, however, and should be included in further work; when combined with amplitude scintillation data, they allow determination [*Hewish*, 1952] of the height of the scattering region (if scale size of the irregularities is measured independently).

Satellites and radio stars provide the signals used to study scintillation. Satellites have the advantage that a

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large area can be covered in a short time, and the signal can be made phase-stable. They have the disadvantages that (*a*) the signal level changes with the distance to the satellite; (*b*) a satellite rarely, if ever, passes along the same path twice; (*c*) data from a given satellite are obtainable in most places only for a few tens of minutes per day; and (*d*) scintillations from low elevation angles tend to be emphasized during any pass because the satellite spends most of its time at low elevation angles relative to any observer.

Radio stars have the advantages that their signal levels remain essentially fixed and that they provide long-term data on a small volume of the ionosphere. Their disadvantages are that too few strong sources exist to cover the sky adequately and that their positions depend on sidereal time, thereby complicating seasonal and diurnal measurements.

The measurement of scintillation usually involves determining an index of scintillation activity. Probably the most popular method is to assign activity indices by qualitatively examining the records; this subjective type of index is easy and quick to apply, but it makes quantitative use of the data difficult, because no two observers at different sites scale in the same way. Other indices involve obtaining a statistical estimate of the ratio of the change in power to the average power in the signal, such as computing the variance or the mean deviation from the mean. One simple but useful method for estimating the scintillation amplitude, introduced by the Air Force Cambridge Research Laboratory (AFCRL) group, is to define the change in signal power as the difference between the third greatest positive and negative excursions in a given sample [*Whitney et al.*, 1969].

Very useful statistical measures of the signal fluctuation are the following, where A is the signal amplitude:

Fractional mean deviation from mean amplitude

$$S_1 = \frac{\langle |A - \langle A \rangle| \rangle}{\langle A \rangle}$$

Fractional variance of amplitude

$$S_2^2 = \frac{\langle (A - \langle A \rangle)^2 \rangle}{\langle A \rangle^2}$$

Fractional mean deviation from mean power

$$S_3 = \frac{\langle |A^2 - \langle A^2 \rangle| \rangle}{\langle A^2 \rangle}$$

Fractional variance of power

$$S_4^2 = \frac{\langle (A^2 - \langle A^2 \rangle)^2 \rangle}{\langle A^2 \rangle^2}$$

Briggs and Parkin [1963] used diffraction theory to relate S_4 analytically to the strength and size of the irregularities, as a function of scattering-layer height and thickness, magnetic-field geometry, zenith angle, and observing frequency. *Chytil* [1967], using statistical theory, showed that S_1, S_2, and S_4 are linearly related for all practical purposes, and that whereas S_3 departs somewhat from linearity with the others, the difference is sufficiently small that it too can be ignored. Chytil's results show that the various indices are related approximately as follows:

$$S_1 = 0.42 S_4$$

$$S_2 = 0.52 S_4$$

$$S_3 = 0.78 S_4$$

Bischoff and Chytil [1969] confirmed that the statistical indices devised by *Chytil* [1967] from the Nakagami *m*-distribution [*Nakagami*, 1960] closely fit experimental data. When they compared experimental scintillation indices, computed by using the difference between the third largest positive and negative excursions (the AFCRL and Joint Satellite Studies Group [JSSG] index), with theoretical values compiled from the *m*-distribution for the 5- and 95-percentile points, *Bischoff and Chytil* [1969] found good agreement. When we then compared theoretical values for the index based on the 5- and 95-percentile values with those from the S_3 index as approximated by *Chytil* [1967], we found an excellent fit. We therefore conclude that using the AFCRL-JSSG index is closely equivalent to using the statistical index S_3.

Relating the subjective indices to the statistical indices and to each other is a difficult matter. The index used at College, Alaska, was carefully calibrated to S_3 [*Little et al.*, 1962], and that used in New Zealand by the Department of Scientific and Industrial Research group was calibrated to S_4 [*Preddey et al.*, 1969]. How the other subjective indices are related, however, is unknown. The fact that the College index, which is similar to some others, varied quite nonlinearly with the statistical indices, whereas the DSIR index varied linearly, suggests caution when comparing results from a number of sites.

WORLDWIDE SCINTILLATION BEHAVIOR

Average scintillation level can be divided into components that depend primarily on latitude and time. In a narrow band of latitudes centered on the geomagnetic equator, *F*-layer scintillations are primarily a nighttime phenomenon, varying with season and with epoch of the solar cycle. At midlatitudes there is a variation with time of day and with latitude but apparently no variation with season or solar activity. High-latitude scintillation shows a sharp equatorward boundary that depends on time of day and solar activity. Poleward of the boundary, scintillation is always strong, showing little diurnal or seasonal variation, some variation with latitude, and possible variation with solar epoch.

Scintillation behavior in each of the above three latitudinal regimes is described in more detail below.

Equatorial scintillation

Quantitative data on the scintillation index from the equatorial region are sparse, although there is considerable evidence for the existence of a zone of enhanced scintillation there [*Millman and Moceyunas*, 1965; *Flood*, 1966; *Coates and Golden*, 1968]. The most extensive collection of data has been obtained in Ghana [*Koster*, 1958; *Koster and Wright*, 1963]. Unfortunately, there is no published information relating the subjective index used in Ghana to the statistical indices.

Latitudinal variation. The scintillation-producing region forms a narrow band about the magnetic equator; the percentage of satellite passes missed by South American tracking stations decreased to one-half the equatorial value ten degrees from the magnetic equator [*Coates and Golden*, 1968].

Diurnal variation. Equatorial scintillations are maximum near local midnight, varying smoothly before and after. Between 0600 and 1800 local time, *F*-layer scintillations are essentially undetectable on frequencies above 40 MHz [*Koster*, 1958; *Koster and Wright*, 1963; *Coates and Golden*, 1968].

Seasonal variation. Equatorial scintillations exhibit about a three-to-one change in magnitude from equinox to solstice [*Koster and Wright*, 1963], as measured by the Ghana index.

Solar cycle variation. Koster and Wright [1963] show about a four-to-one increase in scintillation index from solar minimum to solar maximum, apparently better defined for magnetically quiet than for magnetically active days.

Midlatitude scintillation

Pure midlatitude scintillation data also are relatively few, because most observatories have been located where they have obtained a mixture of midlatitude and high-latitude scintillations. This is particularly true for radio-star observations, because the primary radio stars monitored in the northern hemisphere, where a majority of scintillation work has been performed, are north of the equatorial plane. The extensive work of *Briggs* [1964] in England falls into this category, as does the work of *Lawrence et al.*, [1961] in Colorado. Satellite signals can be used to eliminate the problem of mixing middle- and high-latitude scintillations; to date, however, few long-term, midlatitude studies using satellite signals have been reported.

Latitudinal variation. Data on latitudinal variation (within the midlatitude zone) are limited, but there appear to be some change with latitude, with a maximum near 35° invariant latitude [*Aarons et al.*, 1966; *Whitney et al.*, 1967; *JSSG*, 1968; *Preddey et al.*, 1969; *Preddey*, 1969]. *Preddey* [1969] found about a three-to-one change between about 45° and 35° in the South Pacific, with the maximum best defined at night. The maximum does not appear as marked in the North American and European data.

Diurnal variation. The diurnal variation of midlatitude scintillation appears to be well established, with a maximum near midnight and a minimum near midday [*Lawrence and Martin*, 1964; *Aarons et al.*, 1966; *Whitney et al.*, 1967; *Preddey et al.*, 1969; *Preddey*, 1969]. The night-to-day ratio is rather variable but is about three-to-one on the average.

Seasonal variation. The data of *Preddey et al.* [1969] show no clear seasonal variation, whereas those of *Singleton* [1969] show a weak summertime maximum. Some further study of this factor is needed.

Solar-cycle variation. The data now available show no clear variation with solar activity in the midlatitude scintillation zone [*Aarons et al.*, 1964; *Preddey et al.*, 1969; *Preddey*, 1969]. Observations in England, such as those of *Briggs* [1964], have shown a strong solar-cycle variation, but they cannot be classed as midlatitude observations; they are relevant rather to a description of the variation in the location of the *boundary* between the middle- and high-latitude scintillation zones.

High-latitude scintillation

It has been known for many years that radio-star scintillation increases considerably when the raypath traverses the auroral zone [*Little and Maxwell*, 1952; *Little et al.*, 1962]. Several workers in recent years, primarily using satellite observations, have reported rather abrupt increases in nighttime scintillation level with increasing latitude, equatorward of the auroral zone [*Kent*, 1959; *Aarons et al.*, 1963; *Kaiser and

Preddey, 1968]. The locus of these abrupt transitions has become known as the *scintillation boundary*, and it now appears to form a closed pattern around the geomagnetic pole [*Aarons et al.*, 1969], reminiscent of but generally equatorward from the auroral oval of *Feldstein and Starkov* [1967].

In this paper, we refer to the entire region poleward of the boundary as high latitude. Most of the available observations, however, refer to the scintillation-boundary region itself and few to the region poleward of the boundary. The auroral oval lies within the high-latitude scintillation zone, so scintillations that are aurorally associated contribute to the statistics of high-latitude scintillation. This represents a complicating factor that is difficult to take into account, but it requires attention in scintillation studies.

Latitudinal variation. *Preddey* [1969], using shipboard measurements of satellite signals, has shown data that indicate a diurnally fixed minimum in scintillation near 50° magnetic invariant latitude. The data of *Aarons et al.* [1966], *Preddey et al.* [1969], and *Aarons et al.* [1969] tend to confirm this result, possibly of importance to magnetospheric study. No data exist in the literature on the possible movement of the minimum with season or with solar activity.

Scintillation increases sharply with latitude at night poleward of the fifty-degree minimum and more gradually in the daytime [*Preddey*, 1969]. On the nightside of the earth, the boundary is found near 55° invariant latitude [*Aarons et al.*, 1964; *Basu et al.*, 1964; *Aarons et al.*, 1966; *Whitney et al.*, 1967; *JSSG*, 1968; *Kaiser and Preddey*, 1968; *Aarons et al.*, 1969]. Data are very sparse for the dayside, but *Aarons et al.* [1969] reported that the boundary's high-latitude knee was above 75° during the midday period. This is consistent with observations by *Frihagen* [1969]. The latitude of the boundary decreases with increasing solar activity [*Aarons et al.*, 1964].

The behavior at latitudes well above the boundary is not clear because results are available. The data presented by *Stuart and Titheridge* [1969] show that average scintillations observed at Scott Base in the Antarctic increase slightly between 70 and 80° geomagnetic latitude. *Frihagen* [1969], observing in Spitzbergen, observed no evidence for a decrease at higher latitudes. Further light should be shed on this question in the near future by analysis of data obtained at Thule, Greenland, by the AFCRL group (J. Aarons, private communication, 1970).

Diurnal variation. *Little et al.* [1962] found a two-to-one and *Fremouw* [1966] a three-to-two diurnal variation in scintillation at geomagnetic latitudes of 63 to 74° near solar maximum and minimum, respectively. However, the finding by *Aarons et al.* [1969] that the scintillation-boundary latitude varies diurnally between 55 and 75° in a systematic manner indicates that much, and possibly all, of this reported diurnal variation in scintillation activity is attributable to movement of the boundary. Satellite studies [e.g., *Aarons et al.*, 1966; *Stuart and Titheridge*, 1969; *Singleton*, 1969] show that scintillation is strong nearly all the time poleward of the boundary.

Seasonal variation. No appreciable seasonal variation has been found in high-latitude scintillation level; the data of *Titheridge and Stuart* [1968] show only small seasonal differences in the strength of scintillations in the antarctic *F* region. The College radio-star data reported by *Little et al.* [1962] and *Fremouw* [1966] cannot be used directly because the location of the star, being fixed in sidereal time, varies in local time. At different seasons the radio-star signal traverses a different part of the ionosphere at a given time of day. This behavior, coupled with the diurnal movement of the scintillation boundary, make a seasonal variation difficult to identify. *Liszka* [1964*a*], using satellite data, found no similarity between patterns for 1962 and 1963.

Solar-cycle variation. *Fremouw* [1966] found that between 1961 and 1965 (a period of decreasing solar activity) scintillation magnitude decreased by a factor of one-third at College. However, how much of the decrease was due to the poleward movement of the scintillation boundary with solar epoch, and how much, if any, was due to an inherent decrease in high-latitude scintillation is unknown.

The results of *Stuart and Titheridge* [1969] indicate an increase in average scintillation index between about 70 and 80° geomagnetic latitude between 1965 and 1968 (a period of increasing solar activity). The increase was small but present, on the average, through all hours of the day. The presence of a solar-cycle dependence after latitudinal effects are removed from nighttime data, when the poleward knee of the boundary usually is below 70° magnetic invariant latitude, could imply an inherent dependence of high-latitude scintillation magnitude on sunspot number.

Forsyth and Paulson [1961], who observed at Saskatoon, present data (their Figure 4) quite consistent with an equatorward progression of the scintillation boundary with increasing solar activity unaccompanied by any inherent increase in scintillation level poleward of the boundary's high-latitude knee. The question deserves further study, preferably with observations through the polar-cap ionosphere. At present there is no compelling evidence for an inherent increase in high-latitude scintillation level with increasing solar activity; there is ample evidence, however, for a migration of the boundary as sunspot number varies.

A SUGGESTED EMPIRICAL MODEL

There is interest in describing worldwide scintillation behavior in such a manner that quantitative predictions might be made of signal fluctuations to be expected on an arbitrary satellite-to-ground communication path. For this purpose, and hopefully to spur geophysical insight, it would be useful to describe the published results summarized in the foregoing by a mathematical expression. The most versatile expression would be one that models the scintillation-producing irregularities, allowing geometrical factors to be accounted for by diffraction-theory calculations.

We suggest a tentative empirical model for ΔN, the rms spatial fluctuation in F-layer electron density, that would be consistent with the salient features of worldwide scintillation behavior, as described above. The model consists of three terms, representing, respectively, low-latitude, midlatitude, and high-latitude irregularities, as follows:

$$\Delta N = K_e(1 + K_{er}R)\left[1 - K_{es}\cos\frac{\pi}{91}(D + 10)\right] \cdot \left[\exp\frac{-t^2}{T_e^2} + \exp\frac{-(t-24)^2}{T_e^2}\right]\exp\frac{-\lambda^2}{\lambda_e^2} + K_m\left(1 + K_{mt}\cos\frac{\pi t}{12}\right)\exp\left[-\frac{(\lambda - \lambda_0)^2}{\lambda_m^2}\right] + K_h\left[1 + \operatorname{erf}\left(\frac{\lambda - \lambda_b}{\lambda_h}\right)\right]$$

The variables in the model are the following:

R = mean sunspot number.
D = day of the year.
t = time of day in hours.
λ = magnetic invariant latitude.

The characteristics of high-latitude scintillation are determined primarily by the latitude of the scintillation boundary midpoint and the width of the boundary region, which are described respectively as follows:

$$\lambda_b = \lambda_1 - \lambda_r R - \lambda_t \cos \pi t/12$$

and

$$\lambda_h = K_{h\lambda}\lambda_b$$

where λ_1, λ_r, and λ_t are constants, as are T_e, $\lambda_e\lambda_0$, λ_m, and all the K's.

Tentative values for some of the constants are suggested by the published results summarized in the foregoing section. They are as follows:

$$K_{er} \approx 0.02,\quad K_{es} \approx 0.5,\quad T_e \approx 4 \text{ hours},\quad \lambda_e \approx 12°,$$
$$K_{mt} \approx 0.5,\quad \lambda_0 \approx 35°,\quad \lambda_m \approx 10°,$$
$$\lambda_1 \approx 70°,\quad \lambda_t \approx 10°,\quad K_{h\lambda} \approx 0.1$$

The above model is suggested as being plausible and not necessarily unique or complete. Our intent has been to suggest a simple form that is consistent with known characteristics of scintillation. This is the only basis, for instance, for assuming separability of the variables. The model is based on a number of assumptions. Foremost among these is that, aside from the magnitude of the electron-density fluctuations, the parameters of ionospheric irregularities that are important in determining the magnitude of VHF-UHF scintillations are sensibly constant in magnetic invariant latitude and in time.

To an extent acceptable for a first approximation, existing observations tend to support the prime assumption [*Hewish*, 1952; *Jones*, 1960; *Liszka*, 1963; *Yeh and Swenson*, 1964; *Liszka*, 1964*b*; *Kent and Koster*, 1966; *Aarons and Guidice*, 1966; *Lansinger and Fremouw*, 1967; *Walker and Chan*, 1970], yielding the following parameter values:

Height of the scattering layer = 350 km
Layer thickness = 100 km
Transverse scale-size = 1 km
Axial ratio = 10

A better empirical formula would allow at least for some variation in scale size [*Lansinger and Fremouw*, 1967; *Singleton*, 1969] and in axial ratio [*Kent and Koster*, 1966]. The degree of variability of these parameters is of interest geophysically but of little importance for application to communication channels except in special instances, such as for auroral irregularities.

CONCLUSIONS

In view of the tentative nature of the various terms in the empirical model suggested above, undue attention to evaluation of the constants is to be avoided. On the other hand, testing of the form of the various terms, refinement of the model, and subsequent evaluation of the constants could be carried out by computer simulation of individual sets of observations, using the scattering formulas of, for instance, *Briggs and Parkin* [1963]. As a result of the work of *Chytil* [1967] and of *Bischoff and Chytil* [1969] in relating various scintillation indices, it seems that such computation might now prove fruitful.

The various terms in the suggested model represent approximations with varying degrees of confidence, depending on the accuracy and extent of the observations upon which they are based. The equatorial term could be quantitatively tested and perhaps improved if the scintillation indices used in Ghana [*Koster*, 1958; *Koster and Wright*, 1963] and in Hong Kong [*Walker and Chan*, 1970] were calibrated in terms of the statistical indices. The least confidence is held for the model's accuracy above 80° magnetic invariant latitude. Additional observations are needed there.

The greatest confidence is held for the latitude range covered by the scintillation boundary, where the most extensive observations have been made. On individual satellite passes, the boundary often is manifested as an abrupt change in scintillation index [*Kent*, 1959; *Yeh and Swenson*, 1964; *Kaiser and Preddey*, 1968]. It is shown in the appendix that if a single realization of the F layer contains a latitudinal transition in rms electron-density fluctuation that can be described as a step function whose argument is a random variable with a Gaussian distribution, then the average boundary is described by an error function. This is the basis for the error-function form of the high-latitude term of the model.

APPENDIX. AVERAGE SCINTILLATION BOUNDARY

Let

$$\Delta N_h = \langle \delta N \rangle$$

and let

$$\delta N = H(\lambda - \lambda_t) = \begin{cases} 0 & \text{for } \lambda < \lambda_t \\ 1 & \text{for } \lambda \geq \lambda_t \end{cases}$$

If λ_t is normally distributed with mean λ_b and variance λ_σ^2, then

$$\Delta N_h = \frac{1}{(2\pi)^{1/2}\lambda_\sigma} \int_{-\infty}^{\infty} H(\lambda - \lambda_t) \cdot \exp\left[-\frac{(\lambda_t - \lambda_b)^2}{2\lambda_\sigma^2}\right] d\lambda_t$$

$$= \frac{1}{(2\pi)^{1/2}\lambda_\sigma} \int_{-\infty}^{\lambda} \exp\left[-\frac{(\lambda_t - \lambda_b)^2}{2\lambda_\sigma^2}\right] d\lambda_t$$

Noting that the above approaches unity for $\lambda \to \infty$, and changing the variable of integration to

$$x = \frac{\lambda_t - \lambda_b}{2^{1/2}\lambda_\sigma},$$

we have

$$\Delta N_h = 1 - \frac{1}{\pi^{1/2}} \int_y^{\infty} \exp[-x^2]\, dx,$$

$$\text{where} \quad y = \frac{\lambda - \lambda_b}{2^{1/2}\lambda_\sigma}$$

$$= 1 - \tfrac{1}{2} \operatorname{erfc} y$$

$$= \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{\lambda - \lambda_b}{2^{1/2}\lambda_\sigma}\right)\right]$$

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