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A Simplified Model of the High Latitude Ionosphere for Telecommunications Applications

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A SIMPLIFIED MODEL OF THE HIGH LATITUDE IONOSPHERE FOR TELECOMMUNICATIONS APPLICATIONS

by

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A model of the parameters that specify the structure of the electron density in the polar ionosphere has been developed. The model is based upon the modification of monthly median ionospheric parameters given by the CCIR by use of formulations that characterize specific features of the high latitude ionosphere. In addition to the critical frequency, height of maximum electron density, and semi-thickness of the E, F1, and F2 regions, the model accounts for high latitude features such as the auroral oval, the F2 region ionization trough, the ionization due to auroral E layer formation, auroral absorption, and electron density irregularities in the E and F regions of the polar ionosphere. Observations of ionospheric and geophysical parameters can also be used to modify the structure of the ionosphere as given by the model. The use of the model for telecommunication purposes is illustrated by application of the model to a high latitude, high frequency broadcasting operation.

Key words: auroral oval; E region irregularities; F region irregularities; F2 region trough; Polar Ionospheric Model

1. INTRODUCTION

The ionosphere in the polar regions is a highly variable and dynamic medium. Processes that can be traced to sources involving chemical and physical interactions between the neutral and ionized atmosphere compete for importance in the overall control of the ionization distribution. The chemical and physical processes are further complicated because the earth's magnetosphere exerts a strong influence upon the polar ionosphere. Processes of magnetospheric origin involving electric fields, convection patterns, and particle precipitation lead to interactions in the polar ionosphere that are just now being understood (Vondrak et al., 1977). Because of the highly variable and complex nature of the polar ionosphere, HF radio systems that involve the propagation of energy within and through the polar ionosphere likewise display a highly variable and complex nature. Because of this complexity, the Air Force Geophysics Laboratory (AFGL) requested that the Institute for Telecommunication Sciences (ITS) provide timely information about the structure of the polar ionosphere during times of operation of the 414-L Over-the-Horizon backscatter radar system (designated as OTH-B). The information provided by ITS is in the form of parameters that specify selected characteristics of the polar ionospheric structure. The parameters have been modified by actual observations obtained from vertical

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incidence sounders, satellite sensors, and ground-based sensors such as magnetometers and riometers.

The parameters which taken together comprise the Polar Ionospheric Model are intended to be used to help determine performance characteristics of the OTH-B radar. The model has been cast in the form of sets of parameters to facilitate user operation. The basis of the Model is the median ionospheric structure that is given by the International Radio Consultative Committee (CCIR) and contained in the high frequency (HF) propagation prediction computer programs ITS-78 (Barghausen et al., 1969) and IONCAP (John Lloyd, private communication, 1981). Observations of parameters in the actual polar ionosphere are used to modify the median ionospheric structure. The model contains parameters that characterize the normal ionospheric distribution as well as irregularity distributions in the E and F regions, an auroral absorption indicator that is applicable to the vicinity in which the OTH-B radar operates, and an absorption index that can be used to account for classical HF absorption.

The crucial element in the Polar Ionospheric Model is the location of the auroral oval; first discussed by Feldstein in 1964 and later by Feldstein and Starkov in 1967 and 1970. The auroral oval concept permits an ordering of polar ionospheric processes. The work of Bowman (1969), Wagner and Pike (1971), Pittenger and Gassman (1971), Gassman (1972), Pike (1972), Wagner (1972), Elkins and Rush (1973), Miller and Gibbs (1975), Pike (1976), and Halcrow and Nisbet (1977), for example, have shown how various polar ionospheric phenomena fall into this ordering scheme.

The purpose of this report is to describe the model and the rationale for the selection of the various elements that comprise it. The model is then used to demonstrate the predicted performance of propagation systems indicative of HF broadcast operations involving high-latitude paths. In the next section of this report, the Polar Ionospheric Model is described. Equations for specific elements are given and references to more complete documentation, if applicable, are given. In Section 3, the model is used to demonstrate how signals that characterize HF broadcasting operations in the high latitudes can vary because of the polar ionospheric structure. In the fourth and final section, discussion is given to areas where the Model can be improved and where further work is necessary.

2. ITS POLAR IONOSPHERIC MODEL

The Polar Ionospheric Model is based on a median specification of the polar ionosphere that follows directly from the numerical coefficients given by the CCIR in Report 340 (CCIR, 1978a). The vertical distribution of electrons at any point in the polar ionosphere is characterized by three separate values of the critical frequency, height of maximum ionization and semi-thickness. The critical frequencies, heights of maximum ionization, and semi-thicknesses for the E, F1, and F2 regions of the ionosphere are determined using the CCIR coefficients or specific equations relating to the parameter in question. The parameters determined by the numerical coefficients or specific equations can be modified in accord with observation so that a better representation of the polar ionosphere can be obtained for a given time. In addition to the parameters that characterize the height distribution of electrons in the polar ionosphere, specific features characterizing horizontal variations in the polar electron density are included in the model. It is these features that provide for the detailed specification of the horizontal structure of the polar ionosphere. After the normal horizontal structure has been modified by inclusion of specific features, the vertical distribution of electrons in the ionosphere can be obtained by assuming that in each height region, the electron density follows a distribution that is specified by the user.

The model has been developed into a computer program for ease in performing the necessary calculations to obtain electron density distributions in the polar ionosphere. The model can be used to generate features of the ionosphere at any location on the earth. However because of applications to the OTH-B operations, the computer program developed from the model is limited to the region 12° to 76.5° N latitude and 0.5° to 120.5° W longitude. The details of the model are presented below.

2.1 Generation of Median Polar Ionospheric Parameters

2.1.1 Normal E Region Parameters

There are three parameters that characterize the normal E region ionization distribution: the critical frequency, height of maximum ionization, and semi-thickness. The critical frequency of the E region, foE, is determined from the coefficients developed by Leftin (1976). For a given month, median values of foE are generated at any universal time by specifying the appropriate sunspot number. The height of the E region maximum density is given by a formulation that allows the height to display a smooth transition from day to night conditions. The daytime values of the height of the E region maximum is 110 km and the nighttime value is

120 km. The semi-thickness of the E region is determined by dividing the height of the E region maximum density by 5.5.

2.1.2 Normal F1 Region Parameters

As was the case for the normal E region, the normal F1 region is characterized by the critical frequency, maximum height, and semi-thickness. The critical frequency of the F1 region is given by the model of Rosich and Jones (1973). Values of foF1 are determined for a limited range of solar zenith angles so as to be in accord with observations. The height of the F1 maximum density (hmF1) is given by

$$hmF1 = 165 + .6428\chi, \qquad (1)$$

where χ is solar zenith angle in degrees.

The semi-thickness, YmF1, is given by

$$YmF1 = hmF1/4. \qquad (2)$$

2.1.3 Normal F2 Region Parameters

Like the E and F1 regions, the undisturbed F2 region is characterized by three parameters: critical frequency, maximum height, and semi-thickness. The F2 region critical frequency, foF2, is determined using the coefficients developed by Jones and Obitts (1970). Values of foF2 are obtained for any month, universal time, and sunspot number. The height of the F2 region maximum density is determined using the relationship developed by Bradley and Dudeney (1973). The semi-thickness of the F2 region is determined by subtracting the value of the F region virtual height from the value of the F2 region maximum height. The value of the F region virtual height is determined from the coefficients also given in Report 340 (CCIR, 1978a).

2.2 Changes to Median Parameters

Values of foE, foF1, and foF2 scaled from ionograms (or available from any other source) can be used to adjust the median values of the critical frequencies. Simple additions or subtractions to the median data fields can be made in order to minimize the difference between monthly median values and the observed values. In addition, changes to the maximum heights and semi-thickness can be made if there are data to warrant such changes.

2.3 Specific Features in the Polar Model

There are a number of features in the polar ionosphere that characterize it and distinguish it from other regions of the ionosphere. It is the characterization of these features that formed the major efforts undertaken in developing the Polar Ionospheric Model. Many, if not all, of the features of the polar ionosphere can be specified in terms of specific shapes or ovals. The auroral oval as characterized by Feldstein and Starkov (1967) is used in this model to set the principal features of the polar ionosphere. Specific values of oval position can be obtained from the World Data Center A or using the document given by Whalen (1970) relating oval position to appropriate magnetic activity index.

2.3.1 The F2 Region Trough

A trough of ionization is assumed to exist during nighttime hours immediately equatorward of the auroral oval. The poleward boundary of the trough is taken to coincide with the equatorward boundary of the oval. The location of the equatorward boundary and the depth of the trough can be varied so that the values of foF2 in the trough and the latitudinal extent of the trough can be made to agree with available observations. The trough is confined to the local times between sunset and sunrise.

2.3.2 The Auroral E Region

The model of the auroral E region follows closely the work of Gassman (1973) and Tascione et al. (1979) who combine Gassman (1973), Vondrak et al. (1977), and original Air Force Global Weather Central (AFGWC) results. The critical frequency of the auroral E region, foEa, is determined in terms of a maximum value of the critical frequency, $foEa_{max}$, according to a magnetic index, Q, which is related to the planetary magnetic index, Kp (Tascione et al., 1979). The Q index not only specifies the maximum value of foEa, it also specifies the location of the boundaries of the auroral E region. Observations of foEa obtained from vertical incidence sounding data can be used to corroborate the values and locations of the foEa determined from the model. Since the model of foEa is specified in terms of Q only, any large differences between model and observation are minimized by using a value of Q in the model that yields results agreeing with observation. In other words, the value of Q is adjusted in order that the foEa model yields results that agree with observation. In the absence of any vertical incidence data, the appropriate values of Q such as provided by the World Data Center A can be used to derive the auroral E region model. A given value of Q specifies the location of the auroral E region which is tied to the location of the auroral oval.

The formulation for the auroral E region is given as follows:

The maximum value of foEa designated as $foEa_{max}$ is written

$$foEa_{max} = 2.5 + \frac{Q}{9} \quad \text{for} \quad 0 < Q \leq 2.7, \quad \text{and}$$
$$= \frac{7}{5} Q - 1 \quad \text{for} \quad 2.7 < Q \leq 4.2, \text{ and} \qquad (3)$$
$$= 5 \quad \text{for} \quad Q > 4.2 \quad .$$

The latitude at which $foEa_{max}$ occurs is designated as ϕ_m and is determined by

$$\phi_m = \phi_E \quad \text{for} \quad Q \geq 3.0, \quad \text{and}$$
$$= \phi_E + 1 \quad \text{for} \quad Q < 3.0 \qquad (4)$$

where ϕ_E is the equatorward boundary of the auroral oval. If $\phi_m = \phi_E (Q \geq 3.0)$, there are no values of foEa equatorward of ϕ_m. If $\phi_m = \phi_E + 1$, the value of foEa one degree equatorward of ϕ_m is taken as 0.6 $foEa_{max}$.

The value of foEa at any latitude of ϕ_A poleward of ϕ_m is given by

$$foEa = foEa_{max} - \frac{.4\ foEa_{max}}{[\phi_n - \phi_m]} \quad [\phi_A - \phi_m] \qquad (5)$$

where ϕ_n is the latitude of the poleward boundary of the auroral E region equal to $(\phi_p + \phi_E)/2$, with ϕ_p being the latitude of the poleward boundary of the auroral oval.

The height of the auroral E region maximum ionization, $hmEa_{max}$, is given by:

$$hmEa_{max} = 185 - [foEa_{max} - 2] \times 35 \ , \ 2.5 < foEa_{max} \leq 3.5$$
$$= 145 - [foEa_{max} - 3] \times 10 \qquad (6)$$

The value of height of the auroral E region, hmEa, at any latitude ϕ_A (greater than ϕ_m) is given by

$$hmEa = hmEa_{max} + \frac{10[\phi_A - \phi_m]}{[\phi_p - \phi_m]} \quad \text{for} \quad Q \geq 3.0 \quad ,$$
$$= hmEa_{max} + 10 \quad \text{for} \quad Q < 3.0 \quad . \qquad (7)$$

The value of the semi-thickness of the auroral E region, YmEa, is given by

$$YmEa = hmEa/3 \quad . \tag{8}$$

The E region electron density is determined by the procedures given in Section 2.1.1 if foE $\geq$ foEa and by the procedures outlined above if foEa > foE.

2.3.3 Auroral Absorption Indicator

The auroral absorption indicator is derived from the indicator in Supplement to Report 252-2 (CCIR, 1978b). A median value of auroral absorption, A_M, is sought that is used in the manner described in the Supplement to Report 252-2. A parameter A_1 is defined that is the percentage probability that the absorption measured on a 30 MHz riometer exceeds 1 dB. The following equations, that relate to those contained in the Supplement to Report 252-2, are then obtained:

$$A_1 = A_{1d} \cdot A_{1S} \tag{9}$$

$$A_{1d} = 21 \cdot d_\phi \cdot d_T \cdot d_R \cdot d_\theta \cdot d_m \tag{10}$$

$$A_{1S} = 12 \cdot S_\phi \cdot S_T \cdot S_R \cdot S_\theta \cdot S_m \tag{11}$$

(1) where d_ϕ is a continuous function of latitude defined such that

degrees from oval midpoint	0	±1	±2	±3	±4	±5
d_ϕ	1	.96	.84	.65	.50	.30

(2) d_T is a continuous function of longitude defined such that

UT-θ/15	0	1	2	3	4	5	6	7-21	22	23
d_T	.78	.94	1	.94	.78	.56	.34	.2	.34	.56

where UT = Universal Time and θ = Longitude of the location for which the auroral absorption indicator is being determined.

(3) $d_\theta = 0.58 + 0.42 \sin [0.947(\theta - 85)]$

(4) $d_R = 1 + 0.014 \bar{R}$ is monthly average sunspot number

(5) d_m is a function of season and its value changes with month:

d_m	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Month	Jun	Jul May	Aug April	Mar Sept	Oct Feb	Nov Jan	Dec

(6) $S_\phi = d_\phi$,

(7) $S_T = d_T$,

(8) $S_\theta = d_\theta$,

(9) $S_R = 1 + 0.009 \bar{R}$,

(10) $S_m = 1$.

A_M is defined as

$$A_M = \left[\frac{A_1 + 30}{80}\right]^{1.54} \qquad \text{for} \quad A_1 > 1 \ ,$$
$$A_M = \left[0.23 A_1\right]^{0.2} \qquad \text{for} \quad A_1 < 1 \ . \qquad (12)$$

The auroral absorption indicator given above is only applicable to the longitudes 0.5°W to 120.5°W.

2.3.4 Regular Absorption Indicator

The regular absorption indicator is derived from that used in the HF propagation prediction program IONCAP (J. Lloyd, private communication, 1981). It is provided in a format that is readily amenable for use in raytracing simulations of the performance of HF propagation systems. The equations used are those that are consistent with the assumption that the radio wave is reflected from the F region. Two separate equations are used, one for daytime conditions when the E region critical frequency, foE, is greater than 0.3 MHz and one for nighttime conditions when foE is less than 0.3 MHz. If A_R is defined as the regular absorption component, then

$$A_R = 677.2\ [-0.04 + \exp(-2.937 + 0.8445\ foE)] \quad \text{for } foE > 0.3 \text{ MHz} \qquad (13)$$

$$A_R = 1 + 0.015\ \overline{R} \quad \text{for } foE \leq 0.3 \text{ MHz}. \qquad (14)$$

To use equation (13) to determine the absorption for a specific HF radio wave, A_R must be multiplied by sec α and divided by $[(f_{ob} + f_L)^2 + 10.2]$ where α is the angle of incidence of the radio wave at 100 km, f_{ob} is the frequency of the radio wave in MHz and f_L is the electron gyrofrequency in MHz at 100 km.

To use equation (14) to determine the absorption for a given HF radio wave, A_R must be multiplied by [7 + 0.02 D] and divided by $[f_{ob}^2 + 10]$, where D is the range of the radio wave in km and f_{ob} is the radio wave frequency in MHz.

2.3.5 E Region Irregularity Indicator

The E region irregularity indicator is based on the work of Gassman (1973) and Tascione et al., (1979). The E region irregularity model is defined only for locations within the auroral oval, i.e., between ϕ_p and ϕ_E. The E region irregularity indicator is given by the product XYZ.

The number X is determined from the integer part of the relationship

$$X = \frac{foEa - foE + fEs}{2} \quad ; \text{ if } X < 0, \text{ define } X = 1\ . \qquad (15)$$

The value of foEa is determined from the auroral E region model described in paragraph 2.3.2 and fEs is defined as

$$fEs = 2 + \frac{Q}{3} \quad \text{for} \quad Q \leq 6\ ,$$
$$= 6 \quad \text{for} \quad Q > 6\ . \qquad (16)$$

Y and Z are proportional to the height of foEa and fEs. The height of foEa is determined in the auroral E model (see Section 2.3.2). The height of the fEs is given by h = 155 - 6.2 fEs. The digits for Y and Z are determined according to the heights of foEa and fEs with Y referring to the height of foEa and Z referring to the height of fEs. Table 1 provides a listing of the height intervals corresponding to Y and Z.

Table 1. Values of the Parameters Y or Z for Specific Height Intervals in the E Region Irregularity Model.

HEIGHT INTERVAL (KM)	VALUE OF Y OR Z
100 - 109	0
110 - 119	1
120 - 129	2
130 - 139	3
140 - 149	4
150 - 159	5
160 - 169	6
170 - 179	7
180 - 189	8

2.3.6 F Region Irregularity Indicator

The F region irregularity indicator is modeled in accord with the description provided in Elkins (1980). The F region irregularity model contains two separate geographic representations that depend upon whether the location in question is in daylight or in nighttime. Between sunrise and sunset, the F region irregularity zone exists between the poleward boundary of the oval ϕ_p and 3 degrees further poleward of the oval. The value of the index is simply Q. Between sunset and sunrise the F region irregularity zone is tied to the F2 region trough. The zone exists from one degree poleward of the poleward trough boundary (which is the same as the equatorward oval boundary) to 3 degrees equatorward of the equatorward trough boundary. The value of the index is specified as the product of the depth of the trough and the Q index wherever the F region irregularity zone is defined. The index goes to one (1) if it already is not the number one at the location 1 degree poleward of the oval and at the location 3 degrees equatorward of the trough.

2.4 Example of Polar Ionospheric Model Parameters

Figures 1 through 10 provide an example of maps of various ionospheric parameters obtained from the Polar Ionospheric Model. The maps illustrate the polar ionospheric structure on January 20, 1981, at a Universal Time of 2300 hours. The parameters shown in the figures were obtained using the relationships given in the previous sections along with ionospheric data observed at St. John's, Newfoundland;

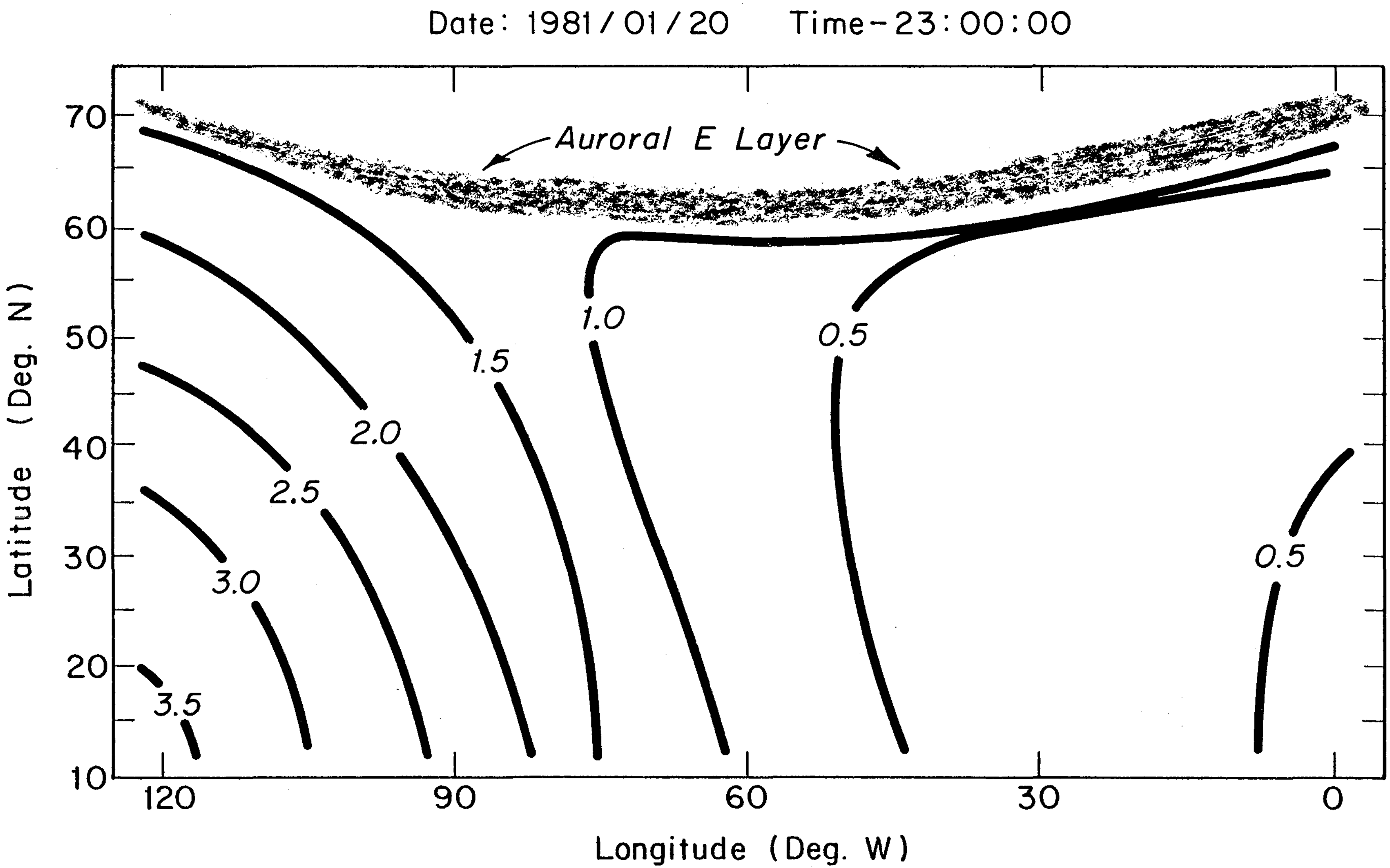

Figure 1. Contours of foE (in MHz) for January 20, 1981, at 2300 UT.

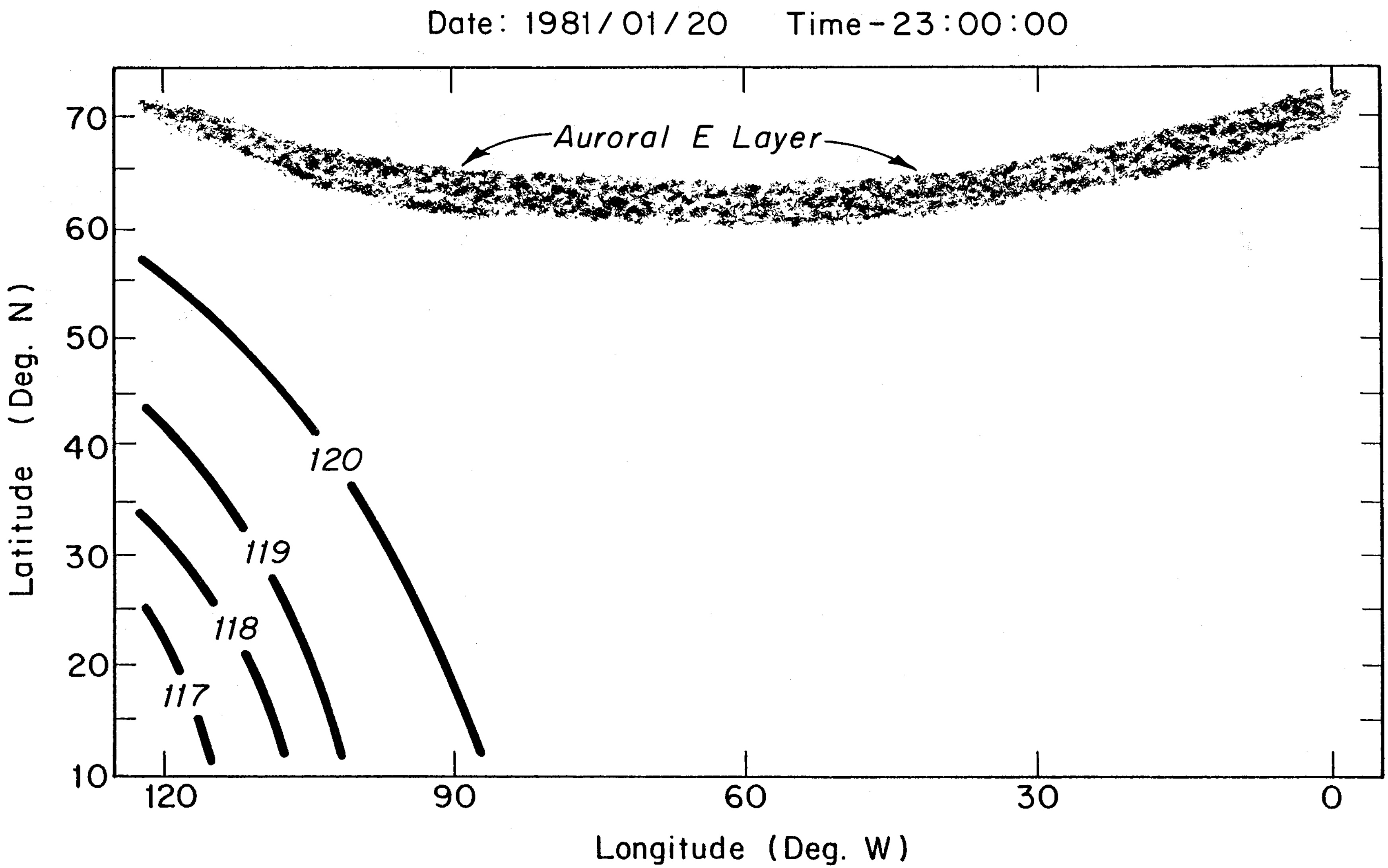

Figure 2. Contours of hmE (in km) for January 20, 1981, at 2300 UT.

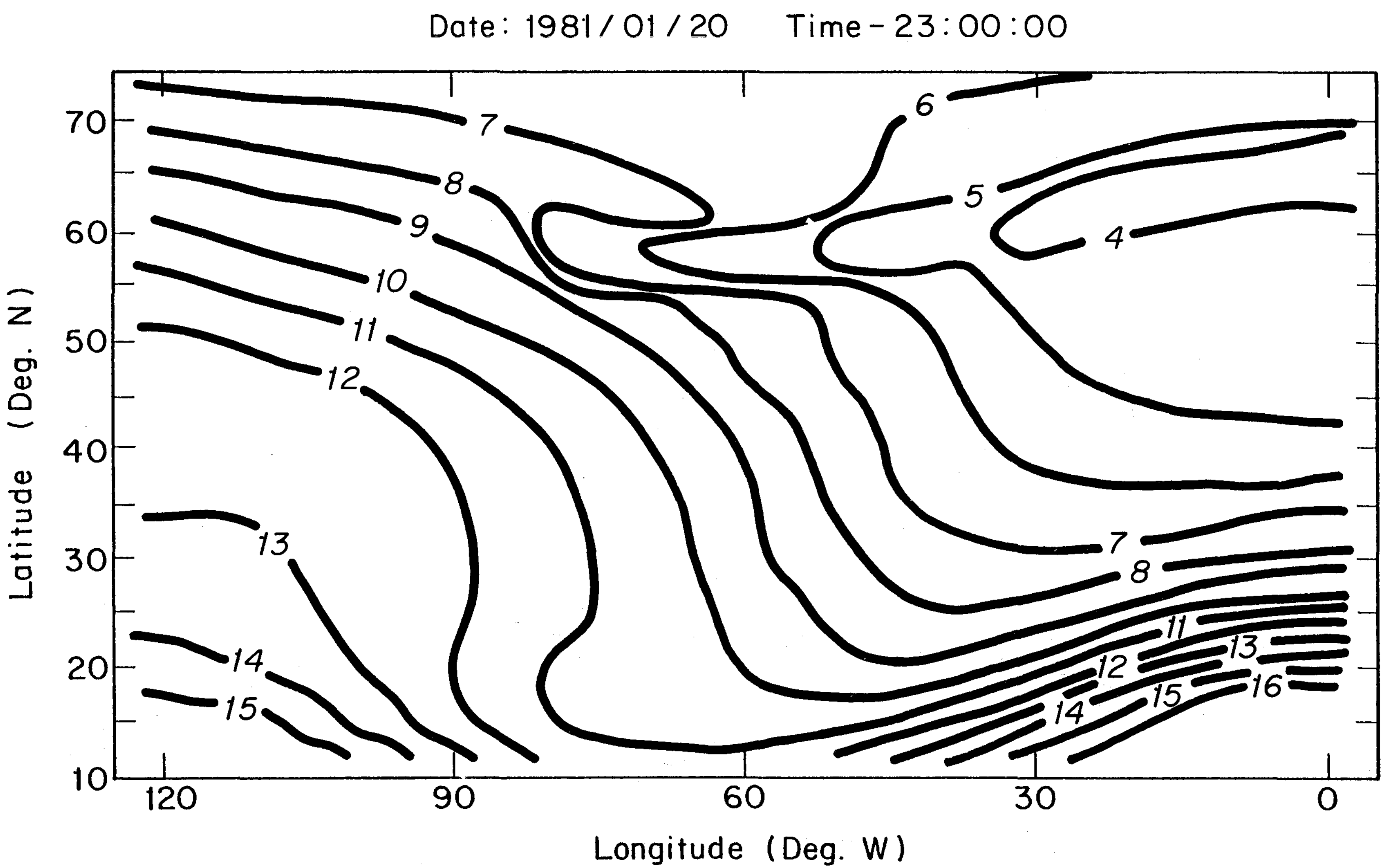

Figure 3. Contours of foF2 (in MHz) for January 20, 1981, at 2300 UT.

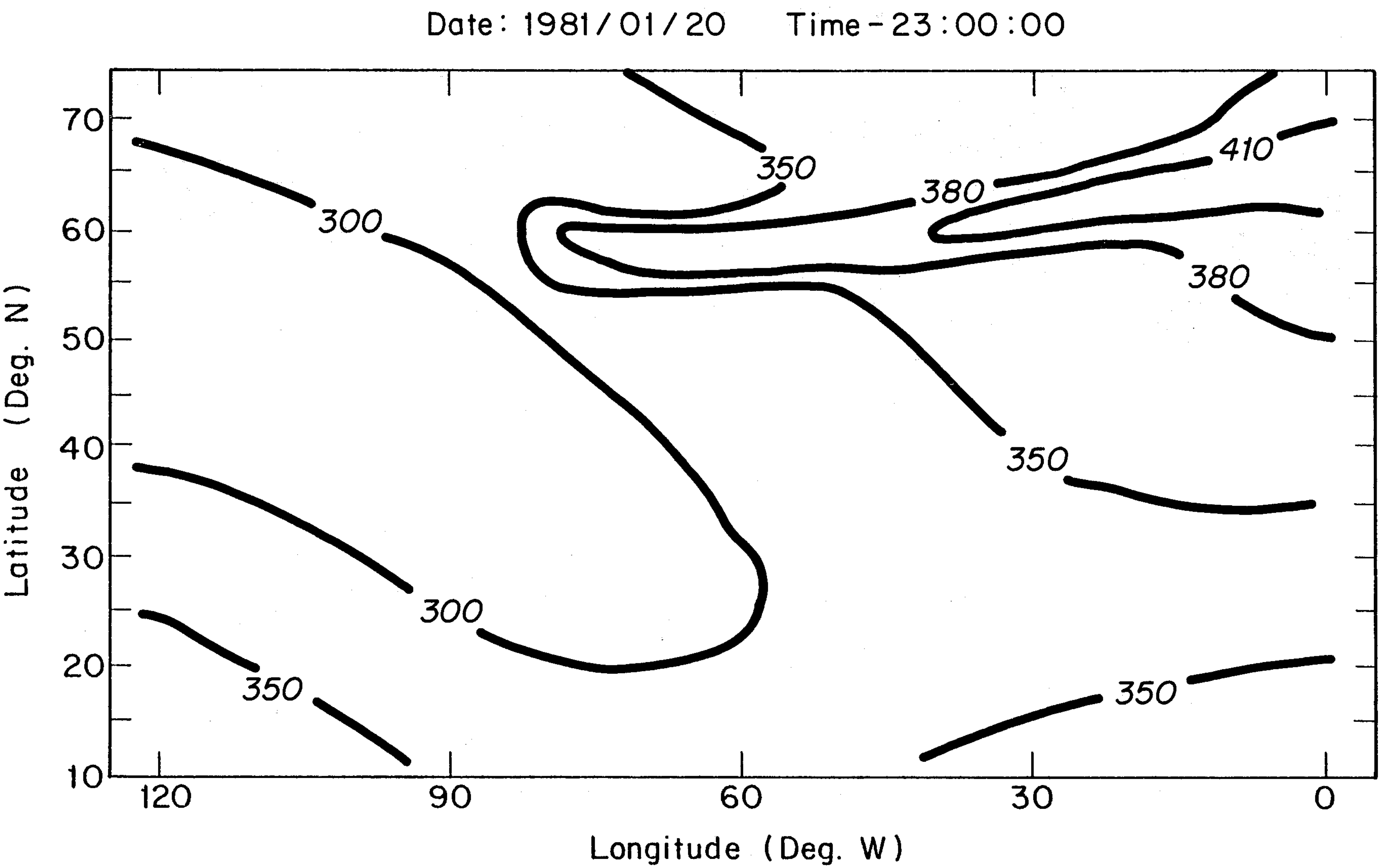

Figure 4. Contours of hmF2 (in km) for January 20, 1981, at 2300 UT.

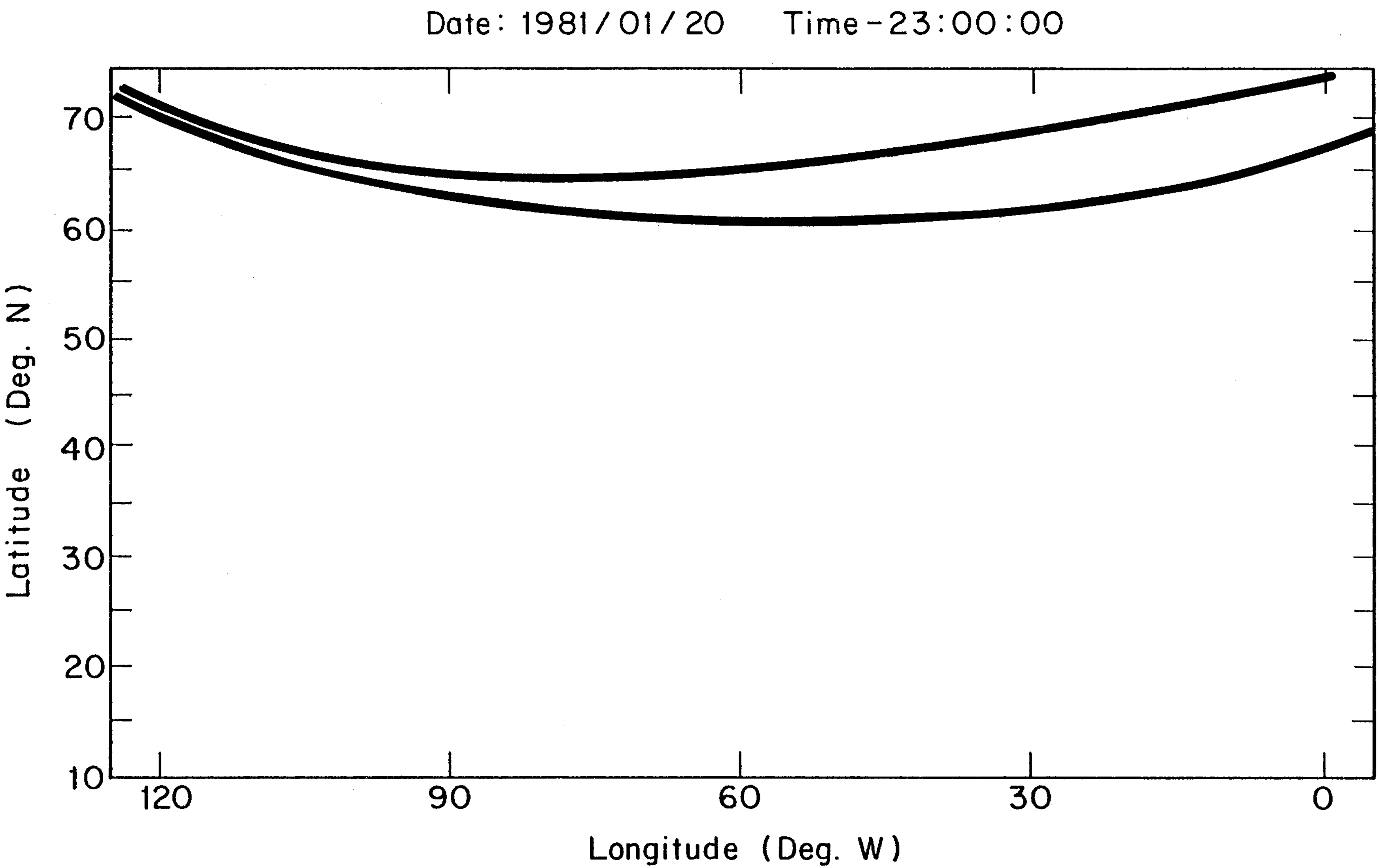

Figure 5. Location of the auroral oval determined from satellite particle data for January 20, 1981, at 2300 UT.

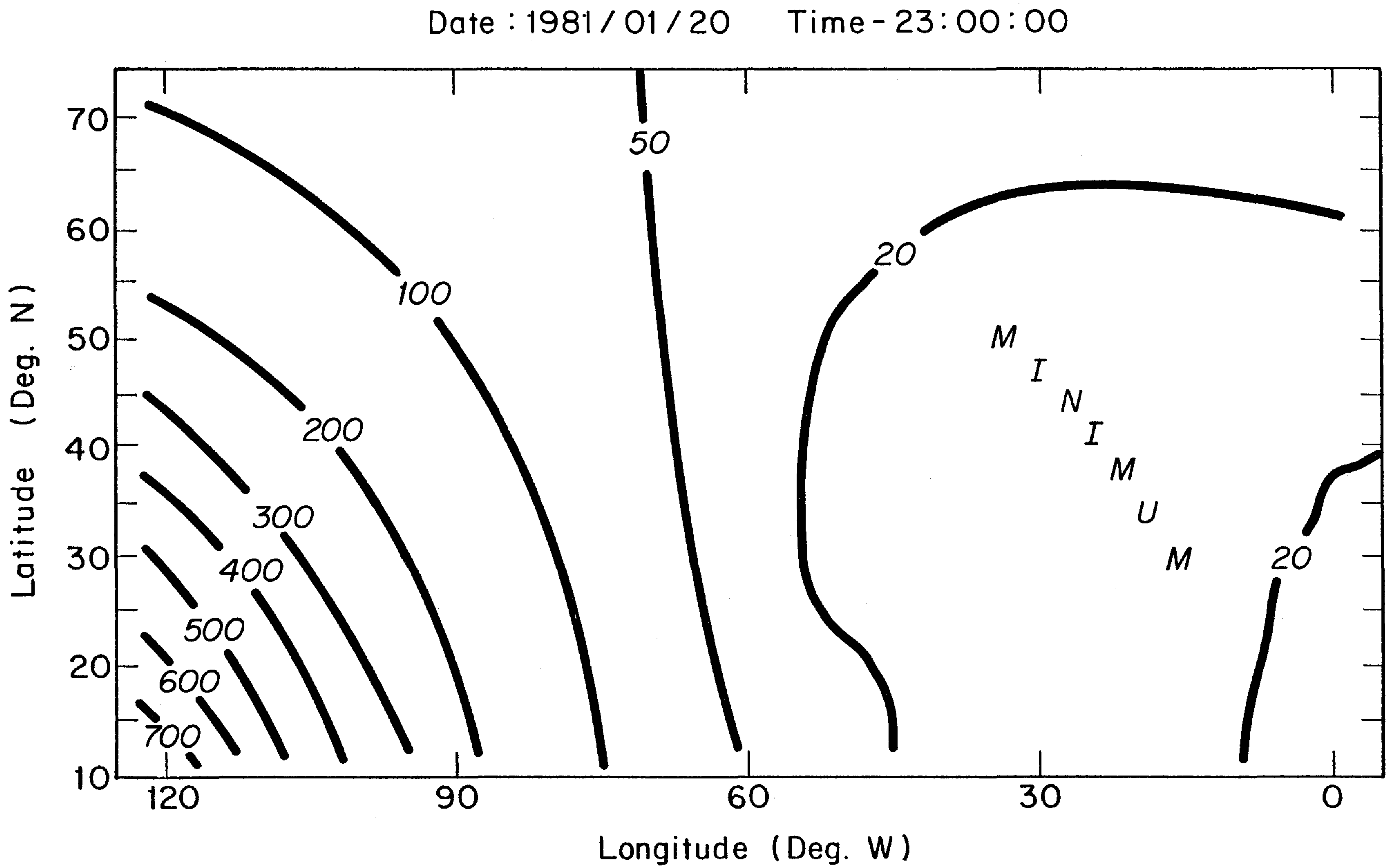

Figure 6. Contours of the regular absorption component deduced from equations (6) and (7) for January 20, 1981, at 2300 UT.

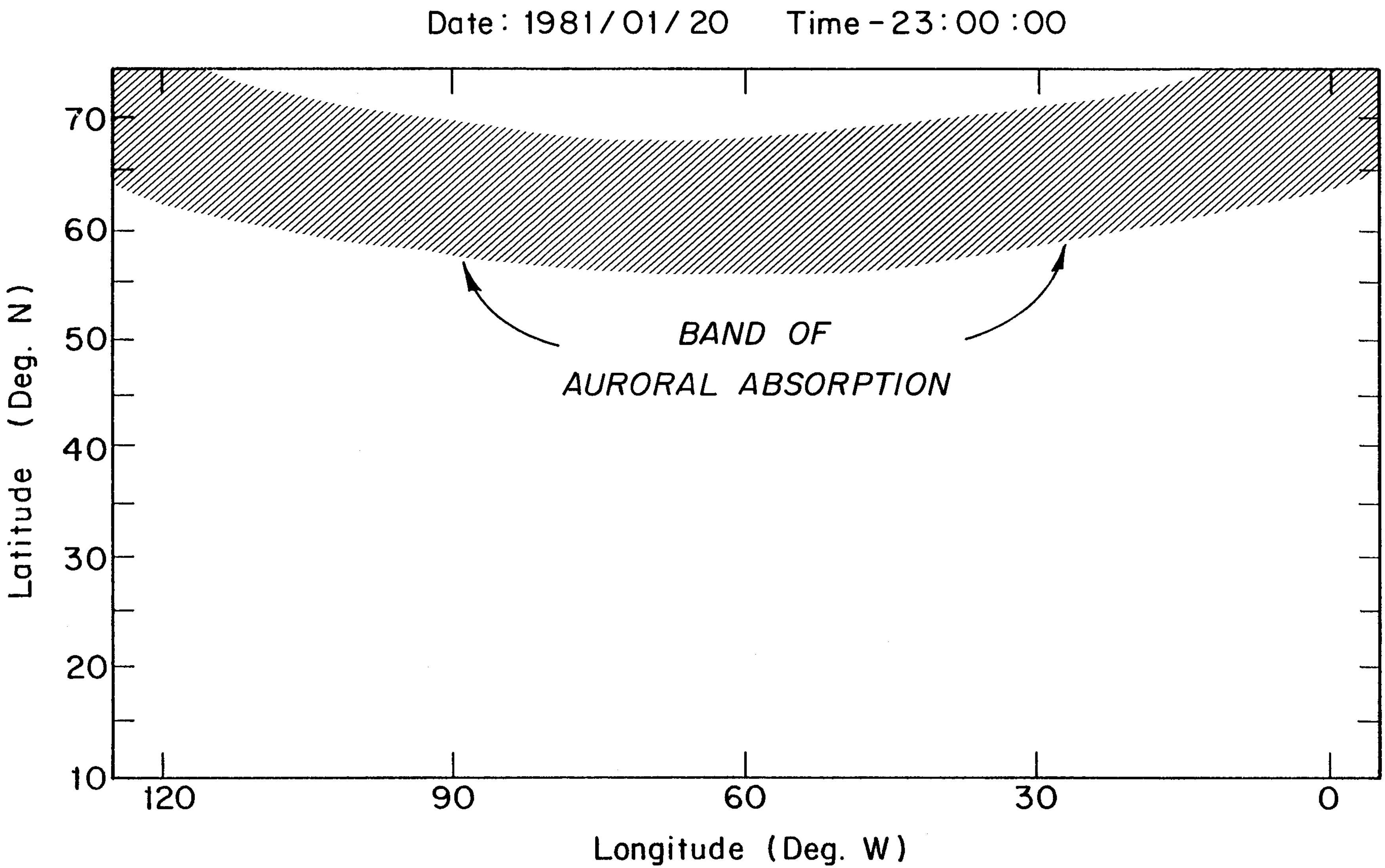

Figure 7. Location of the region of auroral absorption determined from the model described in Section 2.3.3 for January 20, 1981, at 2300 UT.

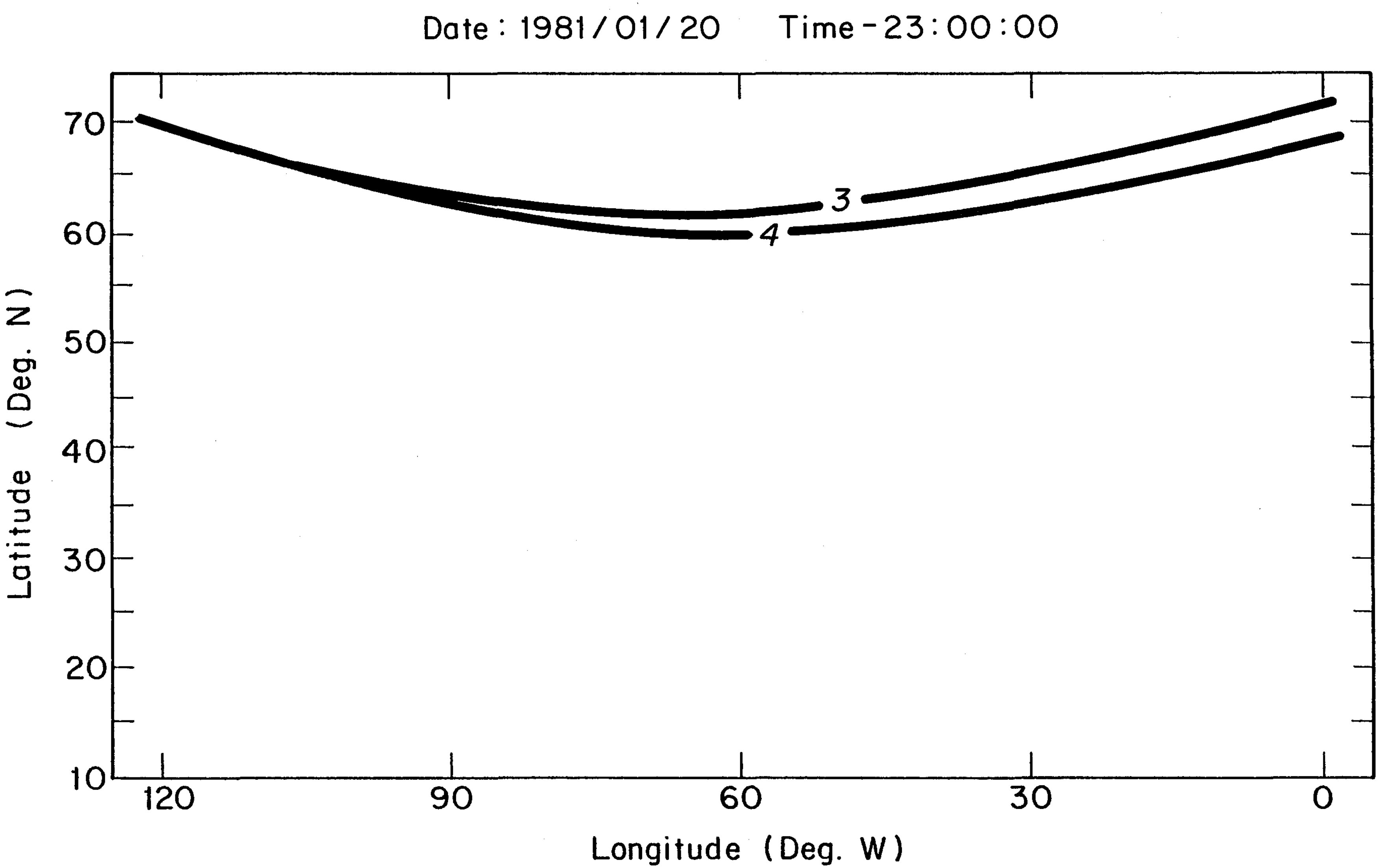

Figure 8. Location of the E region irregularity indices for January 20, 1981, at 2300 UT.

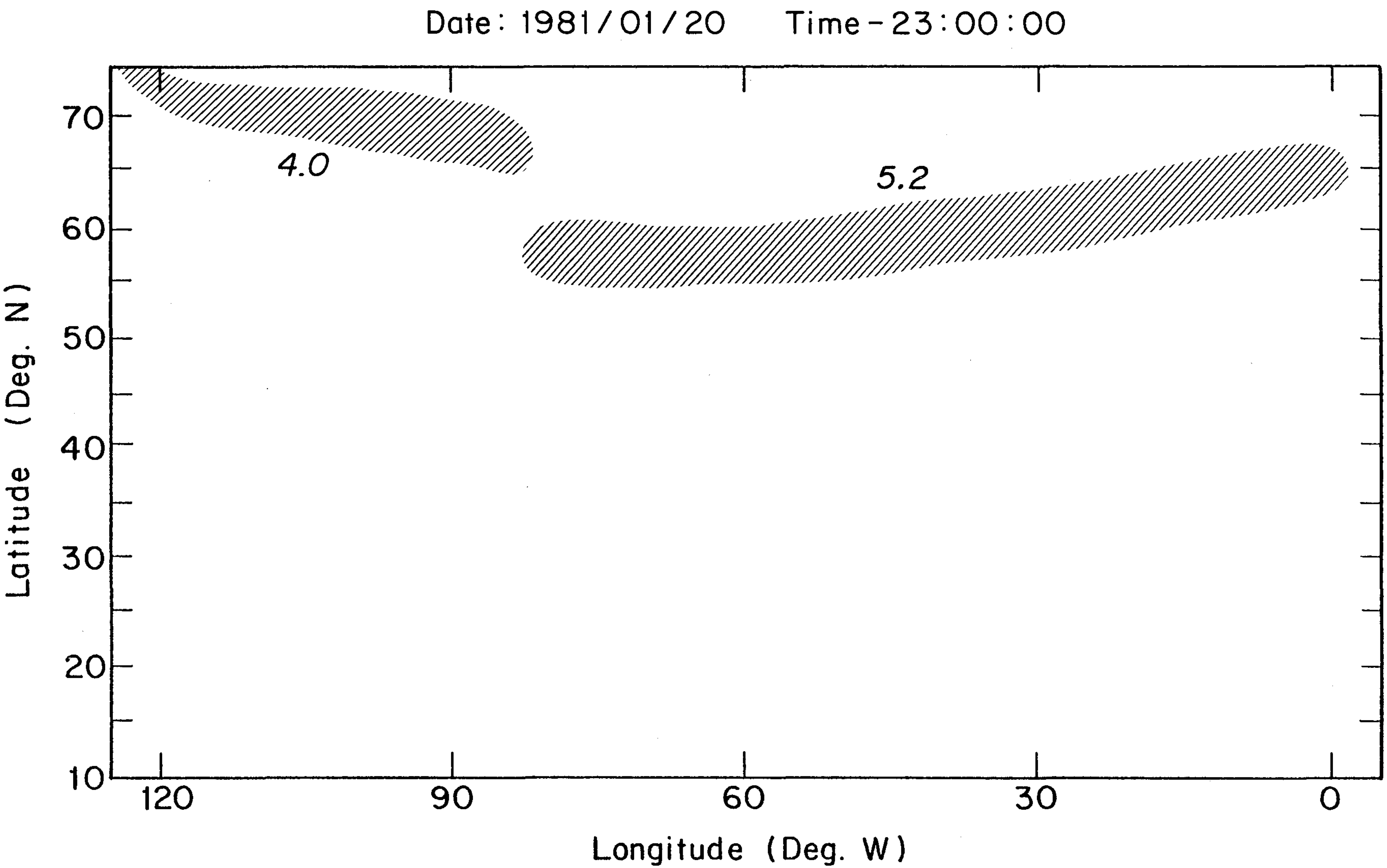

Figure 9. Location of the F region irregularity indices for January 20, 1981, at 2300 UT.

Ottawa, Canada; Goose Bay, Labrador; Narssarssuaq, Greenland; and Godhavn, Greenland. In all the figures illustrated here, the parameters are mapped on a geographic latitude and longitude grid.

Figure 1 provides an indication of the E region critical frequency foE and the location of the auroral E layer at 2300 hours UT on January 20. It can be seen that at the eastern half of the grid, foE is rather low, being indicative of nighttime conditions. The auroral E layer illustrated by a band at high latitudes had a maximum value of 5.4 MHz.

Figure 2 shows the height of the E layer critical frequency, hmE, and the location of the auroral E layer. It is seen that this height is relatively constant throughout the entire grid. In the vicinity of the auroral E layer, the height changes abruptly according to equations (6) and (7). The semi-thickness of the E region (not shown) displays the same behavior as the height of the critical frequency since it is defined by hmE divided by 5.5.

The Fl layer displays little, if any, structure of consequence during this time period and is not illustrated. The F2 region, on the other hand, displays substantial variation as can be seen in Figure 3. The F2 region trough in ionization is clearly evident at the higher latitudes between 0.5°W and 60.0°W. At longitudes further to the west, the sun illuminates the latitudes where the trough would occur. The height of the F2 maximum ionization, hmF2, is shown in Figure 4. The Polar Ionospheric Model increases the height of the F region maximum in the vicinity of the F2 region trough by 50 kilometers above the height in the absence of the trough. This is clearly discernible in Figure 4. The heights above 30 degrees latitude outside of the F2 region trough are higher on the eastern half of the grid than on the western half. This agrees with observation that at middle and high latitudes, the height of the F2 maximum reaches its largest value in the night hours.

Figure 5 illustrate the position of auroral oval deduced from satellite data by H. Kroehl (private communication, 1981). The equatorward boundary of the oval also corresponds in the Polar Ionospheric Model to the poleward boundary of the F2 region trough. In the example shown in Figures 3 and 4 of foF2 and hmF2, the trough was five (5) degrees wide at the longitudes it existed.

Figure 6 shows normal absorption index deduced using the relationships in Section 2.3.4. The normal diurnal variation of the absorption is clearly evident with the values of the index being much larger on the western half of the grid which is in sunlight than on the darkened eastern half.

Figure 7 provides an illustration of the location of auroral absorption that is valid for 2300 hours UT on January 20, 1981. This absorption is dependent upon the location of the auroral oval, but it is obvious that the contribution to the auroral absorption extends in latitude beyond the boundaries of the oval. This can be deduced from the relationships given in Section 2.3.3, but is more obvious in Figure 7.

Figures 8 and 9 provide examples of the E (Figure 8) and F region (Figure 9) irregularity indices. The values of the index for the E region irregularity model varies between 3 and 4 across the grid at this time. The height of foEa and fEs which are assumed to contribute to the formation of the E region irregularities is between 120 to 129 km throughout the entire grid. The F region irregularity model (shown in Figure 9) provides two distinct ranges of values depending upon whether the point in question is in darkness or light. Values of the F region irregularity index at sunlight locations in Figure 9 are given as 4.00 (corresponding to the value of Q for 2300 UT on 20 January) and as 5.20 at the locations in darkness (corresponding to the product of Q and the depth of the F2 region trough).

The parameters given in Figures 1 through 9 provide an illustration of the respective latitudinal and longitudinal variation at 2300 hours UT on January 20, 1981. In order to use the model for system design or system performance studies, it is necessary that the vertical structure of the polar ionosphere be specified in addition to the horizontal structure as given in Figure 1 through 9. The Polar Ionospheric Model as currently constructed does not provide vertical profiles of electron density. However, such profiles can be readily constructed by assuming that the vertical structure of E, F1 or F2 regions can be cast in terms of a specific formulation such as a parabola, hyperbolic secant, Chapman function, exponential, etc. Values of the critical frequency, height of maximum electron density and semi-thickness, are given in the model and are all that is required to yield vertical profiles, once the form of the vertical variation is decided upon.

3. INVESTIGATION OF THE PERFORMANCE OF HIGH LATITUDE HF BROADCAST CIRCUITS

Although the Polar Ionospheric Model was developed principally to aid in determining the performance characteristics of the OTH-B radar operated by the United States Air Force, the model has applicability to other HF telecommunication systems. It can be used to simulate the performance of any telecommunication system that relies upon the propagation of electromagnetic energy within and/or through the ionosphere.

Commensurate with the development of the Polar Ionospheric Model, the Institute for Telecommunication Sciences has been involved in studies to support the activities of the United States in preparation for the HF Broadcasting World Administrative Radio Conference scheduled to begin in 1984. Some of these studies have taken the form of assessing the best frequencies that are needed to assure a given level of signal quality to a broadcast area. The studies have been undertaken using the HF propagation prediction methods given in programs such as IONCAP (J. Lloyd, private communication, 1981). The programs do not contain many of the features in the Polar Ionospheric Model and the results obtained from such programs when applied to the high latitudes may be suspect. In order to ameliorate this situation somewhat, a few of the features of the Polar Ionospheric Model were incorporated into the HF prediction program IONCAP. In particular, the F2 region ionization trough and the enhanced E region ionization that results from the auroral E layer were incorporated into the IONCAP program. These features can be specified independently of any requirements constraining the IONCAP program. Comparing the results of circuit simulations resulting from the IONCAP program with and without the polar ionosphere features permits a convenient means to assess the impact of the structure of the polar ionosphere upon HF propagation system performance.

As an example of how the Polar Ionospheric Model can be used to determine the performance of a high latitude HF broadcast circuit, it was assumed that a fictitious broadcast transmitter was located at 50° north and 75° west. It was further assumed that the transmitter power was 100 kW and that the transmit antenna radiated in all directions with a constant gain of 0 dB. The F2 region ionization trough and the auroral E layer enhancement applicable to January 20, 1981, at 2300 hours UT, illustrated in Figures 1 and 3, were incorporated into the IONCAP program. A number of broadcast circuits were simulated spanning in azimuth from due north of the transmitter (0° azimuth) to 30° south of east of the transmitter (120° azimuth) in 20 degree increments for ranges of 2000, 3000, and 5000 km. For comparisons, the same circuits were simulated using the IONCAP program without the features of the Polar Ionospheric Model included. The simulations were performed to determine the maximum usable frequency (MUF) for each circuit as well as the signal characteristics for frequencies operating at 6.0, 10.0, 14.0 16.0, 18.0, 20.0, and 22.0 MHz. These frequencies were indicative of the range of frequencies typically used for HF broadcasting purposes, although not directly allocated to the broadcasting services.

Tables 2 and 3 provide summary of the results obtained from this simulation study. It was found that only for azimuths of 20° and 40° east of north did the circuits intersect a portion of the ionosphere that included features of the Polar Ionospheric Model and for this reason comparisons are limited to these two azimuths. Table 2 provides summary information of the mode, the take-off angle, and the median field strength at the receiver in dB above 1 microvolt per meter (dBu) for the maximum usable frequency at the two azimuths for both the case of no polar features (designated in the Table as "Normal") and for the case of polar features included in the IONCAP simulation (designated in the Table as "Polar"). Table 3 provides similar information for the frequencies of 10 MHz and 14 MHz.

The only circuits that intersect the enhanced E layer or the auroral E layer, are the 2000 km and 3000 km circuits directed at a 20° azimuth. It is clear from Table 2 that the MUF for the 2000 km circuit is enhanced relative to the simulation done under normal conditions. An E layer mode determines the MUF and the field strength for the mode is less than 10 dBu. Table 3 illustrates that the 10 MHz signal for the 3000 km circuit is also affected by the auroral E layer. This is seen by the fact that 10 MHz is propagated via a 2-hop E mode at 20° azimuth when the polar ionospheric features are included in the simulation.

The 2000 km, 40° azimuth circuit, the 3000 km 20° and 40° azimuth circuit, and the 5000 km, 40° azimuth circuit all show decreased MUF's (Table 2) for the case of the simulation incorporating the polar ionospheric features. All of these circuits have encountered the F2 region ionization trough. The decreased value of foF2 coupled with the increased height of the maximum of the F2 region that is indicative of the trough, lead to decreases in the MUF compared to the undisturbed (or normal) ionosphere. The behavior of the 10 MHz and 14 MHz signals for the same circuits is not as obvious as for the MUF (Table 3 compared to Table 2). However, the field strength for many of the circuits is much less for the case of the polar features compared to the normal IONCAP ionospheric structure.

The decreases in the maximum usable frequency that result from the inclusion of the F2 region ionization trough are particularly important regarding broadcasting operations. A decrease in the MUF results in a decreased number of frequencies available for broadcasting operations. Since the trough is a semi-permanent feature

Table 2. Values of the Mode, Take-off Angle, and Field Strength at the MUF for 2000, 3000, and 5000 km Circuits

		2000 km		3000 km		5000 km	
	AZIMUTH	NORMAL	POLAR	NORMAL	POLAR	NORMAL	POLAR
MUF (MHz)	20°	16.5	19.0	18.4	15.3	13.5	13.8
	40°	16.2	12.9	17.7	13.9	13.7	10.5
MODE	20°	1F2	1E	1F2	1F2	2F2	1F2
	40°	1F2	1F2	1F2	1F2	2F2	1F2
TAKE-OFF ANGLE (°)	20°	15.8	2.6	9.9	11.4	13.5	2.7
	40°	15.9	16.0	10.0	11.0	13.7	2.5
FIELD STRENGTH (dB above 1 μV per meter)	20°	43	6	29	21	17	2
	40°	44	43	29	25	19	7

Table 3. Values of the Mode, Take-off Angle, and Field Strength at 10 and 14 MHz for 2000, 3000, and 5000 km Circuits

		2000 km		3000 km		5000 km	
	AZIMUTH	NORMAL	POLAR	NORMAL	POLAR	NORMAL	POLAR
10 MHz							
MODE	20°	1F2	1F2	2F2	2E	2F2	2F2
	40°	1F2	1F2	2F2	1F2	2F2	2F2
TAKE-OFF ANGLE (°)	20°	11.4	19.5	18.3	4.1	8.4	13.5
	40°	10.9	11.8	18.6	12.6	9.9	16.0
FIELD STRENGTH (dB above 1 μV per meter)	20°	38	29	33	-14	20	-5
	40°	41	41	37	23	21	-10
14 MHz							
MODE	20°	1F2	1F2	1F2	1F2	2F2	1E
	40°	1F2	1F2	1F2	1F2	2F2	--
TAKE-OFF ANGLE (°)	20°	12.2	20.2	4.5	9.9	14.9	2.2
	40°	10.9	18.5	4.7	11.0	15.0	0.0
FIELD STRENGTH (dB above 1 μV per meter)	20°	41	29	31	24	0	-29
	40°	42	34	32	25	-20	---

4. SUMMARY AND CONCLUSIONS

A model of the parameters that specify the structure of the high latitude ionosphere has been developed. The model uses as a basis the numerical coefficients given in Report 340 of the CCIR (CCIR, 1978a). These coefficients provide monthly median values of various ionospheric parameters such as the critical frequencies of the E, F1, and F2 regions. The median specification of the high latitude ionosphere is modified by incorporating into the model specific features that characterize the high latitude ionosphere. Foremost amongst these features is the auroral oval. The auroral oval serves as an anchor-point for all other features included in the model.

With the auroral oval specified in terms of latitude, longitude, and magnetic activity, other high-latitude phenomena are then defined. The F2 region trough in ionization is placed immediately south of the oval and its depth and width can be varied independently. The trough is defined in the model only between the hours of sunset and sunrise. The excess ionization in the E region due to auroral activity is combined with the background E region ionization to form the auroral E layer. It, too, is tied directly to the position of the auroral oval. Methods for determining indices of E and F region irregularity intensity have also been developed as have techniques to calculate the loss of signal strength due to normal absorption and auroral absorption processes.

The model has been used in conjunction with ionospheric data and satellite observations to specify the structure of the ionosphere on numerous occasions when the Over-the-Horizon Backscatter (OTH-B) radar was operating in the 1980-1981 period. These specified ionospheric structures are used to determine performance characteristics of the OTH-B. In addition to the actual specified ionospheric structures, the effort undertaken to support OTH-B activities has provided scaled magnetometer data and specialized studies addressing detailed aspects of OTH-B operation.

The model of the high latitude ionosphere described herein has been used to modify portions of the HF propagation prediction program, IONCAP (John Lloyd, private communication, 1981). This program has been used to illustrate the performance of a HF broadcasting service operating with radio signals passing into the high latitude ionosphere. The results obtained using the version of IONCAP modified to include selected high latitude features were compared with the results obtained from the version of IONCAP that does not contain explicit high-latitude features. It was seen that for the scenario illustrated the maximum usable frequency on a few of the circuits was decreased and the signal strength of many of the frequencies was changed for signals passing through the auroral E layer and the F2 region trough. Techniques that are being used to determine criteria for planning the use of the HF broadcasting service may not yield accurate results unless the techniques used include a realistic specification of the high latitude ionosphere.

It is obvious from the discussion presented in this report that the model of the high latitude ionosphere that has been developed requires further improvement. It would be desirable to establish a relationship between the depth and width of the F2 region ionization trough and magnetic activity. Likewise, the auroral E layer model should be improved to account for a more realistic dependence on magnetic activity than has been used in this study. The auroral absorption model certainly needs to be studied, from the perspective of both the physical assumptions underlying its development as well as the actual data used to corroborate models. The E and F region irregularity models need to be further quantified before they can be used in support of detailed operational applications.

While it is desirable that the studies mentioned above be undertaken, it is not likely that real progress can be made unless companion studies of the interrelationships between magnetospheric and polar ionospheric physical processes are undertaken. The understanding of the mechanisms whereby magnetospheric phenomena are eventually manifested into the polar ionospheric structure will provide not only an improved specification of the high latitude ionosphere but also a real potential to predict the structure of the ionosphere at high latitudes.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*
A model of the parameters that specify the structure of the electron density in the polar ionosphere has been developed. The model is based upon the modification of monthly median ionospheric parameters given by the CCIR by use of formulations that characterize specific features of the high latitude ionosphere. In addition to the critical frequency, height of maximum electron density and semi-thickness of the E, F1, and F2 regions, the model accounts for high latitude features such as the auroral oval, the F2 region ionization trough, the ionization due to auroral E layer formation, auroral absorption, and electron density irregularities in the D and F regions of the polar ionosphere. Observations of ionospheric and geophysical parameters can also be used to modify the structure of the ionosphere as given by the model. The use of the model for telecommunication purposes is illustrated by application of the model to a high latitude high frequency broadcasting operation.

16. Key Words *(Alphabetical order, separated by semicolons)*
auroral oval; E region irregularities; F region irregularities; F2 region trough; Polar Ionospheric Model.

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