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Numerical Maps of foEs for Solar Cycle Minimum and Maximum

M. LEFTIN

S. M. OSTROW

C. PRESTON

Ionospheric Telecommunications Laboratory

INSTITUTE FOR TELECOMMUNICATION SCIENCES
BOULDER, COLORADO 80302
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ABSTRACT

The preparation of world numerical maps of lower decile, median, and upper decile values of the monthly distributions of foEs for all 12 months of both a solar cycle minimum and a solar cycle maximum year is described. Tables of numerical maps of 4 representative months, March June, September, and December, are given as examples of the complete set. Sample contour maps for these months are included to illustrate graphically the geographic, diurnal, seasonal, and solar cycle variation of lower decile, median, and upper decile foEs. No detailed instructions are given for using the maps, but a number of possible applications are indicated. The behavior of Es and problems of Es propagation are discussed, to indicate some limitations of the maps, and to call attention to additional data, such as Es reflection coefficients, needed to improve our knowledge of Es propagation and in particular to permit more accurate calculation of Es maximum usable frequency and transmission loss. The use of combinations of probabilities of both Es and regular layer propagation is recommended to provide improved estimates of actual propagation.

Key Words

Es, fbEs, foEs, FOT, high frequency radio propagation, ionospheric predictions, MUF, numerical maps, probability of propagation, sporadic E transmission loss

NUMERICAL MAPS OF foEs FOR SOLAR CYCLE MINIMUM AND MAXIMUM

by

M. Leftin, S. M. Ostrow, and C. Preston

1. INTRODUCTION

Sporadic E (Es) is often important in ionospheric radio propagation and its effects may be helpful or harmful to high-frequency radio communications. Extension of the range of usable high frequencies is probably the major beneficial effect of Es. On the other hand, Es may attenuate or completely block propagation on the most favorable regular layer mode for a given frequency, may increase multipath problems for high information rate systems, or may permit propagation of more interfering signals than would be possible by the regular layers alone. Knowledge of the variations of Es and Es effects on propagation permits more efficient utilization of the limited high-frequency portion of the radio spectrum. Suitable frequency selection can be used to take advantage of the extension of the usable frequency range by Es while avoiding or minimizing its deleterious effects.

At high levels of solar activity, the extension by Es of the relatively wide range of frequencies propagated by the regular layers is rarely very prominent, and there is greater flexibility in choice of frequencies to minimize deleterious effects of Es. At solar cycle minimum, however, the range of frequencies propagated by the regular layers is quite restricted, and the extension of this range by Es can be relatively large. Increasing congestion in the high-frequency bands is stimulating interest in Es propagation effects over the entire solar cycle. Es can be significant at any level of solar activity, and should be included in propagation calculations, particularly when the probability of occurrence of Es is high.

A vast amount of research on Es has been reported (e.g.,Smith, 1957; Smith and Matsushita, 1962; Bowhill, 1966), but knowledge of Es and Es propagation mechanisms is not yet adequate for accurate calculation and prediction. For this reason, and also because Es propagation is sometimes erratic and unstable, there is a tendency not to include the effects of Es in frequency planning and allocations. Nevertheless, Es propagation is probably one of the major reasons why practical communications are often possible on substantially different frequencies from those predicted only on the basis of regular layer propagation. An early method of estimating Es-MUF was used with the CRPL Series D, "Basic Radio Propagation Predictions,"the predecessor of the current ITS "Ionospheric Predictions" (NBS Circular 465, 1947). A system for estimating Es propagation has been developed by the U.S.S.R. to supplement its "Monthly Forecasts of Radio Propagation" (IZMIR, 1964). It seems desirable, therefore, to develop methods of estimating Es propagation to supplement regular layer propagation predictions derived from the "ITS Ionospheric Predictions."

Numerical maps of foEs, the highest ordinary wave frequency reflected from Es at vertical incidence, have been prepared for all 12 months of both a solar cycle maximum and a solar cycle minimum year. The foEs maps are only the first part of a planned system for use in estimation of Es propagation effects. A similar set of numerical maps of fbEs, the lowest ordinary wave frequency at which the Es layer begins to become transparent at vertical incidence, is being developed to complete the system. Therefore, routine procedures for using the foEs maps will not be presented at this time, but some possible applications to propagation problems will be indicated.

2. Es AND Es PROPAGATION

The term sporadic E, or Es, is applied collectively to a number of different phenomena occurring in the E region. Most of the available information on Es has been obtained from vertical incidence ionosphere sounding, and the usual classification of types is based on the appearance of Es reflections on ionograms (Piggott and Rawer, 1961). At any one location, only a few types, usually two or three, tend to predominate in tabulations of observed vertical incidence ionospheric data. The geographic and temporal patterns of occurrence vary considerably between different types of Es, and the characteristic features that distinguish the ionogram traces of the various types suggest that there may be corresponding differences in morphology and in physical processes producing them.

World patterns of occurrence of Es indicate that the distribution and variations of the different types of Es are influenced by the geomagnetic field. A meteorology of the E region, to be developed in the future, may permit prediction of the occurrence of Es from the interactions between the geomagnetic field and the motions of the charged and neutral constituents of the upper atmosphere. Although such speculations are attractive, a theory suitable for practical predictions has not yet been developed.

In middle latitudes Es occurs as a thin stratification of ionization within the E region. Rocket measurements confirm earlier deductions from ionograms, indicating thickness of the order of a few hundred meters to a kilometer or two. In recent years, theoretical and experimental results indicate that this sort of Es may be caused by wind shear in the presence of the earth's magnetic field. At high latitudes, some Es seems to be produced by charged particle precipitation, and at the magnetic equator, a different type of Es occurs in the daytime in association with the equatorial electrojet.

There is little quantitative information on the finer details of the geographical variations of Es. There is evidence that Es may occur in patches ranging from a few tens to many thousands of square kilometers in area and that these patches or clouds may move, but little conclusive is known about velocities and directions of motion. In both high latitudes and equatorial regions, Es ionization frequently seems to be aligned parallel with the geomagnetic field lines.

It is not always possible to determine whether Es observed at vertical incidence is an approximately uniform thin sheet of ionization, or whether it is composed of relatively dense "blobs" distributed more or less randomly in a less dense sheet of ionization. Differences in structure of this kind, which may be characteristic of different types of Es, would result in different behaviour in oblique incidence propagation.

At vertical incidence, Es may be blanketing, or opaque, up to a frequency called fbEs, and partially reflecting, partially transmitting above fbEs to the top frequency of reflection, fEs, beyond which the Es layer is totally transparent. Nonblanketing Es can be of considerable importance, depending on effective transmitted power and reflection coefficient, and may cause substantial increases in losses on regular layer modes of propagation that are not completely blocked by the Es. Blanketing Es may completely block the most favorable regular layer mode of propagation on a given frequency, altering the number and type of hops possible in a propagation path, and the vertical angle of arrival of received signals. This would result in changes in losses as compared with those occurring in regular layer propagation, and, depending on antenna patterns, could have significant effects on the performance of a communications system. Es may increase the incidence of multipath, which can be particularly harmful for high data rate systems.

For blanketing Es, total reflection can be assumed, and it is reasonable to suppose that transmission loss will be similar to that for reflection from the regular E layer. For nonblanketing Es, calculations for idealized thin sheet or scattering models of Es can suggest trial values of reflection and transmission coefficients in estimation of transmission loss.

In considering Es observations taken at vertical incidence, the comparability of data taken at different time periods, at different locations, and on different types of equipment is often questioned, mainly because of the possibility that the observed value of foEs may be power dependent. The blanketing Es frequency, fbEs, does not vary greatly with large changes in power, but foEs can show an appreciable variation with power, the magnitude of which depends on the type of Es. The problem is aggravated by the common practice at ionospheric stations of using different receiver gain settings for day and night to compensate for the diurnal variations of absorption and noise. For the range of power commonly used in ionosondes, the values of foEs for most types of nonblanketing Es may vary by several tenths of a megahertz. We have to assume that, for practical purposes, this variation is relatively insignificant when comparing observations from many locations over the world and over many years. Even if it were significant, the required measurements of effective power have not been made at most stations. This uncertainty should be kept in mind in any studies of foEs variations.

3. foEs DATA PREPARATION

Observations of the maximum reflection frequency of Es have been made at ionosphere stations for many years. At first, the maximum reflection frequency was recorded without regard to whether it referred to the ordinary or extraordinary wave and was designated fEs. For the International Geophysical Year (July 1957-December 1958), rules were formulated for distinguishing the maximum frequency of the ordinary wave, designated by foEs. The recording of foEs was generally adopted toward the beginning of the IGY, although there are exceptions (Piggott and Rawer, 1961).

Comparison of fEs and foEs observations from many ionosphere stations for many years indicated that solar cycle variations were appreciable in some areas of the world and negligible in others. In addition, at most locations there are fairly large year-to-year variations that are considered random because no obvious physical relationship explaining them has yet been discovered.

Ideally, it would have been desirable to analyze data for several years, representing all phases of the solar cycle, to determine the solar cycle variations over the world, and also the random variations from year to year. The effort required and the cost made this impractical. Also, the various uncertainties mentioned in the preceding section indicated that the benefits resulting from analysis of several additional years of data at this time were probably not worth the very large additional effort involved. Therefore, one solar cycle minimum year-1954- and one solar cycle maximum year-1958-were selected for analysis. Comparison of corresponding maps for the 2 years should make it possible to distinguish areas of the world for which solar cycle variation of Es may be significant and other areas where it may be negligible.

For each month of 1954 and 1958 and for each hour, the daily values of foEs or fEs, whichever was reported, were keypunched for all available ionosphere stations, together with the values of foE and fmin. This was the most expensive and time-consuming part of the work. The upper decile, median, and lower decile values of foEs were calculated by computer for each hour of the day for each month.

The computer was programmed to convert fEs to foEs, when necessary, by subtracting half the E-region gyrofrequency, computed from the local value of the total geomagnetic field, from the fEs value. This may be an overcorrection, particularly for some types of Es, but the error introduced is probably small compared with other uncertainties. In the computations, when a value of foEs was missing, the corresponding value of foE, fmin, or the lower frequency limit of the ionosonde was inserted, in this order of preference, following the recommendations of the World Wide Soundings Committee of URSI (Piggott and Rawer, 1961). The effects of these substitutions will be discussed in section 5.

During the IGY, more ionospheric stations were in operation than at any other time, but not all reported foEs. For 1958, there were data tabulations from approximately 140 stations per month. To help fill some of the major gaps in the world distribution of stations during this year, data for 1957 and 1959, also years of high solar activity, were added from a few additional locations. Although more ionospheric stations were operating in 1964 than in 1954, much of the 1964 data had not been received when the work was initiated. Because there were only about 55 stations per month for 1954, with relatively few equatorial locations, and none at all south of lat. 52° S., data from about 65 additional stations for 1963 and 1964 were added to the 1954 data to improve world coverage. Consequently, while we identify the solar cycle minimum maps by the year 1954, they were actually made by combining data from the two solar cycle minima of 1954 and 1964. The two solar cycle minima were assumed similar, to a first approximation, for purposes of constructing the solar cycle minimum maps.

In the tabulations of foEs, or fEs, used for this study, values were included for all types of Es and it is, therefore, impossible to tell, from the maps alone, which types of Es predominate in any given area. Since different types of Es may behave differently in oblique incidence propagation, variations in methods of using these maps in propagation calculations may be desirable in different areas or different seasons. In the future it may be desirable to make up separate sets of maps for those types of Es that are most important in oblique incidence radio propagation.

4. DATA ANALYSIS AND NUMERICAL MAPPING

Jones and Gallet (1960, 1962a, 1962b, 1965), in their original numerical mapping procedures for F2-layer characteristics, used local time in the first analysis of data, and geographic latitude and longitude coordinates of the stations to derive the numerical map function. For the foEs maps, we adopted the modified procedures developed by Jones, Graham, and Leftin (1966) for the F2-layer, where universal time, instead of local time, is used in the first analyses of the data. This eliminates ambiguities of the numerical map function at the poles inherent in the local time analysis. As the main latitude coordinate, a modified magnetic dip, which provides a better fit to observed foF2 at low latitudes where geomagnetic control is pronounced, was used instead of geographic latitude.

The general form of the numerical map function is

$$\Omega(\lambda,\theta,T) = a_o(\lambda,\theta) + \sum_{j=1}^{H} \left[a_j(\lambda,\theta) \cos jT + b_j(\lambda,\theta) \sin jT \right], \qquad (4.1)$$

where Ω is the characteristic mapped (in this case upper decile, median, or lower decile foEs), $a_o(\lambda,\theta)$ is the diurnal average of the characteristic at the point (λ,θ), λ is geographic latitude, θ is geographic longitude, T is universal time expressed in degrees, and H is the number of harmonic terms retained. The relationship

$$I' = \arctan\left[\frac{I}{\sqrt{\cos\lambda}}\right], \qquad (4.2)$$

where I is magnetic dip and I' is modified dip (Jones, Graham, and Leftin, 1966), is used to convert (4.1) to a function of I', θ, and T for data analyses and computation.

To define the $a_j(\lambda,\theta$ and $b_j(\lambda,\theta)$, we use the relations

$$a_j(\lambda,\theta) = \sum_{k=0}^{K} U_{2j,k} G_k(\lambda,\theta), \quad j = 0, 1, \ldots, H \qquad (4.3)$$

and

$$b_j(\lambda,\theta) = \sum_{k=0}^{K} U_{2j-1,k} G_k(\lambda,\theta), \quad j = 1, 2, \ldots, H, \qquad (4.4)$$

where the cutoff value of K is determined by statistical test in the analysis (Jones and Gallet, 1962a), K + 1 is the total number of G_k functions used, G_k are geographic coordinate functions, and $U_{s,k}$ terms, where s is 2j or 2j-1, are determined from the data analyses. Jones, Graham, and Leftin (1966) give detailed discussion of these expressions and their application to the numerical mapping of data. An advantage of using the same mapping procedure and coordinate system for foEs as for F2 layer characteristics is that the same computer programs may be used for both the foEs maps and the F2 layer maps from the monthly ITS "Ionospheric Predictions."

The total set of foEs maps consists of 72 maps, three for each month of a year at solar cycle minimum and a year at solar cycle maximum. Examples of the numerical map coefficients, $U_{s,k}$, defining the function $\Omega(\lambda,\theta,T)$ for lower decile, median, and upper decile foEs for the years 1954 and 1958 are reproduced in tables 1 through 8. The examples chosen are for the months of March, June, September, and December. Coefficients for lower decile, median, and upper decile foEs for March 1954 are given in tables 1a, b, c, and for March 1958 in tables 2a, b, c. Tables 3a, b, c through 8a, b, c give the coefficients for June, September, and December

1954 and 1958. The numerical map coefficients of the foEs maps for all 12 months of both 1954 and 1958 are available either as tables of coefficients similar to tables 1 through 8, or on punched cards. Using the appropriate numerical map coefficients, one can calculate upper decile, median, and lower decile values of foEs for any location and time of day. A sample computer program for making this type of calculation is given by Jones, Graham, and Leftin (1966). Requests for copies of the coefficients should be addressed to Prediction Services, Institute for Telecommunication Sciences, Environmental Science Services Administration, Boulder, Colorado 80302.

As an aid in visualizing the geographic, diurnal, seasonal, and solar cycle variations of foEs, contour maps for hours 00, 06, 12, and 18 u.t., derived from the coefficients of tables 1 through 8, are given in figures 1 through 48. The maps are reproduced to the same scale as the maps of the ITS "Ionospheric Predictions" (issued monthly). The figures are arranged with the map for 1954 at the top and the corresponding map for 1958 at the bottom of each page.

5. COMMENTS ON THE foEs MAPS

The monthly statistical distribution of foEs at any location can be determined by use of the separate maps of lower decile, median, and upper decile values of foEs. The nature of the data, however, should be kept in mind when inferences about the distributions are made. In section 3 we noted that the value of foE, fmin, or the lower frequency limit of the ionosonde was inserted for a missing value of foEs to determine the lower decile, median, and upper decile values. The implicit assumption is that when no Es appears on an ionogram, foEs must be obscured by the regular E layer in the daytime, or by absorption, or must be below the lower frequency limit of the ionosonde. At such times, the inserted value should be read as "foEs equal to or less than the inserted frequency," the inserted value being an upper limit to the possible value. These limiting values were used in computing the deciles and medians of the distribution, since calculations involving values an uncertain amount below a limiting value are difficult. There would be no such difficulty if all values fell below the lower decile but, unfortunately, in many cases the lower decile was equal to or less than the foE, the fmin, or the lower frequency limit of the ionosonde, and sometimes this was true of the median. Conceivably, this could also occur for the upper decile.

It is clear, therefore, that the lower part of the monthly distribution of foEs is apt to be distorted when foEs falls below foE, fmin, or the lower frequency limit of the ionosonde. Since there are solar cycle variations of foE and of absorption, some differences between corresponding maps of lower decile foEs for 1954 and 1958 may reflect these variations. Similar comments apply to maps of median foEs, but to a lesser extent. In addition, relatively low values of foEs are often difficult to measure accurately because of interference from broadcasting stations, particularly in densely populated areas. For these reasons, the lower decile values of foEs are considered less certain than the median or upper decile values. Fortunately, for purposes of radio propagation, relatively low values of foEs are seldom of practical interest.

Comparison of the observed data with corresponding values calculated from the numerical map coefficients indicates that the representation is quite good. Table 9 gives the average root mean square of the differences between the observed data and corresponding values calculated from the maps. Considering the nature of the data, the average residuals are surprisingly small. The relatively small residuals for the lower decile maps probably result from the inclusion of relatively stable values of foE and ionosonde lower frequency limits. The same is true, to a lesser extent, of the median map residuals. The relatively large residuals of the upper decile maps reflect the rather large hour-to-hour fluctuations of the diurnal variation of upper decile foEs observed at most stations.

Examination of individual stations disclosed some areas with rather large residuals for certain times of day, particularly near the auroral zones and the geomagnetic equator. In most of these cases, data from fairly closely spaced stations in the area indicate steep horizontal gradients in foEs. Since smoothing is inherent in the analysis and mapping program, steep gradients tend to be leveled off, and the representation in limited areas tends to be too high if the area is low and too low if the area is high. Increasing the number of harmonic terms retained in the analysis would provide a better representation in these limited areas, but might also introduce spurious variations in other parts of the world. The number of harmonic terms retained in the analysis program represents a compromise between the various considerations, the cutoff being determined by the statistical "noise" inherent in the data (Jones and Gallet, 1962a). In general, these foEs maps are probably oversmoothed. The relatively small number of locations from which data were available and the statistical noise or variability of the data support the conclusion that this is preferable to accepting spurious variations over much of the world to make a relatively small improvement in representation in a few areas. Specialized mathematical techniques, such as the superposition of an additional function in limited areas of of steep gradients, could be used to derive a better representation, but would complicate the calculations. This problem merits further study.

The contour maps of figures 1 to 48 give the impression that foEs tends to increase from low to high solar activity. Actually, the situation is quite complicated. Depending on time of day and season, areas can be found showing little or no change between solar cycle minimum and maximum, while other areas show a decrease between low and high solar activity. Also, lower decile, median, and upper decile maps do not show changes in the same direction between low and high solar activity in all areas. In addition, for all seasons at middle latitudes there are large areas, primarily in the lower decile and median maps, in which the apparent increase with solar activity is obviously due mainly to the solar cycle variation of foE.

Previous studies (e.g., Smith, 1957; Chadwick, 1962; Mitra and Dasgupta, 1962, 1963) indicate a marked positive correlation of the occurrence of Es with sunspot number in some areas, negligible correlation in some, and negative correlation in others. These conclusions are generally confirmed by our maps of foEs. The maps also indicate that the correlation with sunspot number at any given location may have a diurnal variation, in some areas changing from positive to negative at different times of day.

A very interesting point is the often considerable change in the general shape of the contour patterns between corresponding maps for low and high solar activity. The changes are not necessarily similar on the lower decile, median, and upper decile maps for the same hour and month. The statistical uncertainties of the data are probably partly responsible. Also, since all types of Es, plus foE and fmin, were combined in the data for the foEs maps, it is quite possible that the shift in the world pattern of distribution of foEs with phase of the solar cycle may be due to changes in the relative amounts of the different types of Es and to solar cycle variation of foE and fmin. Separate mapping of different types of Es would be required to sort out these effects.

6. DISCUSSION

The primary purpose of the maps of foEs described in this report is to provide a tool for radio propagation calculations. In the preceding sections we have indicated some of the reasons why maps of this type cannot, by themselves, provide all the information that may be needed. However, they can be quite useful in a number of applications. No attempt will be made to provide detailed instructions for use of the maps, since different methods may be necessary for different problems, but some uses of the maps are indicated below, with alternative approaches suggested in some cases. A pragmatic attitude should be taken by users because of the many uncertainties in our knowledge of Es and because of the limitations of the maps. A method that gives good results in one area of the world may not do very well in another.

The maps of foEs can be used as a supplement to the monthly ITS "Ionospheric Predictions" to provide estimates of Es-MUF and Es-FOT. In a sense, they can be considered successors to the more limited Es charts that were included in the former monthly CRPL D-series, "Basic Radio Propagation Predictions," the predecessor of the current ITS "Ionospheric Predictions" (issued monthly). NBS Circular 465 (1947) suggested multiplying the monthly median predicted values of foEs by 5, taken as M(2000)Es, to estimate monthly median MUF(2000)Es. The E-layer distance interpolation nomogram, which is reproduced as figure 40 in NBS Handbook 90 (Ostrow, 1962) was used to convert to MUF for distances less than 2000 km, or the secant law was used if the height was known or assumed. FOT(2000)Es was derived by subtracting 4 MHz from the MUF(2000)Es. Similar procedures can be used with the new maps of foEs. The monthly median MUF(2000)Es is estimated by multiplying values of the predicted monthly median foEs by a MUF factor of 5. The value of FOT(2000)Es can be estimated by multiplying the predicted lower decile foEs by the same factor. The use of a constant value of MUF factor follows from assuming an average value of Es reflection height for all cases. A study of Es reflection heights is needed to determine whether there is sufficient systematic variation with location and time to warrant taking this into account in estimating Es-MUF factors. The MUF and FOT for the path can be estimated by comparing the MUFs for the regular E layer, the F2 layer, and Es in the usual way.

To obtain a predicted value of foEs, interpolate linearly between the solar cycle minimum and maximum maps, adopting the predicted sunspot number in the issue of ITS "Ionospheric Predictions" used for the F2-layer predictions. If the Es reflection points fall in areas showing little or no change from solar cycle minimum to maximum, some computation can be saved by using only the maps for solar cycle minimum or maximum, whichever is more convenient. If desired, the sunspot number interpolation can be made using the observed 12-month smoothed mean Zurich sunspot numbers for the middle of the month for each month of 1954 and 1958 with the corresponding solar cycle minimum and maximum maps. For routine practical use, assuming a sunspot number of 10 for all months of 1954 and 180 for all months of 1958 should be adequate.

The gross probability of occurrence of Es may not be adequate in some cases, if some types of Es are less effective than others in supporting propagation. For example, oblique incidence observations at high latitudes indicate that the r type of Es is important in supporting propagation, and that other types of Es have negligible effect (D. K. Bailey, personal communication). DeGregorio, Finney, Kildahl, and Smith (1962) found that different types of Es had different reflection coefficients for an 805-mile east-west path in central United States and concluded that the variation in the relative occurrence of different types of Es could cause considerable differences in Es propagation observed. Also, the beam widths of directional antennas could determine, in part, the effective Es reflection coefficient by the amount of discrimination against signals arriving from directions off the great circle path (Smith, 1958). These observations suggest the need for information on the variation of reflection coefficients with type of Es in various parts of the world. Separate mapping by type of Es for those most effective in propagation could increase the accuracy of calculation and prediction of Es-MUF and transmission loss.

Frequently, the probability of propagation by Es at a given frequency is desired, rather than the value of the MUF. This can be estimated from the probability that the equivalent value of foEs at the reflection point is equaled or exceeded. The probability distribution of foEs for a given location and time can be estimated from the lower decile, median, and upper decile map values in a variety of ways, such as: (1) a curve may be fitted to the three points; (2) the best straight line fit to the three points may be determined; (3) a separate interpolation may be made between each decile and median; etc. Any simple interpolation method would probably yield estimates of probability of occurrence of given values of foEs that would permit better propagation predictions than would be possible by ignoring Es entirely. However, some of these methods would be difficult to use, and could lead to serious error if used indiscriminately.

A better means of estimating the probability that a given value of foEs will be equaled or exceeded is the Phillips frequency dependence rule (Phillips, 1943, 1944, 1947). Smith (1957) developed some useful variant forms of the relationship, but the original empirical expression seems most suitable for our purposes:

$$\log_{10}\left(\frac{P_1}{P_2}\right) = b\left(f_1 - f_2\right), \qquad (6.1)$$

where P_1 is the probability that foEs will equal or exceed frequency f_1, P_2 is the probability that foEs will equal or exceed frequency f_2, and b is a constant of proportionality. If two different values of frequency and their corresponding probabilities are known, the constant can be determined. Although (6.1) was originally developed for fEs, it seems reasonable to assume that it also applies, to a first approximation, to foEs, particularly since foEs is often estimated from fEs by assuming the latter to be fxEs (Piggott and Rawer, 1961, 47-55).

The relationship (6.1) is valid only for frequencies above the median. Although often used for the distribution below the median, probably because it is simple to apply, this extension is questionable. In general, the relationship was established using values of fEs above about 3 MHz, because values below this are apt to be affected by foE, fmin, broadcast station interference, and the low frequency limit of the ionosonde. Unfortunately, very little has been done to determine the probability distribution of foEs below 3 MHz, because of the difficulties in separating Es from the complicating factors. For lack of better guidance from data analysis or theory, it is probably most convenient to use (6.1), or perhaps simple linear interpolation with frequency. In most practical communications problems, when foEs is low enough to be influenced by foE, fmin, broadcast interference, or the low frequency limit of the equipment, regular layer propagation is usually dominant.

Davis, Smith, and Ellyett (1959), and DeGregorio, Finney, Kildahl, and Smith (1962), using observations of Es effects on VHF propagation, have noted that an expression related to (6.1),

$$\log_{10} r_1 - \log_{10} r_2 = n \log\left(\frac{f_1}{f_2}\right), \qquad (6.2)$$

where r_1 and r_2 are the Es reflection coefficients for frequencies f_1 and f_2, may be useful in predicting Es signal intensities. However, comparing their observations with other experiments, they found that the value of n seems to vary in different parts of the world, and in different seasons at a given location. This emphasizes the need for better information on Es reflection coefficients in various parts of the world, and for the various types of Es.

To determine whether the lower decile, median, or upper decile value of foEs is influenced by foE, we may use the predicted or observed monthly median foE for comparison. As a rough rule, if the difference from monthly median foE is less than about 0.5 MHz, the median or decile value of foEs in question can be considered affected. When both the upper decile and median are so affected, the incidence of Es is so low that Es propagation usually can be considered negligible. When the median is affected, but not the upper decile, equation (6.1) can be used by inserting the upper decile foEs and, assuming b = -0.23, solving for the probability of the desired frequency. The value of b = -0.23 is an average based on fairly recent data (Phillips, 1963). In general, the value of b is in the neighborhood of -0.2, and the use of two significant figures may be more than are warranted by the data. Some seasonal variation of b may be expected (Phillips, 1947), and there may be diurnal, seasonal, solar cycle, and geographical variations. Such variations may be caused, at least in part, by changes in the relative frequency of occurrence of different types of Es. This question requires further investigation.

It is difficult to determine when fmin, interference, or the lower frequency limit of the ionosonde influence the decile or median values of foEs. Again, some rough rules are suggested: (a) if the difference between the median and lower decile foEs is equal to or less than about 0.5 MHz, the lower decile should be considered unduly affected; (b) if the difference between the upper decile and median foEs is equal to or less than about 0.5 MHz, the median should be considered unduly affected; (c) as in the case of influence by foE, the values of median or decile foEs not affected can be used in (6.1); (d) if only the upper decile is not affected, the average value of b = -0.23 can be used; (e) if neither the median or upper decile values are affected, both may be used with (6.1) to determine the value of b. These rules are probably not very accurate and the user may prefer to modify them according to his experience and judgment. They should be replaced as soon as better information can be obtained. However, the errors introduced by using them are probably less than would result from ignoring Es propagation in calculations.

Assuming that equation (6.1) applies to vertical incidence foEs, we can convert it to an expression for the distribution of Es maximum usable frequencies by multiplying the right side by the reciprocal of M, the maximum usable frequency factor for the given distance, and substituting the values of Es-MUF, f_1' and f_2', for the corresponding equivalent vertical incidence values of foEs, f_1 and f_2, to give

$$\log_{10}\left(\frac{P_1}{P_2}\right) = \frac{b}{M}\left(f_1' - f_2'\right). \tag{6.3}$$

For many communications problems, the primary concern is to determine the probability of propagation of a given frequency, regardless of which modes are effective. In the past, it has been customary to select the most probable mode of propagation, and take its probability as that pertinent to propagation of the given frequency. Less probable modes of propagation have been considered only when necessary, as an example, determining the probability of multipath. Some consideration of elementary probability theory suggests that the practice of selecting the higher of the Es-MUF or the regular layer MUF as the MUF for the path may be too conservative, giving a value of MUF lower than could actually be used.

If a given event can occur by two different and independent mechanisms, the following relationship, found in many texts on statistics or probability (e.g., Mood, 1950), gives the probability of occurrence of the event:

$$P = P_1 + P_2 - P_1 P_2 , \qquad (6.4)$$

where P is the total probability of the event, and P_1 and P_2 are the separate probabilities of occurrence by the two independent mechanisms. Substitution of values between 0 and 1 for P_1 and P_2 will show that P is generally appreciably higher than either P_1 or P_2. For example, if $P_1 = P_2 = 0.5$, $P = 0.75$. The increase in P over the higher of P_1 and P_2 is proportionately greater for lower values of P_1 and P_2 than for higher values.

A recent study (D. H. Zacharisen, personal communication) has indicated that there is little or no correlation between foF2 and foEs. Consequently, for practical purposes, we may assume that Es-MUF and F2-MUF vary independently, and (6.4) may be used to determine the total probability of propagation of a given frequency by both F2 and Es. Use of this relationship should provide a better prediction of probability of propagation, particularly when the probability of occurrence of Es is high, and will usually give a higher path MUF than the current method.

Expression (6.4) is quite general and could be extended to include any number of independent modes of propagation. It could be particularly useful in interference problems, since even quite low values of probability could combine to give significant probability of propagation of an undesired signal.

In the U.S.S.R. system (IZMIR, 1964) for predicting Es propagation as a supplement to the Russian monthly predictions of regular layer propagation, solar cycle variations are assumed negligible, and three sets of maps, one each for summer, winter and equinox periods, are used for all years.

7. CONCLUSION

Numerical maps of lower decile, median, and upper decile foEs have been completed for all 12 months of a solar cycle minimum and a solar cycle maximum year. The solar cycle maximum maps were based primarily on data for 1958, while the solar cycle minimum maps were prepared from data for both 1954 and 1964. They are similar in form to the maps of predicted foF2 and M(3000)F2 of the monthly ITS "Ionospheric Predictions."

The maps of foEs should be considered the first part of a system for prediction and calculation of Es effects on propagation. A similar set of fbEs maps is now being prepared. Together, these maps can provide a basis for the calculation and prediction of Es-MUF and probability of propagation of a given frequency, to supplement calculation and prediction of propagation by the regular ionospheric layers. With additional information on reflection coefficients, transmission losses could also be calculated.

To improve the accuracy of Es propagation calculations, better information is needed on Es reflection and transmission coefficients, on the differences between the various types of Es that may be significant for radio propagation, and on the separate statistical variations with time and space of different types of Es. In addition to accurate measurements in various parts of the world to provide much of this information, collateral theoretical research is required to develop effective methods of applying the results to propagation calculations. Improved methods of calculating the effects of Es propagation are urgently needed to improve the efficiency of utilization of the high-frequency part of the radio spectrum and the reliability of HF radio communications.

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