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An empirical model for average *F*-layer scintillation at VHF/UHF

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An empirical approach to modeling the electron-density irregularities in the *F* layer that are primarily responsible for amplitude scintillation of VHF/UHF signals has been devised and tested. An irregularity model was postulated as a function of geomagnetic latitude, local time of day, season, and sunspot number. The primary parameters of the irregularities that were postulated were their strength and transverse scale-size. The irregularities were assumed to be aligned along the geomagnetic field, and their axial ratio was taken as constant, as were the height and thickness of the irregular layer.

The model was tested by computing the fractional rms fluctuation in received power to be expected in a given situation, under the weak-scatter assumption, and comparing the results against values of this or related quantities reported in the literature. The model then was improved by iteration. The development made use of 12 data sets, and final testing employed those 12 plus an independent one. Lack of appropriate data precluded testing poleward of about 70° geomagnetic latitude.

The model is offered as a tool for VHF/UHF communication-systems planning, to the extent that the average value of scintillation in a specified circumstance is of engineering value. Geophysical application should be limited to such uses as experiment planning, guiding of intuition, and serving as a basis for more refined modeling.

INTRODUCTION

In an earlier paper [*Fremouw and Bates,* 1971] an analytical framework was suggested for summarizing the large amount of data available on radio scintillation of ionospheric origin. The objectives for such a summary were to provide a means for predicting the magnitude of signal fluctuations to be expected on an arbitrary satellite-to-ground communication path and, hopefully, to contribute some insight into the production of electron-density irregularities in the *F* layer.

The procedure envisioned was to model the scintillation-producing irregularities and to account for geometrical factors by diffraction-theory calculations. A tentative model for the rms spatial fluctuation in *F*-layer electron density, which seemed consistent with salient features of worldwide scintillation behavior, was postulated as a starting point. Since most of the data available are for amplitude scintillations, such a model is inherently limited to irregularities having a scale small compared with the Fresnel zone of the observing wavelength at the distance of the ionosphere. This observational bias has been described, for instance, by *Rufenach* [1971].

A first attempt at modeling has now been completed and is the subject of this paper. The method is outlined in the next section, and the resulting model is presented in the third section, along with comparisons of results with various observations. The final section contains an evaluation of the model's reliability for obtaining scintillation estimates, a discussion of its limitations, and an assessment of scintillation data.

The model is suitable for estimating the rms fluctuation in received signal strength (i.e., the scintillation index) to be expected on a given transionospheric VHF/UHF (but not SHF) communication link, under average scintillation conditions. By average scintillation conditions is meant those to be expected, on the average, for a given geomagnetic latitude, time of day, day of the year, and sunspot number. Thus the model does not address the question of variations in scintillation index from its mean value for a given set of the above independent variables.

Such variations are to be expected, for instance, with changes in geomagnetic activity. At subauroral and auroral latitudes, scintillation increases during geomagnetic storms [*Little et al.,* 1962; *Aarons et al.,* 1964; *Aarons,* 1970], while near the geomagnetic equator there is a negative correlation between the two phenomena at solar minimum [*Koster and Wright,* 1960] and a slightly positive (or perhaps zero) correlation near solar maximum [*Bandyopadhyay and Aarons,* 1970].

Another phenomenon with a definite but complicated relationship to scintillation is ionospheric spread *F* [*Briggs,* 1964; *Singleton,* 1969]. From a geophysical point of view, comparison between the scintillation model reported in this paper and a recently completed survey of spread *F* [*Davis,* 1972] may be instructive, but such a comparison has not yet been performed.

The relation of scintillation to other geophysical phenomena may be of engineering, as well as scientific, interest. The thrust of this work, however, has been to develop a model of mean scintillation trends as functions of readily accessible parameters such as latitude and time. In this context, sunspot number is treated as a measure of epoch for describing long-term trends in scintillation, a measure which is a physical variable, to be sure, but one which is routinely predicted a year in advance.

Clearly, the engineer has more detailed questions to ask the ionospheric physicist than the model reported here will answer, questions such as the percentage of time that a signal may be expected to fade below a given level. For such questions, the relation of scintillation index to other geophysical observables and the statistics of those variables may be very important. For the specific question above, a more fundamental need is for the underlying first-order distribution of the amplitude of a scintillating signal for a given ionospheric state. A theory relating this distribution to ionospheric scattering parameters and showing that it is not necessarily unique for a given value of scintillation index (second moment) will be described in a subsequent paper.

ASSUMPTIONS AND PROCEDURE

The basis for modeling was the theory of diffraction by a weakly modulating phase screen developed by *Briggs and Parkin* [1963]. Accordingly, the following assumptions are inherent in the work: weak, narrow-angle scatter; a layer that is thick compared with an irregularity but thin compared with the free-space propagation distance; and a Gaussian spatial autocorrelation function.

The above assumptions, for the most part, are acceptable for a working model of the normal *F* layer at VHF/UHF, although two of them have practical implications for the modeling. The weak scatter assumption represented the most serious limitation of the theory for our purpose. Checks on the assumption were carried out by calculation, and modeling was terminated when the necessary condition was violated. This happened rather often at the common observing frequencies of 40 and 54 MHz, except in the midlatitude region.

Arbitrary assumption of a form for the autocorrelation function limits the frequency range over which the model will give reliable results; the greatest accuracy is achieved near the observing frequencies used in modeling. Since most data available are from VHF observations, the greatest reliability may be expected there; it probably extends into the low UHF spectrum. As will be described in the next section, the model's reliability does not extend to the SHF spectrum, at least near the geomagnetic equator.

The basic calculation in the modeling employed the following expression, *Briggs and Parkin*'s [1963] equation 20, for the fractional rms fluctuation in signal intensity (square of real amplitude) at the ground as a function of ionospheric and geometrical parameters (illustrated in their Figures 1 and 2):

$$S_4 = 2^{1/2}\phi_0[1 - (\cos u_1 \cos u_2)^{1/2} \cos (u_1 + u_2)/2]^{1/2} \quad (1)$$

All ionospheric parameters appear in the factor ϕ_0, given by Briggs and Parkin in their equation 13 as

$$\phi_0 = \pi^{1/4} r_e \lambda[(a\xi_0 \sec i)^{1/2}/\beta^{1/2}](\Delta h)^{1/2}(\Delta N) \quad (2)$$

which is the rms fluctuation in radio-frequency phase across a plane at the output boundary of the scattering layer. The primary ionospheric parameters are the rms fluctuation ΔN in electron density, the thickness Δh of the irregular layer, the transverse irregularity scale-size ξ_0 to the e^{-1} point, and the irregularity axial ratio a. In addition, ϕ_0 depends on the incidence angle i of the radio wave on the irregular layer and on the irregularity projection factor β, where $\beta = (a^2 \sin^2 \psi + \cos^2 \psi)^{1/2}$ and ψ is the angle between the geomagnetic field and the radio line of sight. The radio wavelength is given by λ, and r_e is the classical electron radius.

The Fresnel-distance parameters u_1 and u_2 in equation 1 are defined as

$$u_1 = \tan^{-1} (2\lambda z/\pi\xi_0^2) \quad (3)$$

$$u_2 = \tan^{-1} (2\lambda z/\pi\beta^2\xi_0^2) \quad (4)$$

where

$$z = z_1 z_2/(z_1 + z_2) \tag{5}$$

where z_1 is the distance from the receiver to the center of the scattering region and z_2 is that from the region center to the transmitter. The geometry is further specified in Briggs and Parkin's equations 1, 2, and 3.

Equations 1 through 5 were coded, along with a number of auxiliary expressions, to permit calculation of the scintillation index S_4 as a function of the F-layer model being developed and of various satellite and radio-star observing conditions. The main modeling endeavor was to provide proper parameter values for use in calculating the rms phase fluctuation, ϕ_0. By far the greatest effort was put into selecting the appropriate behavior of rms electron-density fluctuation, ΔN.

Before describing the ΔN modeling, we shall discuss selection of the other geophysical quantities involved in the calculations. The simplest to handle was the layer thickness Δh which was easily treated as a constant. Doing so means that model testing was actually of the product $\Delta N(\Delta h)^{1/2}$; separating the effects of the two variables would be impossible, given the published scintillation data. Nonetheless, in order to model ΔN as accurately as possible, a value was taken for Δh from measurements reported in the literature, namely, 100 km [*Liszka,* 1964; *Yeh and Swenson,* 1964; *Kent and Koster,* 1966]. While it is possible that, from time to time, the center height h varies through much of the F layer, it too was taken as constant. Observations published in the above literature suggest an average value of 350 km without systematic trends, and this value was used.

For the axial ratio a the constant value 10 was used, based on observations performed under a variety of conditions [*Jones,* 1960; *Liszka,* 1963; *Koster,* 1963]. More recent observations of *Kent and Koster* [1966] and especially of *Koster et al.* [1966] show that the irregularities can be much more elongated in the equatorial region. In this region the field-aligned irregularities are nearly horizontal, however; thus, they are usually viewed from a quasi-transverse aspect, and the value of a then has little effect on the scintillation index.

The remaining irregularity parameter to be considered is the transverse scale size ξ_0. At the outset of the work it was planned to treat it as a constant also. During the course of the modeling, this idealization was found unacceptable for treating scintillation frequency dependence. Therefore, a rudimentary model for ξ_0 as a latitudinal variable was introduced into the work in addition to the more complete one, involving latitude, time of day, season, and sunspot number, for ΔN.

The essence of the procedure was to postulate models for ΔN and ξ_0, to insert the model values in equation 2 along with the other parameters needed, and then to employ equations 2 and 1 to calculate the value of S_4 expected for a given set of published observations. In this manner, the model was tested and improved, using 12 data sets from a variety of observational circumstances. A thirteenth set, not used in model development, was included in final testing.

The procedure was designed to account for dissimilar experimental circumstances and data-reduction procedures. For each data set, the transmitter and receiver locations used in calculation were chosen to be representative of the actual ones, and the magnetic-field geometry was accounted for on the basis of an earth-centered, but axially tipped, dipole model. After the scintillation index was calculated, averages were performed in a manner similar to those performed by the observer. The final result then was compared with the reduced data presented in the literature.

The index first calculated was S_4. The program also converted to S_1, S_2, or S_3, on demand. The conversions made use of the simple proportionality between the four indices suggested by *Briggs and Parkin* [1963] on the basis of the Rayleigh distribution and verified by *Bischoff and Chytil* [1969] for conditions under which the Nakagami approximate distribution may be employed. We note that the latter conditions have not been established clearly and suggest this as a fruitful topic for theoretical investigation.

The papers used gave scintillation magnitude either as one of the above four indices or as some other index calibrated in terms of one of the above. In the latter case, the quoted index was converted to one of the above for comparison with the calculations.

The initial model postulated contained the following parameters: $\Delta h = 100$ km, $h = 350$ km, $a = 10$, $\xi_0 = 1$ km, and

$$\Delta N = \Delta N_e(R, D, t, \lambda) + \Delta N_m(t, \lambda) + \Delta N_h(R, t, \lambda) \tag{6}$$

where the independent variables are the following: mean sunspot number R, day of the year D, time of day t, and geomagnetic latitude λ. The three terms specifying ΔN were, respectively, equatorial, midlatitude, and high-latitude contributions to the rms fluctuation of electron density, as described mathematically in the third section of the paper by *Fremouw and Bates* [1971].

In the initial model, equation 6 was defined quantitatively by 14 numerical constants, to be evaluated by comparison of model-based calculations of scintillation index against observed values. For the most part, the changes in the initial model that came about through iterative testing were in the nature of evaluating the constants. Some changes in form were made, however, most notably the addition of a fourth term to account for aurorally associated scintillation. The result is presented in the next section; the reader concerned with calculational details may find a complete description of the model's evolution in report form [*Fremouw and Rino,* 1971].

THE RESULTING MODEL AND ITS LIMITATIONS

As a result of the procedure described in the preceding section, the following empirical model for scintillation-producing irregularities in the F layer is put forth: center height of the irregular layer = 350 km, thickness of the irregular layer = 100 km, ratio of the scale size along the geomagnetic field to that transverse = 10, transverse scale size (to e^{-1} spatial autocorrelation) = ξ_0, and rms fluctuation of electron density = ΔN. Mathematical expressions are given below for ξ_0 and ΔN in equations 7 and 8, respectively, in terms of the following independent variables: λ = geomagnetic latitude in degrees (ξ_0 is treated as a function of λ only), t = local time of day in hours, D = day of year out of 365, R = sunspot number.

The model for ξ_0 is as follows:

$$\xi_0 = 300 + 600\{1 + \text{erf}\,[(\lambda - 12)/3]\} - 450\{1 + \text{erf}\,[(\lambda - 62)/3]\} + 200\{1 + \text{erf}\,[(\lambda - 69)/3]\}\ m \qquad (7)$$

It consists essentially of steps at particular geomagnetic latitudes; in order to avoid discontinuities, steps are described by error functions, the widths of which are about 6°. This model is very rudimentary as compared with that for ΔN, but it is a considerable improvement over assuming a constant value for scale-size, especially as regards the frequency dependence of scintillation.

The model for ΔN consists of four additive terms, the influence of each being dominant in different regimes of geomagnetic latitude, as follows:

$$\Delta N = \Delta N_{eq}(R, D, t, \lambda) + \Delta N_{mid}(t, \lambda) + \Delta N_{hi}(R, t, \lambda) + \Delta N_{aur}(R, t, \lambda) \qquad (8)$$

where

$$\Delta N_{eq} = (5.5 \times 10^9)(1 + 0.05R) \cdot \left[1 - 0.4 \cos \pi\left(\frac{D + 10}{91.25}\right)\right] \cdot \left\{\exp\left[-\left(\frac{t}{4}\right)^2\right] + \exp\left[-\left(\frac{t - 23.5}{3.5}\right)^2\right]\right\} \cdot \left\{\exp\left[-\left(\frac{\lambda}{12}\right)^2\right]\right\}\ \text{el}/m^3 \qquad (9)$$

$$\Delta N_{mid} = (6.0 \times 10^8)\left(1 + 0.4 \cos \frac{\pi t}{12}\right) \cdot \left\{\exp\left[-\left(\frac{\lambda - 32.5}{10}\right)^2\right]\right\}\ \text{el/m}^{-3} \qquad (10)$$

$$\Delta N_{hi} = (2.7 \times 10^9)\left\{1 + \text{erf}\left[\frac{\lambda - \lambda_b(R, t)}{0.02\lambda_b(R, t)}\right]\right\}\ \text{el/m}^{-3} \qquad (11)$$

$$\Delta N_{aur} = (5.0 \times 10^7)R \cdot \left\{\exp\left[-\left(\frac{\lambda - 70 + 2\cos(\pi t/12)}{0.03R}\right)^2\right]\right\}\ \text{el/m}^{-3} \qquad (12)$$

where

$$\lambda_b = 79 - 0.13R - (5 + 0.04R) \cdot \cos(\pi t/12)\ \text{degrees} \qquad (13)$$

Equation 9 describes the well-known peaking of equatorial scintillation in the midnight hours and the decay of activity through the early morning hours, a simple harmonic seasonal dependence with peaks at the equinoxes, a linear dependence on sunspot number, and a Gaussian latitudinal dependence which drops to e^{-1} 12° on either side of the geomagnetic equator. Equation 10 describes the simple diurnal and latitudinal variations of scintillation at middle latitudes that were suggested by *Fremouw and Bates* [1971].

The behavior of high-latitude scintillation other than that directly associated with auroral disturbance is described in equation 11. This behavior is attributed to diurnal and solar-cycle migrations of the scintillation boundary, as described in equation 13. The basis for the error-function form of equation 11 was developed in the appendix of *Fremouw and Bates*' [1971] paper. Equation 12 describes what is believed to be aurorally associated scintillation arising in a region, near the auroral oval, of which the latitudinal extent is proportional to sunspot number, as is the strength of the irregularities it contains.

Comparisons of the scintillation index calculated from the above model with the observations used in iterative evaluation of the model are shown in Figures 1 through 6. This is followed, in Figure 7, by comparison of calculated values with a set of observed values not employed in the development of the model. The calculated curves are solid where the assumption of weak scatter is satisfied ($\phi_0 < 0.7$), and dashed where the assumption is questionable ($0.7 \leq \phi_0 \leq 1.0$). Where the assumption is invalid ($\phi_0 > 1.0$), no calculated value is given. These somewhat arbitrary numerical choices were made by inspection of *Briggs and Parkin*'s [1963] Figure 3.

Comparison of results with the observations of *Koster* [1968] appear in Figure 1; the fits are reasonably close where the weak-scatter assumption holds. The rise of the observed values in the evening hours which is more abrupt than those calculated could be accounted for by a change in form of the equatorial term of the ΔN model, and parameter adjustments could reduce other discrepancies. This hardly seems justified, however, in the light of two more serious limitations of the model at equatorial latitudes.

The first limitation stems from lack of an opportunity to test the predicted sunspot-number dependence of scintillation. There appear to be no long-term equatorial data available in terms of quantitative indices, although there remains the possibility of calibrating some earlier observational results in such terms (J. R. Koster, personal communication, 1971). The equatorial term of the scintillation model may be considered relatively reliable at VHF/UHF under average ionospheric conditions for sunspot numbers on the order of 100 (typical of solar maximum). For other sunspot numbers, however, it is only an untested estimate, and more experimental work is needed.

The second limitation may be inherent in the average nature of the model but is of some practical concern and a good deal of scientific interest. In the past few years, instances of significant scintillation on surprisingly high frequencies (as high as 6 GHz) have been reported by equatorial observers [*Christiansen*, 1971; *Skinner et al.*, 1971; *Craft and Westerlund*, 1972]. The model developed in this work would not have predicted this turn of events.

It may be that the observed SHF scintillations are

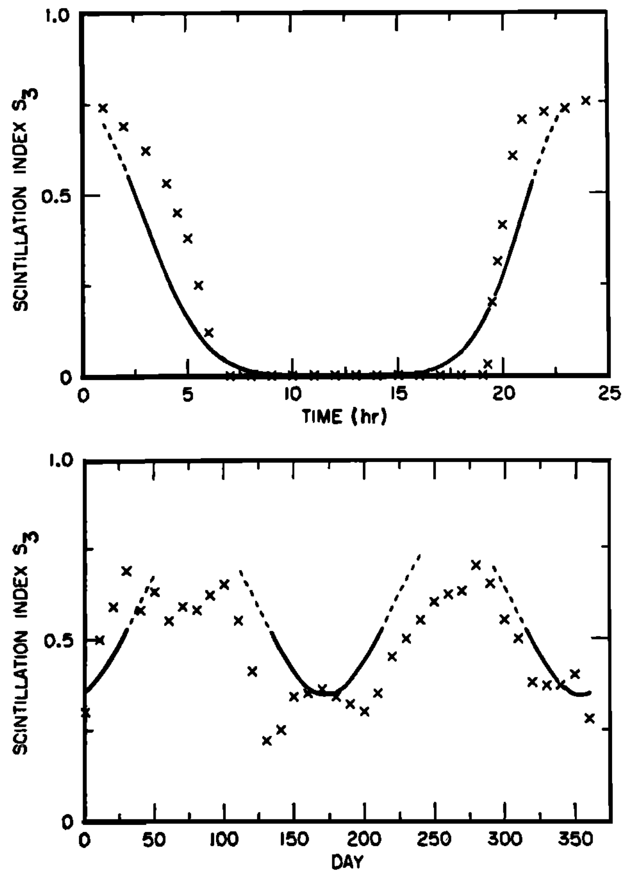

Fig. 1. Comparison of model calculations with geostationary-satellite observations from Ghana [*Koster*, 1968]. The top is diurnal variation: frequency = 136 MHz, sunspot number = 107, and day number = 31. The bottom is seasonal variation: frequency = 136 MHz, sunspot number = 97, and time is 0200. As in all figures, the observations are shown as discrete points, and the calculations as a curve. The curve is solid where the weak-scatter assumption is valid and dashed where it is questionable. Where it is invalid, no calculated results are given.

not a manifestation of average ionospheric conditions, as the term is meant herein. On the other hand, this inadequacy of the model may stem from the assumption of an unproven spatial autocorrelation function (Gaussian) in the diffraction calculations, as described in the preceding section. For reliable extrapolation over a wide frequency range, it is necessary to have a realistic description of the spatial spectrum of the *F*-layer structure. Work has begun toward this end for middle latitudes [*Rufenach*, 1971], but the need is more pressing at equatorial, and probably auroral, latitudes from the modeling viewpoint.

At middle latitudes the model produced quite acceptable fits to the data of *Preddey et al.* [1969] and *Preddey* [1969]. Figure 2 shows the comparison of calculated diurnal variation at middle latitudes, with the former data. Figure 3 compares calculated and observed latitudinal dependence for daytime and for nighttime, using the data of *Preddey* [1969]. The bars shown on the data points indicate the range of day-to-day variations observed in the scintillation index (they are not measurement uncertainties).

Figure 3 also shows latitudinal dependence in the scintillation-boundary region, under essentially solar-minimum conditions (sunspot number = 30). The fit is seen to be quite good at night, the time of most practical concern. The match is less satisfactory in the daytime, reflecting the dictates of data sets from other stations, notably the observations of *Aarons et al.* [1964] and of *Fremouw* [1966].

Similar observations were conducted by Preddey in the boundary region near solar maximum (sunspot number = 103), and the corresponding calculations were performed. In general the fit is not so satisfactory as for solar-minimum conditions, with the nighttime results again being better than those for the daytime. The mismatch is due largely to the dictates of the extreme solar-maximum (sunspot number = 184) data obtained by *Lawrence et al.* [1961] at Boulder during the International Geophysical Year.

One of the most disappointing comparisons of calculated results with observation was for the data of *Aarons et al.* [1964], shown in Figure 4. While a good fit was obtained in the boundary region at an early stage of the modeling, incorporation of additional data, especially those of *Preddey* [1969], caused a deterioration. It simply was not possible to maintain consistently good fits between the model and the various data sets.

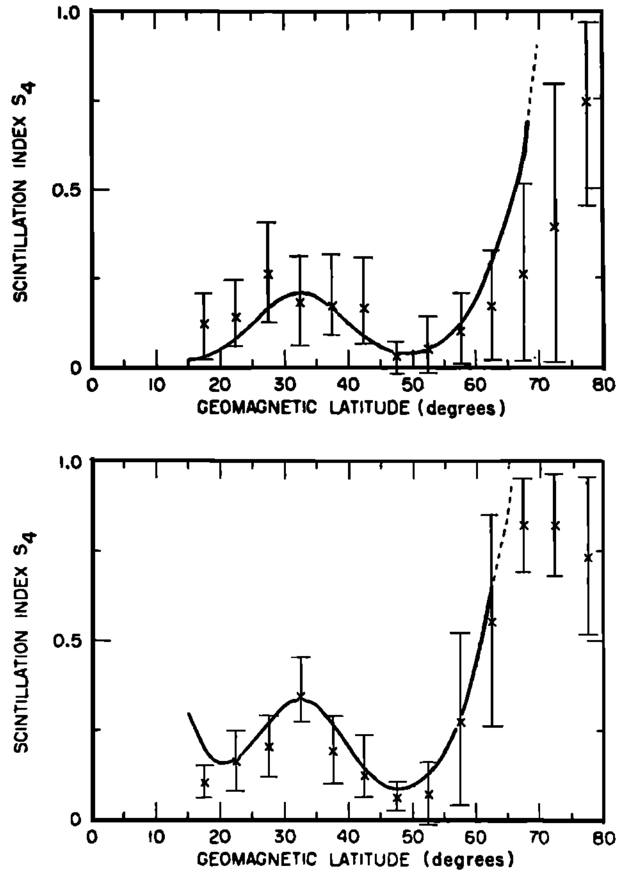

Fig. 3. Comparison of model calculations with high-inclination-satellite observations in the middle-latitude and scintillation-boundary regions of the South Pacific [*Preddey*, 1969]. The top is daytime: frequency = 40 MHz, and sunspot number = 30. The bottom is night: frequency = 40 MHz, and sunspot number = 30.

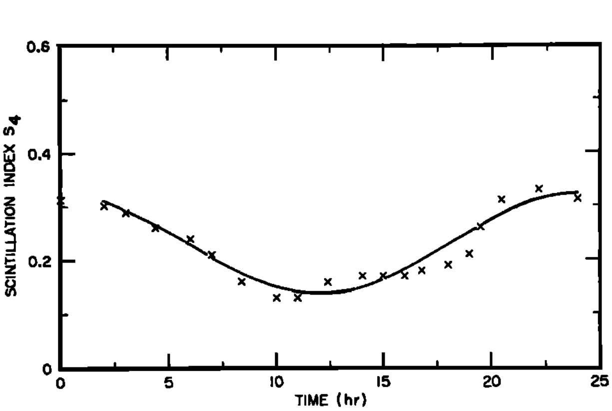

Fig. 2. Comparison of model calculations with high-inclination-satellite observations of the diurnal variation of scintillation from Brisbane, Australia [*Preddey et al.*, 1969]. Frequency = 40 MHz; the sunspot number = 13.

Comparison of the calculated diurnal variation of 108-MHz scintillation with the Boulder data of *Lawrence et al.* [1961] is given in Figure 5. In general, the fit is seen to be reasonably close, although there is some discrepancy near both noon and midnight. The midday discrepancy is due to at least two causes. First, most midday scintillations at Boulder were ascribed by Lawrence et al. to *E*-layer irregularities, on the basis of ionosonde data, whereas our model is for *F*-layer irregularities only. Second, the influence of the Preddey solar-maximum data was to depress the calculated daytime index in the latitude region of the Boulder observations. Regarding the midnight discrepancy, little can be said because the calculations indicate breakdown of the weak-scatter

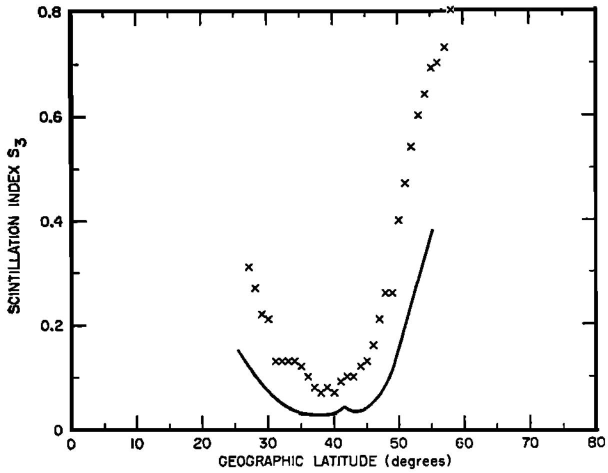

Fig. 4. Comparison of model calculations with high-inclination-satellite observations in the middle-latitude and scintillation-boundary regions of eastern North America [*Aarons et al.,* 1964]. Frequency = 54 MHz, sunspot number = 47, time is all hours.

assumption even at 108 MHz in the Boulder International Geophysical Year data.

Turning to auroral-zone observations, Figure 5 also shows the diurnal variation of the observed and calculated scintillation index for the Alaska radiostar data of *Little et al.* [1962] and of *Fremouw* [1966]. The fits are considered quite good, although the calculations produced a slightly stronger diurnal variation near solar minimum (sunspot number = 15) than was observed by Fremouw. For the solar-maximum (sunspot number = 200) data of Little

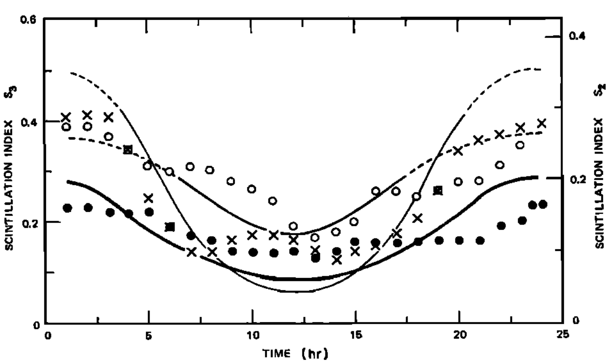

Fig. 5. Comparison of model calculations with radio-star observations of the diurnal variation of scintillation from Boulder, Colorado (*Lawrence et al.* [1961]: ××× frequency = 108 MHz, and sunspot number = 184) and College, Alaska (*Little et al.* [1962]: ○○○ frequency = 223 MHz, and sunspot number = 200. *Fremouw* [1966]: ··· frequency = 68 MHz, and sunspot number = 15).

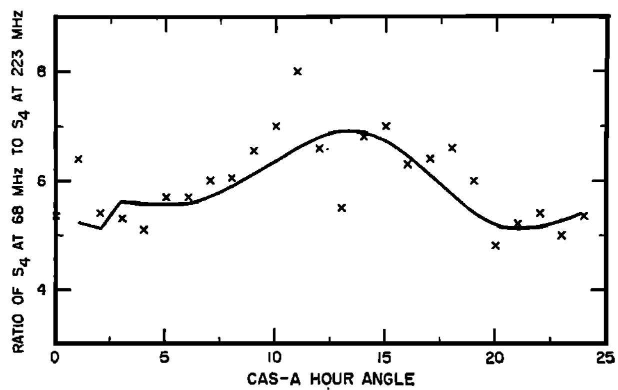

Fig. 6. Comparison of model calculations with radio-star observations of the ratio-of-scintillation index at two frequencies from College, Alaska [*Lansinger and Fremouw,* 1967]. The apparent discontinuity in the calculated curve is a magnetic-field effect and would be smooth for a denser calculation grid. Sunspot number = 15.

et al. the calculated values are heavily dependent on the fourth term of the ΔN model.

Results of the only direct test of frequency dependence made in the modeling are presented in Figure 6, comparing calculations against the two-frequency, scintillation-ratio observations of *Lansinger and Fremouw* [1967]. The fit is quite good but is a test of frequency dependence only in the auroral zone near solar minimum. The apparent discontinuity near hour angle = 2 occurs near the geomagnetic zenith and results from performing the calculations only at intervals of integral hour angle (see Figure 2 of *Lansinger and Fremouw* [1967]).

Finally, Figure 7 displays a comparison of scintillation values observed by the Joint Satellite Studies Group [*JSSG,* 1968], which were not used in model

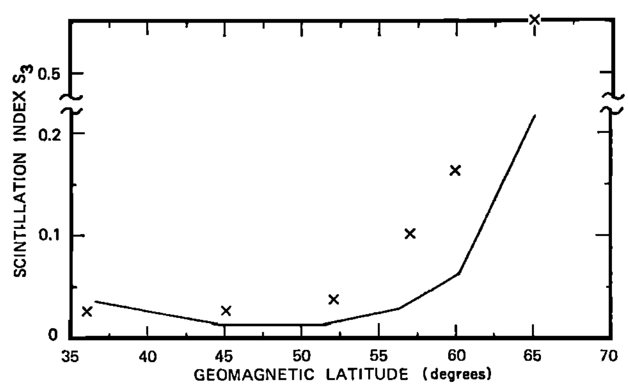

Fig. 7. Comparison of model calculations with high-inclination-satellite observations in Europe [*JSSG,* 1968]. Frequency = 54 MHz; sunspot number = 30.

development, against values predicted for the JSSG observational circumstances by the model. Figure 7 may be taken to represent the reliability of the model for predicting average scintillation. An additional indication is given in Figure 3, where the bars on the observed data points represent day-to-day variations from the average values of scintillation index. By the latter standard, most of the model results appear to be meaningful for systems-planning purposes, providing a basis for calculating scintillation index within the range to be encountered in a given situation. Figure 4 shows one of the poorest fits, where the calculated values are consistently lower than the observed ones by a factor of about two, which is similar to the discrepancy in Figure 7.

It may be significant that the observations in both Figures 4 and 7 were in terms of the ARCRL index [*Whitney et al.,* 1969], whereas the model relied rather heavily on observations given in terms of the index used by *Preddey* [1969]. This suggests the possibility of error in relating one or both of these empirical indices to the statistical one calculated from the theory of *Briggs and Parkin* [1963] and/or in interrelating the latter authors' four distribution-dependent indices. While some progress has been made in recent years toward relating scintillation indices used by various workers, it is not clear that the task is complete.

CONCLUSIONS

The *F*-layer irregularity model described in the foregoing section is offered as a synoptic tool for communication systems planning. The model and the diffraction and geometry formulas necessary for its utilization have been combined in a FORTRAN computer program suitable for calculations in a variety of situations [*de la Beaujardiere and McNeil,* 1971]. There has been no demonstration of the model's uniqueness, and therefore geophysical application should be limited to experiment design, guidance of intuition, and/or more refined modeling.

The model has been tested against a number of published scintillation observations sufficient enough that it is thought to describe most major trends in scintillation activity, at least relatively. In most instances, the model is expected to produce better than order-of-magnitude (but not better than factor-of-two) estimates of the strength of scintillation to be expected under average ionospheric conditions. It is believed that the calculated value will usually fall within the range of day-to-day variation to be experienced in a given circumstance (e.g., for a given time of day, season, or geometry).

There are a number of significant limitations to the model, however. The degree of confidence held for it under different circumstances is summarized in Table 1 in the form of qualitative evaluations of data fit, where tests have been made. Table 1 lists six scintillation dependences in five regimes of geomagnetic latitude that appear pertinent to scintillation evaluation. Among these 30 categories, it has been possible within the scope of this work to completely test the model quantitatively in only eight; the current model clearly is underdetermined.

However, among the remaining categories of Table 1, partial tests were conducted in three; qualitative review of the scintillation literature revealed no significant trend in four others. Four more were essentially redundant with other categories, and there was sound basis for estimating behavior in an additional five. The remaining categories are the six scintillation dependences at polar latitudes (above 70° geomagnetic latitude for the ionospheric penetration point).

At other latitudes (equatorial, middle, boundary, and auroral), the most generally absent types of data for complete quantitative modeling are those extending over sufficiently long periods to test sunspot dependence and those extending over wide frequency ranges. It was possible to perform some quantitative tests at decidedly different solar-cycle epochs even though continuous testing was not performed; testing of frequency dependence, however, was extremely limited.

There is a special need for long-term data in the form of a statistically quantitative index, from near the geomagnetic equator. In addition to long-term observations, data are needed for detailed evaluation of the latitudinal dependence of scintillation there. Any longitudinal dependence that may exist was not explored in this work.

These equatorial data could be combined with some published data from boundary and auroral latitudes that could not be included in the scope of the present work, to fill in several of the gaps in complete quantitative testing of the existing model. However, filling of two other more pressing needs would make a greater contribution to refining our ability to accurately predict average scintillation on a worldwide basis.

The two most pressing needs are for higher quality, rather than greater quantity, in scintillation data and

TABLE 1. Qualitative evaluation of model's data fits

Dependence	Equatorial latitudes	Middle latitudes	Boundary latitudes	Auroral latitudes	Polar latitudes
Latitude	Untested	Day: fair, Night: good (see Figure 3) Average: fair (see Figure 7)	Low sunspot number Day: fair, Night: good (see Figure 3) Average: poor (see Figure 7) Moderate sunspot number Average: poor (see Figure 4) High sunspot number Day: poor Night: fair	Untested	Untested
Time	Fair (see Figure 1)	Good (see Figure 2)	Fair (see Figure 5)	Low sunspot number Fair (see Figure 5) High sunspot number Fair (see Figure 5)	Untested
Season	Fair (see Figure 1)	Untested	Untested	Untested	Untested
Sunspot number	Untested	Untested	Untested	Untested	Untested
Frequency	Untested	Untested	Untested	Weak to moderate scintillation Good (see Figure 6)	Untested
Azimuth and/or elevation	Untested	Untested	Untested	Untested	Untested

for complimentary measurements of the spatial spectrum of scintillation-producing irregularities. For purposes of quantitative modeling, continued collection of qualitative and semiquantitative scintillation indices will be of little value, although this procedure has contributed heavily to existing knowledge of gross morphology. In spite of progress in recent years in relating various indices, the conversions used probably are not reliable in all instances.

What are needed are digitally recorded data from which various moments of the amplitude distribution could be calculated. Except at middle latitudes, these data should be collected near or above about 100 MHz in order to avoid the serious complications of strong or multiple scatter. The commonly available tracking frequencies near 136 MHz are very useful for the purpose, whereas 40 and 54 MHz, which have been widely used for scintillation observations, often are too low. In addition to measurements of scintillation per se, accompanying measurements of irregularity spectrum are necessary for evaluation of scintillation frequency dependence.

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REFERENCES

Aarons, J. (1970), The high-latitude *F*-region irregularity structure during the October 30–November 4, 1968, magnetic storm, *Radio Sci., 5*(6), 959–966.

Aarons, J., J. P. Mullen, and S. Basu (1964), The statistics of satellite scintillations at a subauroral latitude, *J. Geophys. Res., 69*(9), 1785–1794.

Bandyopadhyay, P., and J. Aarons (1970), The equatorial *F*-layer irregularity extent as observed from Huancayo, Peru, *Radio. Sci., 5*(6), 931–938.

Bischoff, K., and B. Chytil (1969), A note on scintillation indices, *Planet. Space Sci., 17*(5), 1059–1066.

Briggs, B. H. (1964), Observations of radio star scintillations and spread-*F* echoes over a solar cycle, *J. Atmos. Terr. Phys., 26,* 1–23.

Briggs, B. H., and I. A. Parkin (1963), On the variation of radio star and satellite scintillations with zenith angle, *J. Atmos. Terr. Phys. 25*(6), 339–366.

Christiansen, R. M. (1971), Preliminary report of S-band propagation disturbance during Alsep Mission Support (November 19, 1969—June 30, 1970), *Rep. X-861-71-239,* Goddard Space Flight Center, Greenbelt, Md.

Craft, H. D., Jr., and L. H. Westerlund (1972), Scintillations at 4 and 6 GHz caused by the ionosphere, paper presented at AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17-19.

Davis, R. M. (1972), The occurrence of spread *F* and its effect on HF propagation, *Rep. OT/TRER 28,* Institute of Telecommunication Science, Boulder, Colo.

de la Beaujardiere, O., and D. McNiel (1971), A Fortran program for calculating *F*-layer-produced scintillation, Tech. Note, SRI Project 1079, Stanford Research Institute, Menlo Park, Calif.

Fremouw, E. J. (1966), Abberations of VHF-UHF signals traversing the auroral ionosphere, *Rep. UAG R-181,* Contract NAS5-3904, Geophysical Institute of the University of Alaska, College, Alaska.

Fremouw, E. J., and H. F. Bates (1971), Worldwide behavior of average VHF-UHF scintillation, *Radio Sci., 6*(10), 863–869.

Fremouw, E. J., and C. L. Rino (1971), Development of a worldwide model for *F*-layer-produced scintillation, Final Rep., Contract NAS5-21551, SRI Project 1079, Stanford Research Institute, Menlo Park, Calif.

Jones, I. L. (1960), Further observations of radio stellar scintillation, *J. Atmos. Terr. Phys., 19*(1), 26–36.

JSSG [Joint Satellite Studies Group] (1968), On the latitude variation of scintillations of ionosphere origin in satellite signals, *Planet. Space Sci., 16*(6), 775–781.

Kent, G. S., and J. F. Koster (1966), Some studies of nighttime *F*-layer irregularities at the equator using very high frequency signals radiated from earth satellites, in *Spread-*F *and its Effects Upon Radiowave Propagation and Communications,* edited by P. Newman, pp. 333–356, Technivision, Maidenhead, England.

Koster, J. R. (1963), Some measurements of the irregularities giving rise to radio-star scintillations at the equator, *J. Geophys. Res., 68*(9) 2579–2590.

Koster, J. R. (1968), Equatorial studies of the VHF signal radiated by Intelstat II, F-3, 1, Ionospheric scintillation, *Progr. Rep. 3,* contract F61052-67-C00027, University of Ghana-Legon, Accra, Ghana.

Koster, J. R., and R. W. H. Wright (1960), Scintillation, spread *F,* and transequatorial scatter, *J. Geophys. Res., 65,* 2303–2306.

Koster, J. R., I. Katsriku, and M. Tete (1966), Studies of the equatorial ionosphere using transmissions from active satellites, *Annu. Sum. Rep. 1,* contract AF61(052)-800, University of Ghana-Legon Accra, Ghana.

Lansinger, J. M., and E. J. Fremouw (1967), The scale size of scintillation-producing irregularities in the auroral ionosphere, *J. Atmos. Terr. Phys., 29,* 1229–1242.

Lawrence, R. A., J. L. Jespersen, and R. C. Lamb (1961), Amplitude and angular scintillations of the radio source Cygnus-A observed at Boulder, Colorado, *J. Res. Nat. Bur. Stand., Sect.D, 65D,* 333–350.

Liszka, L. (1963), A study of ionospheric irregularities using transmissions at 54 Mc/s, *Ark. Geofys., 4,* 227–246.

Liszka, L. (1964), An investigation of the height of scintillation-producing irregularities, *Ark. Geofys., 4,* 523–528.

Little, C. G., G. C. Reid, E. Stiltner, and R. P. Merritt (1962), An experimental investigation of radio stars observed at frequencies of 223 and 456 megacycles per second from a location close to the auroral zone, *J. Geophys. Res., 67*(5), 1763–1784.

Preddey, G. F. (1969), Midlatitude radio-satellite scintillation: The variation with latitude, *Planet. Space Sci., 17*(8), 1557–1561.

Preddey, G. F., J. Mawdsley, and W. Ireland (1969), Midlatitude radio-satellite scintillation: The morphology near sunspot minimum, *Planet. Space. Sci., 17,* 1161–1171.

Rufenach, C. L. (1971), A radio scintillation method of estimating the small-scale structure in the ionosphere, *J. Atmos. Terr. Phys., 33,* 1941–1951.

Singleton, D. G. (1969), The occurrence of scintillation-producing irregularities over Australasia, *J. Geophys. Res., 74*(7), 1772–1785.

Skinner, N. J., R. F. Kelleher, J. B. Hacking, and C. W. Benson (1971), Scintillation fading of signals in the SHF band, *Nature, Phys. Sci., 232,* 19–21.

Whitney, H. E., J. Aarons, and C. Malik (1969), A proposed index for measuring ionospheric scintillations, *Planet. Space Sci., 17,* 1069–1073.

Yeh, K. C., and G. W. Swenson, Jr. (1964), *F*-region irregularities studies by scintillation of signals from satellites, *J. Res. Nat. Bur. Stand., Sect. D, 68D*(8), 881–894.