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THE RECONCILIATION OF AN F-REGION IRREGULARITY MODEL WITH SUNSPOT-CYCLE VARIATIONS IN SPREAD-F OCCURRENCE

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THE RECONCILIATION OF AN F-REGION IRREGULARITY MODEL WITH SUNSPOT-CYCLE VARIATIONS IN SPREAD-F OCCURRENCE

D.G. Singleton

SUMMARY

A recently proposed means of combining models of ionospheric F-layer peak electron density and irregularity incremental electron density (ΔN) so as to simulate the global occurrence probability of the frequency-spreading component of spread-F is discussed. This procedure is then used to model experimental spread-F occurrence results. It is found possible to readily simulate the sunspot-maximum results, independently of season, with only small adjustments to the amplitudes of the empirical expressions used to model ΔN in the several latitude regimes. However, at sunspot minimum and for each season, the ΔN model requires modification in the equatorial and mid-latitude regions of high irregularity incidence, before successful simulations of the spread-F data can be obtained. These modifications, which include a broadening of the equatorial region and a polewards shift of the mid-latitude region with decreasing sunspot number, are discussed in detail. It is concluded that the scintillation data base, from which the original ΔN model derives, is not sufficiently representative with regard to sunspot number and magnetic index. The use of the spread-F adaptation of the ΔN model, as well as its original scintillation version, to rectify these failings of the ΔN model are also discussed.

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1. INTRODUCTION

In an earlier paper (reference 1, subsequently referred to as Paper 1), a method of modelling the global occurrence characteristics of spread-F ionospheric echoes(ref.2) was outlined. The approach adopted involved the combination of existing models of both the incremental electron density of the responsible ionospheric irregularities(ref.3) and the maximum electron density of the F-layer(ref.4) in such a way as to be able to predict the occurrence of the frequency-spreading component of spread-F(ref.5). It was shown that such a procedure yielded a viable model of spread-F occurrence, at least for sunspot-maximum conditions.

The model of the incremental electron density (ΔN) of the ionospheric irregularities used was derived from radio-star and satellite scintillation data(ref.6,3). It was heavily biased towards high sunspot-number conditions. The minimal attempts made at incorporating sunspot-cycle variations were largely untested. Thus, while its adequacy for incorporation in a spread-F model for sunspot-maximum conditions was confirmed by the work reported in Paper 1, its applicability to other epochs of the sunspot cycle remained an open question. This paper investigates this point further.

The next section outlines the analytical framework of the spread-F model. Its ability to predict spread-F occurrence during sunspot-maximum conditions is then illustrated. This is followed by sections dealing with the sunspot-minium situation and with suggestions as to how the incremental electron density model might be altered to obtain better agreement with the observations. The last section discusses this and other areas where the ΔN model might be improved by comparison with experimental data via the spread-F model.

2. THE MODEL EMPLOYED

Spread-F manifests itself on ionograms as range spreading and/or frequency spreading. Range spreading involves a spread in F-layer range at frequencies below the critical frequency(ref.7), while frequency spreading involves a spread in the critical frequency of the F-layer(ref.5). Of these two types of spread-F, frequency spreading has received more attention as far as the study of the morphology of its global occurrence is concerned, mainly because of the ease with which suitable occurrence data can be obtained from the bulletins published by the world's network of ionosonde stations (ref.8). Consequently, there are a number of studies of the world-wide occurrence of the frequency-spreading component of spread-F (ref.8,9,10,11) available which render this phenomenon susceptible to the modelling process.

In Paper 1 an occurrence-probability model of the frequency-spreading component of spread-F is developed. This model involves a combination of existing models of (a) the maximum electron density N of the F-layer(ref.4) and (b) the incremental electron density ΔN of F-layer irregularities(ref.3). It assumes that the spread in critical frequency of the 0 ray (Δf_0) results from the presence of irregularities at the peak of the height distribution of the F-layer electron density. Consequently

$$\Delta f_0 = 2.85 \{ (N + \Delta N)^{1/2} - N^{1/2} \}, \tag{1}$$

where the units of MHz and 10^5 electrons cm^{-3} are used for frequency and electron density respectively.

Since the model provides the mean values of the distributions of N and ΔN which might be observed at any location, time, season or epoch of the sunspot cycle, Δf_0 is also the mean value of a distribution of possible frequency-spreading events. Assuming that this distribution is normal and involves predominantly positive values of Δf_0, it is shown in Paper 1 that the percentage occurrence of frequency spreading P is given by

$$P = 50 [1 - \text{erf} \{ \sqrt{2} (\Delta f_c / \Delta f_0 - 1) \}], \tag{2}$$

where Δf_c is the minimum spread in critical frequency which can be detected and is of the order of 0.1 MHz for a conventional ionosonde(ref.5).

Spread-F data is invariably presented in terms of percentage occurrence P. Consequently, equations (1) and (2) allow a combination of the N and ΔN models to form a P model which can be tested conveniently against experimental data. This process was illustrated in Paper 1. The maximum electron density (N) model used (ref.4) is a phenomenological model employing simple empirical formulae which are functions of local time, day of year, geographic and geomagnetic latitude and the monthly smoothed Zurich sunspot number. The accuracy of this model, over the full range of each of these variables, has been demonstrated by its authors. In what follows it has been assumed to be beyond reproach. However, the same can not be said for the ΔN model used in Paper 1.

The incremental electron density model due to Fremouw and Rino (ref.3) is based on radio-star and satellite scintillation index data taken predominately in years of high sunspot number. Moreover, the sunspot-cycle variations which were incorporated in the model were based on essentially subjective information and these dependencies were not tested by the authors of the model. In this paper, an attempt will be made to throw some light on the nature of the sunspot-cycle dependence of the global distribution of ΔN by comparing the spread-F adaptation of the ΔN model with spread-F occurrence data obtained in both sunspot-minimum and maximum years. Consequently, the ΔN model of Fremouw and Rino is outlined in detail below so as to allow easy reference to areas of the model in which improvements might be effected.

The model consists of four additive terms, the influence of each being dominant in different regimes of geomagnetic latitude, namely equatorial, mid, high and auroral latitudes. These terms are functions of local time (t hours) day of year (d days), geomagnetic latitude (λ degrees) and the monthly smoothed Zurich sunspot number (R). In order to preserve some flexibility in fitting the final spread-F model to the experimental data, a factor m will be included in each term which allows the adjustment of its magnitude. Thus the model is represented by

$$\Delta N = m_e\,\Delta N_e(R,d,t,\lambda) + m_m\,\Delta N_m(t,\lambda) + m_h\,\Delta N_h(R,t,\lambda) + m_a\,\Delta N_a(R,t,\lambda) \tag{3}$$

Using units of 10^5 electrons cm^{-3} for electron density, the ΔN terms in equation (3) are as follows (ref.3)

$$\Delta N_e = 5.5 \times 10^{-2}\,(1 + 0.05R)\,[1 - 0.4\cos\{\pi(d + 10)/91.25\}]$$
$$[\exp\{-(t-4)^2\} + \exp\{-(t - 23.5)^2/3.5^2\}]\exp\{-(\lambda/\lambda_e)^2\} \tag{4}$$

$$\Delta N_m = 6.0 \times 10^{-3}\,\{1 + 0.4\cos(\pi t/12)\}\,\exp\{-(\lambda - \lambda_0)^2/\lambda_m^{\,2}\}. \tag{5}$$

$$\Delta N_h = 2.7 \times 10^{-2}\,[1 + \mathrm{erf}\{(\lambda - \lambda_b)/\lambda_h\}]. \tag{6}$$

$$\Delta N_a = 5.0 \times 10^{-4}\,R\,\exp[-\{\lambda - 70 + 2\cos(\pi t/12)\}^2/\{0.03R\}^2]. \tag{7}$$

where

$$\lambda_b = 79 - 0.13R - (5 + 0.04R)\cos(\pi t/12). \tag{8}$$

$$\lambda_h = 0.2\,\lambda_b. \tag{9}$$

$$\lambda_e = 12^{\circ},\ \lambda_m = 10^{\circ}\ \text{and}\ \lambda_0 = 32.5^{\circ} \tag{10}$$

Note that the sunspot-cycle variations included in the model are limited to the amplitude of the equatorial component, the position of the steep increase in irregularity activity at high latitudes (the scintillation boundary) and the amplitude and width of the auroral component.

Another aspect of the spread-F adaptation of the ΔN model which must be considered is the need for the inclusion of a blackout factor (Paper 1) at latitudes in excess of 70° geomagnetic. This factor, which was applied directly to the predicted occurrence probability, was found to be necessary to adequately model the experimental data at these latitudes. The need for such a factor is believed to be due to polar-blackout effects on the statistics of bottomside spread-F and/or inadequate knowledge of the behaviour of ΔN at these latitudes. Variations in the nature of the blackout factor with season and sunspot number will be considered in the following sections.

3. SUNSPOT-MAXIMUM CONDITIONS

Experimental results for the probability of occurrence of spread-F under sunspot-maximum conditions for the northern solstice (July 1957), equinox (September 1957) and southern solstice (January 1958) are presented in figure 1(a), (b) and (c) respectively (ref.8). In each of these diagrams, the probability of occurrence of spread-F, expressed as a percentage, is plotted contour fashion on a grid of local time versus geomagnetic latitude. The ionosonde stations which provided the data for these diagrams were distributed throughout the indicated range of latitude but were confined to within $\pm 25^{\circ}$ of 75°W geographic longitude.

Paper 1 describes in detail the simulation of the September 1957 data (figure 1(b)) with the aid of the model. The result of the simulation is shown in figure 1(e) which is drawn using the same format as that used in the experimental contour diagrams. Here the m factors were chosen to be 1.0, 2.7, 3.0 and 3.0 in the equatorial, middle, high and auroral latitudes respectively. Also, a blackout factor (B) was applied to the spread-F occurrence probability at geomagnetic latitudes in excess of 70°. This had the form

$$B = 1 + A\left[\cos 2\pi \left\{(t - \tau)/T\right\} - 1\right] + C\left[\cos 4\pi \left\{(t - \tau)/T\right\} - 1\right] \qquad (11)$$

where the period $T = 24$ hours, the phase time $\tau = 1$ hour and the coefficients A and C were 0.09 and 0.17 respectively. As indicated in Paper 1, the significant agreement attained between the simulation and the experimental data, both in this and other similar comparisons, is strong evidence in favour of the modelling procedures adopted, at least at sunspot maximum and in the equinoxes.

In a similar way, the occurrence data for the northern solstice (figure 1(a) and southern solstice (figure 1(c) were simulated with the aid of the model and the results are shown in figures 1(d) and (f) respectively. The values of m used are shown in Table 1. These are generally small and similar in magnitude to those required to fit the model to the data under equinoctial conditions. An exception to this occurs in the case of the auroral term for the southern solstice where m is required to be an order of magnitude larger than that required elsewhere. It should also be noted, that, while in the equatorial region $m_e = 1$ gives a reasonable fit in September 1957 and January 1958, this value is apparently too large in July 1957. This point will be considered further in a later section.

In order to simulate the experimental spread-F occurrence data at high latitudes during the solstices, a blackout factor (B) is required of similar form to that used in the equinoctial case. The equation used is

$$B = \left[1 + A\left\{\cos 2\pi(t - \tau)/T - 1\right\} + C\left\{\cos 4\pi(t - \tau)/T - 1\right\}\right]\exp\left\{-(\lambda - \lambda_c)^2/\lambda_d^2\right\} \qquad (12)$$

This is a generalization of equation (11) in that it allows for a variation of B with geomagnetic latitude where this latitude is greater than the minimum latitude (λ_c) at which B is applied. Equation (12) reduces to equation (11) when the parameter λ_d is large compared to $\lambda - \lambda_c$. In the following, it will be necessary to refer to the individual terms of equation (12) which is thus conveniently rewritten as

$$B = \left[1 + D + E\right].F \qquad (13)$$

The parameters used in equation (12) to simulate the high latitude portions of figures 1(d), (e) and (f) are given in Table 1. Note that in the southern solstice (figure 1(f)), equation (12) is reduced to the form $B = 1 + D$ giving the simulation a minimum at local midnight as observed (figure 1(c)). In order to model the complex high latitude structure observed in the northern solstice (figure 1(a)), the form of the blackout factor is changed from $B = (1 + D) . F$, in the geomagnetic latitude range of 70° to 80°, to $B = (1 + D + E). F$, for 80° to the pole.

Comparison of figures 1(d), (e) and (f) with figures 1(a), (b) and (c) shows that the spread-F adaptation of the ΔN model produces acceptable simulations of the spread-F occurrence data, independent of season, for sunspot-maximum conditions. In the main, only small adjustments of the level of activity via the m factor are found to be necessary. Also, a blackout factor of consistent form allows the modelling of the high latitude data to be completed. Consequently, the incremental electron-density model of F-region irregularities, derived from scintillation studies, adequately depicts the global occurrence characteristics of spread-F for sunspot-maximum conditions not only during the equinoxes but also during the solstices. This generalization of the main result of Paper 1 to include all seasons will now be continued so as to embrace other epochs of the sunspot cycle.

4. SUNSPOT-MINIMUM CONDITIONS

Experimental results for the probability of occurrence of spread-F under sunspot-minimum conditions for the northern solstice (July 1964), equinox (September 1964) and southern solstice (January 1964) are presented in figures 2(a), (b) and (c) respectively (ref.10). In each of these diagrams, the probability of occurrence of spread-F, expressed as a percentage, is plotted contour fashion on a grid of local time versus geomagnetic latitude. This format is identical to that used in figure 1, as is the chain of ionosonde stations providing the data in the two cases. A season by season comparison of the sunspot minimum data with that for sunspot maximum is possible with the aid of figures 1(a), (b) and (c) and figures 2(a), (b) and (c). Such a comparison suggests immediately two changes in the occurrence behaviour of spread-F with changing sunspot number. First, the equatorial region of high occurrence has a larger latitude extent in sunspot minimum than in sunspot maximum. Secondly, a subpeak of high occurrence in the middle latitudes (about 50° geomagnetic latitude) is clearly visible under sunspot-minimum conditions whereas this tends to merge with the high latitude occurrence peak at sunspot maximum. A successful spread-F model must necessarily predict these changes in occurrence behaviour.

In Paper I it was shown that the ΔN model plays a predominant role in the simulation of the spread-F occurrence patterns. The maximum electron density (N) model influences the simulation only in a second order manner. Consequently, if the existing model is to accommodate the sunspot-cycle changes in the equatorial and mid-latitude spread-F occurrence behaviour just noted, the ΔN model should include sunspot-cycle variations. Examination of the appropriate terms of the model shows that in the mid latitudes (equation (5)), no account whatsoever is taken of the sunspot cycle, while at equatorial latitudes, a sunspot dependence is introduced only via the overall amplitude (equation (4)). This type of sunspot-cycle dependence at the equator seems unlikely to produce the desired result, as similar overall levels of occurrence in this region exist at the two points of the sunspot cycle investigated (vide figures 1(a), (b) and (c) and 2(a), (b) and (c)). These speculations were confirmed, when attempts to use the spread-F adaptation of the ΔN model of Fremouw and Rino (ref.3) failed to adequately simulate the equatorial and mid-latitude behaviour noted above.

Examination of equation (4) shows that, in the model, the extent of the equatorial region north and south of the geomagnetic equator is controlled by λ_e, which is set at 12° by Fremouw and Rino. While this value is adequate for the sunspot-maximum situation, the expansion of this region during sunspot minimum suggests that λ_e should be increased by a factor of the order of three at this time.

Equation (5) shows that the mid-latitude region of occurrence is controlled in position and width by λ_o and λ_m respectively. Again, the values of $\lambda_o = 32.5°$ and $\lambda_m = 10°$ adopted by Fremouw and Rino, while being adequate at sunspot maximum, appear to require modification at sunspot minimum to account for the relatively narrow peak in occurrence which occurs near 50° geomagnetic latitude.

Figures 2(d), (e) and (f) show successful simulations of the sunspot-minimum spread-F occurrence patterns observed during the northern solstice (figure 2(a)), equinox (figure 2(b)) and southern solstice (figure 2(c)) respectively. The parameters λ_e, λ_o and λ_m used are as indicated in Table 2. The values of these parameters, which were suggested by Fremouw and Rino (ref.3) and found to be adequate for the prediction of spread-F occurrence at sunspot maximum, are listed in brackets at the head of Table 2.

The m values used in the sunspot-minimum simulations are listed in Table 2. This table also gives the parameters used to successfully simulate experimental data for April 1964. These data and their simulation are not shown diagramatically.

In order to obtain successful simulations of the spread-F occurrence behaviour at high latitudes under sunspot-minimum conditions, it was found necessary to apply a blackout factor to the spread-F occurrence values predicted with the aid of equations (1) and (2) and the ΔN and N models. The procedure used was similar to that described in Section 3 for sunspot-maximum conditions, the blackout factor employed being identical in form to that used there (equation (12)). The parameters used in the blackout factor are listed in Table 2 and the resulting high latitude simulations of spread-F occurrence appear in figures 2(d), (e) and (f).

Under sunspot-minimum conditions the blackout factor takes its simplest form, namely B = 1 + D, during the equinox. This factor is applied at all geomagnetic latitudes greater than 65° giving, in figure 2(e), a simulation of the high-latitude experimental results shown in figure 2(b). The blackout factor required to simulate the two-minima configuration found in the high-latitude southern-solstice results of figure 2(c) is also relatively simple, being of the form B = 1 + E. The resulting simulation is given in figure 2(f). As in the sunspot-maximum situation (Section 3), the blackout factor takes on its most complex format during the northern solstice. In this solstice at sunspot minimum, it is again found necessary to change the form of the blackout factor on proceeding to very high latitudes. Between 65° and 80° geomagnetic latitude the blackout factor takes the form B = (1 + D) . F, while at higher latitudes the form B = 1 + E is used. As shown in figure 2(d), this allows successful simulation of the change from a one-minimum structure at auroral latitudes, to the two-minima structure at the polar latitudes found in the experimental occurrence diagram (figure 2(a)).

It is interesting to compare the m factors required at sunspot minimum (Table 2) with those used in sunspot maximum (Table 1). At the equatorial latitudes small values close to unity are required at both the maximum and minimum of the sunspot cycle. However, at the higher latitudes, the relatively small values required at sunspot maximum are replaced by values of the order of 10 at sunspot minimum. The significance of this sunspot-cycle effect will be discussed in the next section.

5 SUGGESTED MODIFICATIONS TO THE ΔN MODEL

The foregoing sections have demonstrated that a considerable measure of success can be obtained in simulating the occurrence characteristics of spread-F by using the modelling procedure outlined initially in Paper 1. Under sunspot-maximum conditions the ΔN model, on which the procedure is based, is substantially the same as that proposed by Fremouw and Rino(ref.3) on the basis of scintillation studies. The only change found necessary involves a small adjustment (via the m factors) of the amplitudes of the terms which represent ΔN in the several latitude regimes. Under sunspot-minimum conditions however, not only are slightly larger m factors required, but modification of three of the parameters defined by Fremouw and Rino(ref.3) is also found necessary. This suggests that the ΔN model of Fremouw and Rino may need modification in order to include sunspot cycle variations not previously identified. It will be recalled that Fremouw and Rino's model was defined using predominantly high sunspot-number data and that it was not tested for sunspot cycle variations.

In figure 3 the several parameters of the model which have been shown to be sunspot-cycle dependent are plotted against sunspot number. As the available points cluster at low and high sunspot numbers, it is not possible to define the sunspot-cycle trends unambiguously. However, a number of interesting possibilities suggest themselves and these should be noted.

Figure 3(a) presents the variation of the equatorial-width parameter λ_e with sunspot number R. There is only one point at sunspot maximum (R = 195) corresponding to the value adopted by Fremouw and Rino(ref.3), while at sunspot minimum there are four points each marked with an abbreviation indicating the month in which the data were taken. If no significance is placed in the scatter of points at low sunspot numbers, then the data might be represented by the full line, i.e. by the linear relation

$$\lambda_e = -11.5R + 34.5 \quad (14)$$

On the other hand, the scatter at low sunspot number disappears if the broken line curve is taken as indicating the trend. In this case, the sunspot number dependence of λ_e is given by

$$\lambda_e = 82R^{-0.365} \quad (15)$$

More information in the middle sunspot number range is obviously required in order to choose which, if either, of these variations is appropriate.

Figure 3(b) is a plot of the width parameter (λ_m) of the mid-latitude occurrence region against the sunspot number (R). Again there is only one point at sunspot maximum corresponding to the value adopted by Fremouw and Rino(ref.3). At sunspot minimum there is considerable scatter. If this scatter is ignored then the data might be represented by the full line, i.e. by the linear relation

$$\lambda_m = 0.0165R + 6.75 \quad (16)$$

In this case, the scatter cannot be removed by adopting a simple non-linear relationship. However, examination of the scatter suggests that there might be a cyclic variation based on season. Proceeding from January through April, July and September back to January, a loop such as that indicated by the dotted line is traced out. Such a variation could be presented by a term of the form cos (πd/182.5), where d is the day of the year. This cyclic variation apparently has zero amplitude at high sunspot number. The decrease in its amplitude with increasing sunspot number might be represented by Q as illustrated in the lower part of figure 3(b), i.e. by

$$Q = -0.0165R + 3.25$$

The complete expression for λ_m then becomes

$$\lambda_m = 0.0165R + 6.75 + (0.0165R - 3.25)\cos(\pi d/182.5) \quad (17)$$

Which describes a "damped" oscillatory variation of λ_m with increasing sunspot number and day of year. This variation would be confined between the two broken straight lines in figure 3(b). Again mid sunspot-cycle data is necessary to test the reality of such a suggestion.

Figure 3(c) shows the variation of the position parameter (λ_o) of the mid latitude occurrence region with sunspot number (R). The single point at high sunspot number corresponds to the value chosen by Fremouw and Rino (ref.3) and the points at low sunspot number are the values suggested by the present investigation. Two curves showing possible connections between λ_o and R appear on the diagram. The full line represents the linear relationship

$$\lambda_o = -0.085R + 49 , \qquad (18)$$

while the broken line gives the power law relationship

$$\lambda_o = 69R^{-0.145} \qquad (19)$$

The scatter of points at low sunspot number precludes distinguishing between these two possibilities. Indeed, if the low sunspot number points are considered in seasonal order, it is also possible to visualize a cyclic pattern similar to that described in figure 3(b). Mid sunspot cycle data is required in order to choose which, if any, of these three possible relationships is appropriate

Figures 3(d), (e), (f) and (g) give the sunspot-cycle variations of the m factors in the equatorial (m_e), mid (m_m), high (m_h) and auroral (m_a) latitude regions respectively. Again only values at the very low and very high sunspot numbers are available. The scatter at low sunspot number is greater than that at high sunspot number. The following possible linear relationships are indicated on the figure:

$$m_e = -0.011R + 3.2, \qquad (20)$$

$$m_m = -0.032R + 8.6, \qquad (21)$$

$$m_h = -0.041R - 11 \qquad (22)$$

and

$$m_a = -0.066R + 15 \qquad (23)$$

Interpretation in terms of non-linear relationships and seasonal-cyclic variations also appear to be possible in some cases. Again, however, justification of a relationship more complex than a simple linear one is hampered by the limited data available.

While it is realised that the lack of information at medium sunspot numbers seriously limits the velocity of the sunspot-cycle variations proposed above, they are put forward as a first attempt at defining these variations. Further work is required in this area, employing both the scintillation and spread-F modelling techniques, to fully define the variations.

6. DISCUSSION

The above demonstrates that considerable success can be obtained in simulating the observed occurrence characteristics of spread-F using the modelling techniques originally proposed in Paper 1. Also it has been shown that the incremental electron density model can be further defined in the process. However, there are several points which require further discussion.

In the equatorial latitudes, an apparent discrepancy exists between the model's predictions and experiment during the northern solstice under sunspot-maximum conditions. Comparison of figures 1(a) and (d) indicates that the simulation suggests there should be more spread-F than is actually observed in the vicinity of the geomagnetic equator. This can be explained in terms of an inadequacy of Fremouw and Rino's (ref.3) model of ΔN. Scintillation results obtained at high sunspot number (about 100) show a seasonal variation at the equator which peaks in the equinoxes, has a narrow and shallow minimum in the southern solstice and a broad deep minimum in the northern solstice(ref.12). Fremouw and Bates(ref.[illegible]) originally modelled this by a simple sinusoidal variation and this was carried over into Fremouw and Rino's (ref.3) model. Obviously such a model can only approximate the observed variation and, depending how the mean level of the sinusoid is set, at least one season must be poorly modelled. Apparently the levels are such as to provide a good match for the equinoxes and the southern solstice and therefore are too high for the northern solstice.

It should be noted also that at sunspot minimum, the model with $m_e = 1$ gives a good simulation in the equatorial region in the equinoxial periods but larger values of m_e are needed in the solstices (figure 2 and Table 2). Further, m_e for the southern solstice is nearly three times its value for the northern solstice. This indicates that the inequality of the solstice minima, referred to above at high sunspot number, is also present at sunspot minimum. However, the amplitude of the ΔN variation is evidently less in sunspot minimum than in sunspot maximum. These results should be confirmed with suitably designed scintillation studies.

This discussion indicates that variations of the equatorial ΔN model proposed by Fremouw and Rino(ref.3) are evidently necessary, if it is desired to simulate more than the gross effects. Also, the models currently provide no provision for the effect of short term changes in magnetic activity which are known to influence the occurrence of F-layer irregularities in equatorial regions(ref.12).

In the mid latitudes, Fremouw and Rino(ref.3) base their model on the scintillation observations reported by Preddey (ref.13) which were obtained during a period when the sunspot number was of the order of 30. Here the mid latitude peak in scintillation index occurred in the vicinity of 32^o geomagnetic latitude. It is interesting that this model proves to be adequate to explain the spread-F data at these latitudes at the peak of the sunspot cycle but needs radical modification to simulate the spread-F occurrence situation when the sunspot number is of the order of 10. The modification required involves increasing the latitude of the peak to about 48^o, decreasing its width by about a factor of 2 and increasing its magnitude by a factor of nearly 4 (Table 2). The picture which seems to emerge is as follows. On proceeding from sunspot minimum to maximum, the mid latitude sub peak in the occurrence and/or strength of the F-region irregularities diminishes in intensity and moves towards the equator, vanishing altogether at sunspot maximum. Such behaviour would be consistent with a variation of λ_0 with R similar to that shown by the broken line in figure 3(c). It would also suggest that a similar non-linear variation of m_m with R might be more appropriate in figure 3(e). More observational data involving both scintillations and spread-F at medium sunspot numbers would allow these aspects of the model to be further defined.

The spread-F adaptation of Fremouw and Rino's(ref.3) model of ΔN provides an adequate simulation of the spread-F occurrence situation at high latitudes at both extremes of the sunspot cycle. The inclusion of the blackout factor at auroral and higher latitudes may mask deficiencies of the ΔN model at these latitudes at either or both of the extremes of the sunspot cycle. As discussed in Paper 1, more scintillation data at these high latitudes are needed, if the ΔN model is to be more rigidly defined there and indeed, if the physical significance of the blackout factor is to be fully understood. The success of the spread-F adaptation of the ΔN model in simulating the high latitude data at latitudes lower than that at which the blackout factor must be applied, speaks highly of its accuracy in this region over the whole sunspot cycle.

Pope(ref.14) has recently suggested a variation of Fremouw and Rino's(ref.3) model in the high latitude region. This is based on the observed control by magnetic activity of the movement of the steep increase in irregularity activity between 50^o and 70^o geomagnetic latitude. The high latitude term in the ΔN model (equation (6)) is replaced by one which depends on the planetary magnetic index K_p rather than on the sunspot number R. While this modification provides an improved representation of the scintillation data, it was not employed in the present investigation because the spread-F data used were not analysed with regard to magnetic activity. To have employed Pope's model would have meant using an average value of K_p for each season in each part of the sunspot cycle. It is doubtful whether such an approach would have yielded comparisons any more meaningful than those presented here.

In conclusion, the present study indicates that the scintillation data base, from which the original ΔN model derives, is not sufficiently representative with respect to sunspot number and magnetic index. It is also clear that further improvement of the spread-F and scintillation modelling process will only be achieved when the effects of sunspot number and magnetic index are explicitly written into the models. The present work suggests the form the sunspot number dependence might take. However, more analyses of spread-F and scintillation data must be carried out, before it will be possible to clearly define the roles these effects play in the models.

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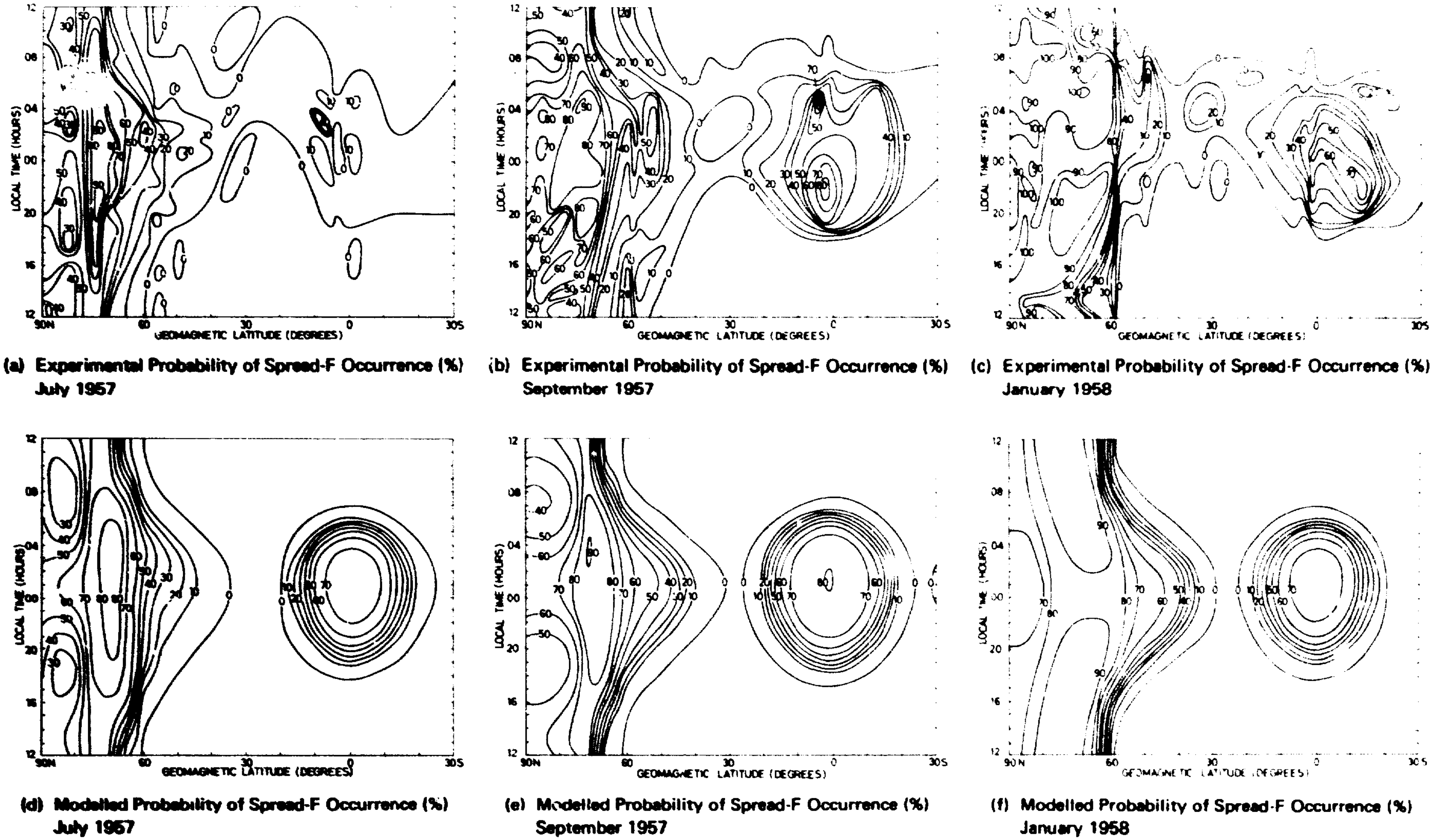
TABLE 1. MODEL PARAMETERS FOR SUNSPOT-MAXIMUM CONDITIONS

Season	Sunspot number	ΔN parameters				Blackout factor parameters					
		m_e	m_m	m_h	m_a	λc (°)	λd (°)	A	C	T (hour)	τ (hour)
Northern solstice (July 1957)	190	1	2.5	3	3	70 80	33 33	0.13 0.13	0 0.22	24 24	1 1
Equinox (September 1957)	197	1	2.7	3	3	70	∞	0.09	0.17	24	1
Southern solstice (January 1958)	199	1	2	3	20	50	∞	0.03	0	24	12

TABLE 2. MODEL PARAMETERS FOR SUNSPOT-MINIMUM CONDITIONS

Season	Sunspot number	ΔN parameters							Blackout factor parameters					
		m_e	m_m	m_h	m_a	λe (°) (12)	λm (°) (10)	λo (°) (32.5)	λc (°)	λd (°)	A	C	T(hour)	τ(hour)
Northern solstice (July 1964)	10	1.9	8	8	8	38	10	43	55 82	18 ∞	0.22 0	0 0.14	24 24	3 4
Equinox (September 1964)	10	1	5.3	12	12	38	5	48	65	∞	0.17	0	24	2.5
Southern solstice (January 1964)	20	5	10	10	20	26.5	4	50	80	∞	0	0.1	24	3
Equinox (April 1964)	13	1	10.5	12	12	30	7.5	48	78	∞	0.17	0	24	-1



(a) Experimental Probability of Spread-F Occurrence (%) July 1957

(b) Experimental Probability of Spread-F Occurrence (%) September 1957

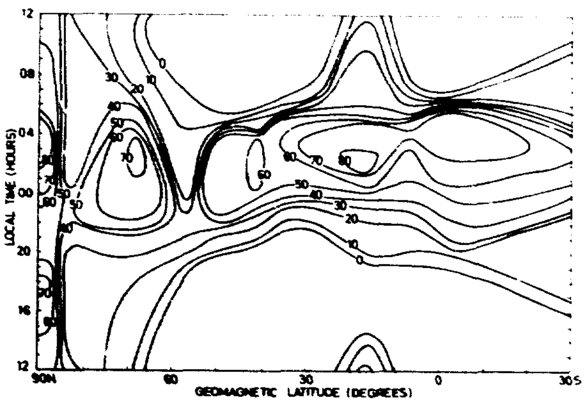
(c) Experimental Probability of Spread-F Occurrence (%) January 1958

(d) Modelled Probability of Spread-F Occurrence (%) July 1957

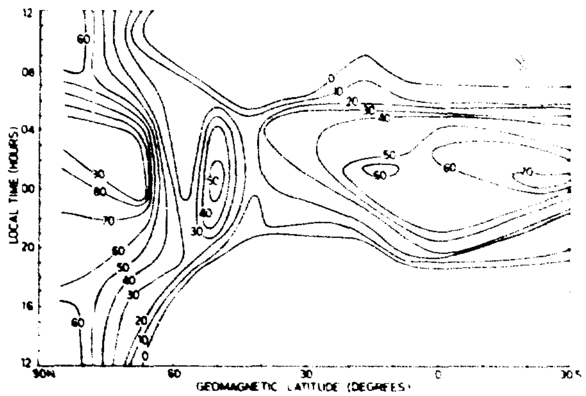
(e) Modelled Probability of Spread-F Occurrence (%) September 1957

(f) Modelled Probability of Spread-F Occurrence (%) January 1958

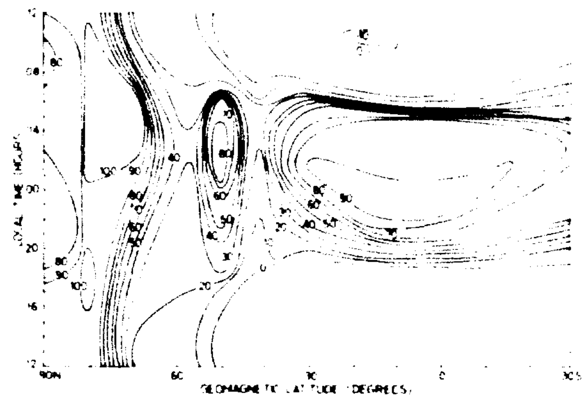
Figure 1. Experimental local time versus geomagnetic latitude contour plots of spread-F occurrence for the northern solstice (a), equinox (b) and southern solstice (c), under sunspot-maximum conditions, compared with their simulations ((d), (e) and (f))



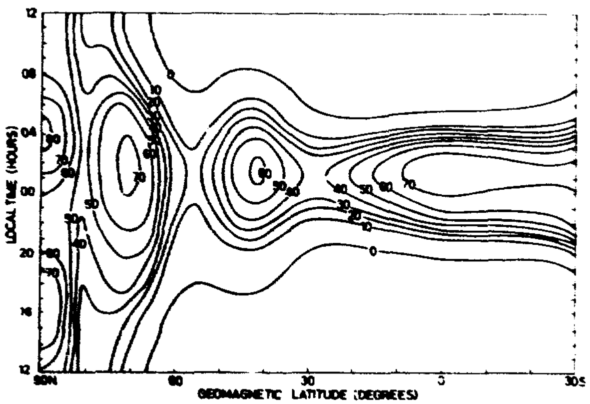
(a) Experimental Probablity of Spread-F Occurrence (%) July 1964



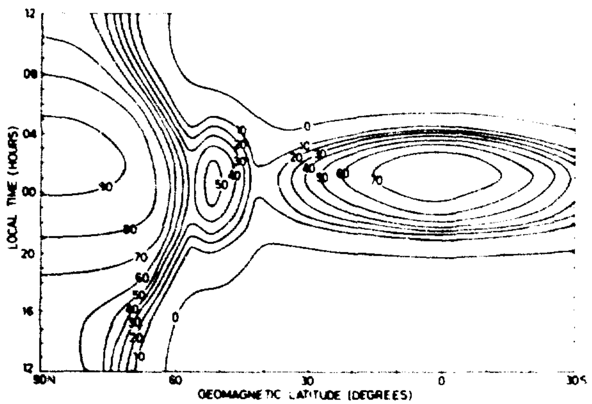
(b) Experimental Probability of Spread-F Occurence (%) September 1964



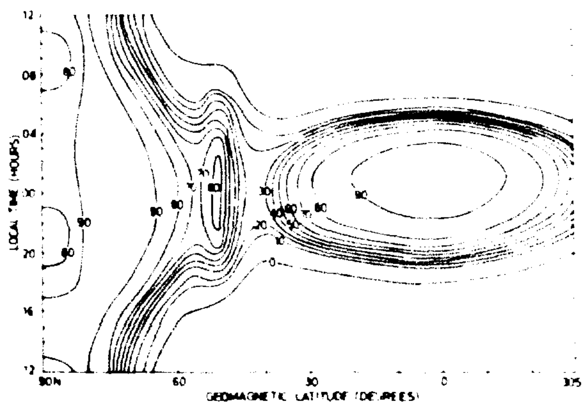
(c) Experimental Probability of Spread-F Occurrence (%) January 1964



(d) Modelled Proability of Spread-F Occurence (%) July 1964



(e) Modelled Probability of Spread-F Occurrence (%) September 1964



(f) Modelled Probability of Spread-F Occurrence (%) January 1964

Figure 2. Experimental local time versus geomagnetic latitude contour plots of spread-F occurrence for the northern solstice (a), equinox (b) and southern solstice (c), under sunspot-minimum conditions, compared with their simulations ((d), (e) and (f))

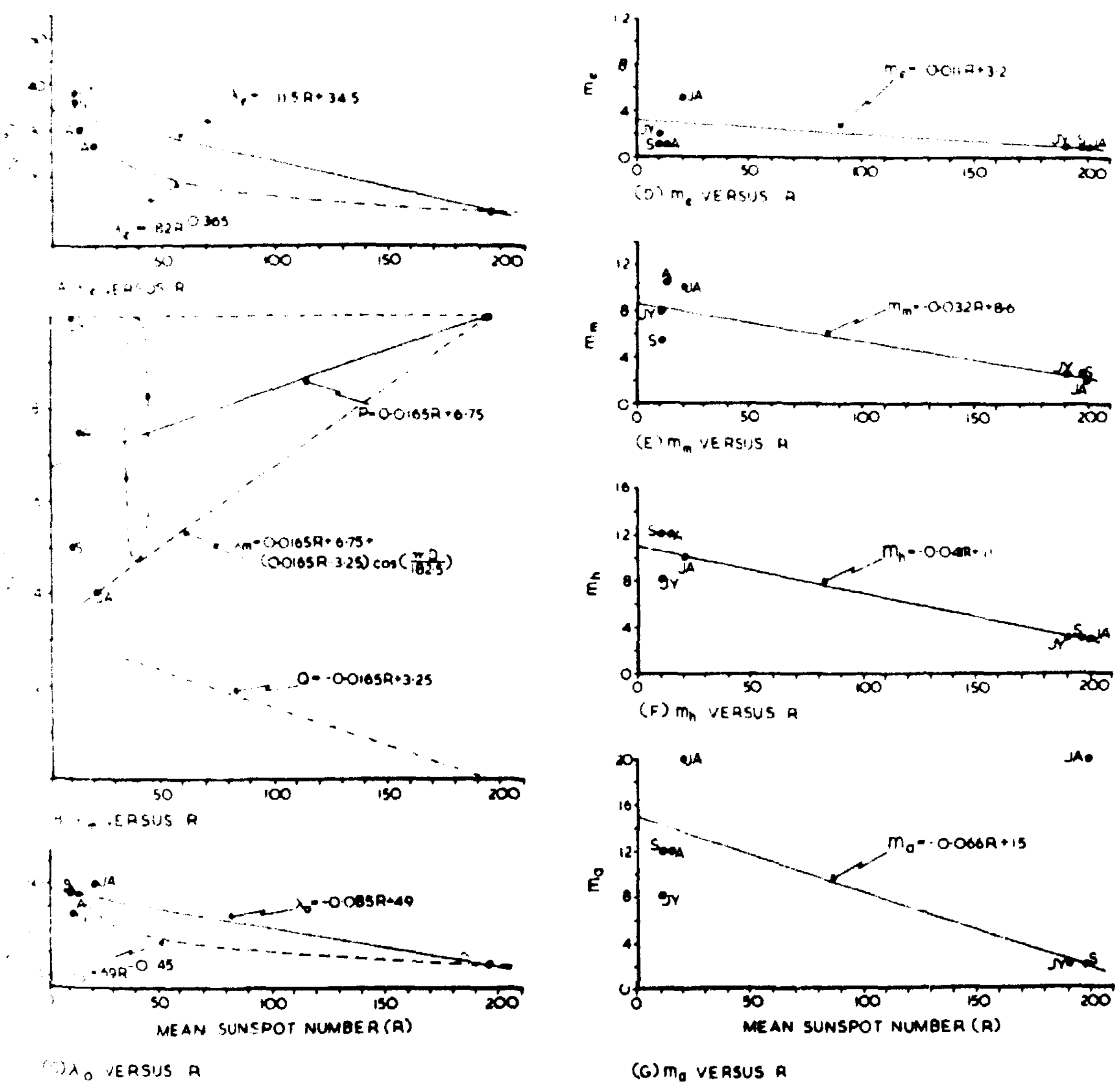


Figure 3. Suggested sunspot-number variations of the model parameters λ_e, λ_m, λ_o, m_e, m_m, m_h and m_a

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7. Summary

A recently proposed means of combining models of ionospheric F-layer peak electron density and irregularity incremental electron density (ΔN) so as to simulate the global occurrence probability of the frequency-spreading component of spread-F is discussed. This procedure is then used to model experimental spread-F occurrence results. It is found possible to readily simulate the sunspot-maximum results, independently of season, with only small adjustments to the amplitudes of the empirical expressions used to model ΔN in the several latitude regimes. However, at sunspot minimum and for each season, the ΔN model requires modification in the equatorial and mid-latitude regions of high irregularity incidence, before successful simulations of the spread-F data can be obtained. These modifications, which include a broadening of the equatorial region and a polewards shift of the mid-latitude region with decreasing sunspot number, are discussed in detail. It is concluded that the scintillation data base, from which the orginial ΔN model derives, is not sufficiently representative with regard to sunspot number and magnetic index. The use of the spread-F adaptation of the ΔN model, as well as its orginial scintillation version, to rectify these failings of the ΔN model are also discussed.

8. Descriptors F-region Mathematical models Sunspots Spread-F Ionospherics Electron density (concentration) Latitude Scintillation	9. Cosati Codes 0401 1201 0302 2014 2008 2009 0805 2006 10. Task Reference Number
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