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A QUANTITATIVE MODEL OF IONOSPHERIC ELECTRON DENSITY.(U)
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A QUANTITATIVE MODEL OF IONOSPHERIC ELECTRON DENSITY

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1.0 INTRODUCTION

The many ways in which the earth's upper atmosphere and ionosphere influence military hardware systems have been discussed in past MDAC reports and proposals to ONR. This annual report is concerned with work in progress on the development of a quantitative global model of the density of electrons, $N_e^{\uparrow}$, in the upper atmosphere. Knowledge of the ionosphere electron density is essential for the quantitative determination of radio wave propagation through this region of the earth's environment.

Ultimately $N_e^{\uparrow}$ will be described on a completely physical basis. This approach to the electron density problem has been taken by NRL and should eventually provide the best models of $N_e^{\uparrow}$. The purpose of the current contract has been to provide the current best model ~~we are capable of producing currently~~ for the electron density. In order that this model be useful to groups whose function is impacted by ionospheric variability on communications, the model must meet several requirements. First, it must be global (there have been several models developed of $N_e^{\uparrow}$ for a given latitude or local time region. They all encounter difficulties when attempts are made to link them with models describing other regions). The model must be analytic. There are two reasons for this. First, an analytic model will almost certainly be capable of being described in a computer code that is fast running. Second, the model almost has to be analytic if it is to be used to describe in real time changes in $N_e^{\uparrow}$. It is also prudent to use an analytic model to determine total electron content (TEC) by integrating $N_e^{\uparrow}$ along some path. The model is intended only to describe gross features of the ionosphere → next page cont

and their temperal variations. It is not capable of describing the more isolated rapid fluctuations in N_e that occur in some regions of the ionosphere.

The intended form of the model may be further described by comparing it with other ionospheric models. The NRL one-dimensional model is meant to be based on a rather complete understanding of the physics and chemistry of the upper atmosphere and ionosphere. The model determines atmospheric density and winds and uses a detailed knowledge of chemistry of the upper atmosphere together with other physical phenomena to finally determine at a given latitude the variation in N_e and local time. This model takes a fairly large amount of computer time and cannot be considered usable for real time specification and prediction of N_e. However it is clearly one step in the approach toward the ultimate 3D physical model (which also, by virtue of its complexity, may not be useful for the solution of real time problems). The Aerospace Corporation has developed an ionospheric model that is analytic but is merely a functional representation of N_e. In its construction, little consideration was given to the relation between the quantitative model and the input parameters it might use. This model is therefore quite limited in the sense that it cannot be used in a predictive mode. Its associated computer code, however, is much faster than the NRL model. Work begun at Air Force Global Weather Central and continuing now at the Air Force Geophysics Laboratory describes a statistical ionospheric model. Such a model will be of use to GWC in making average daily forecasts but will be of limited value for the real time specification of prediction of N_e. In the modeling exercise described here, an attempt has been made to meet all of the requirements discussed above (that the model be global, fast, analytic, and describe all gross global ionospheric features). This has dictated that the model be unlike all of the others just discussed. Instead, it is semiempirical, based on as much physics as can be used to accurately and quickly describe features of N_e. Also, a great deal of attention has been paid to the relation between the model and the sources of data that might be input to it. Any model is really no more accurate than the input data supplied to it. These inputs hopefully will include information provided from sensors on the SOLRAD-HI, DMSP, and HELIOCENTRIC satellites. Such data, we believe, will result in a much more accurate description of N_e than can be provided merely by use of the 10.7 cm flux index and magnetic indices such as K_p. This permits the model to use real time data and not indices that are averaged over space and sometimes not available for at least minutes and sometimes days and weeks after the time of interest. Some of the data, for example the interplanetary and solar wind information provided by the HELIOCENTRIC satellite, may permit the prediction of some of those high latitude ionospheric features under the control of low energy charged particles emanating from the sun. This might provide "lead times" of up to one-half hour. Other changes in the density of the neutral atmosphere and in N_e at low latitudes caused by events initiated in the polar and auroral regions may be predictable with lead times of several hours.

In the model both "primary" and "secondary" parameters are used. The primary parameters are those whose temporal variations are described directly by input data to the model. The set of secondary parameters are constants used to describe several ionospheric features. These constants do not vary with the input parameters. Rather they have been determined from various observational data sets describing particular gross ionospheric features. A particular feature in the model then is first described in some average sense in terms of secondary parameters. Temperal and spatial variability of a particular feature is determined by the changes in its primary parameters which are in turn controlled directly by input data to the model.

Not all of the input parameters will link the model directly to spacecraft data. Instead, some of them will be tied to other MDAC models of environmental features. Most important, the model of N_e relies directly on the MDAC model of neutral atmospheric density. Conceptually, the electron density may be thought of as a product of the neutral atmospheric density times some flux function. Actually, the neutral density model is used to integrate the flux of electromagnetic energy from the sun down through the atmosphere in order to determine ionization profiles. Use is also being made of the MDAC magnetospheric magnetic field model. This is because many ionospheric features are under control of the geomagnetic field. In particular, several of the high latitude dayside features vary as the dayside cleft (or dayside cusp) regions change their position. These other MDAC models themselves have inputs from satellite data. For example, the neutral density model relies on data describing the solar electromagnetic spectrum and other parameters describing charged particle energy sources at high latitudes. A detailed description of the model is provided in the following section where the geomagnetic control of some ionospheric features and this model's relations to other MDAC models are discussed.

As mentioned above it is our intent that this model provide the current most accurate description of N_e in some global sense and that the model be constructed such that it is fast on the computer and capable of describing N_e in both the specification and prediction modes. We anticipate that the model will be used immediately for both systems applications and scientific purposes. We would hope that it might be used with our neutral density model to provide the first accurate quantitative descriptions of global atmospheric wind systems (a major difficulty concerning workers on atmospheric winds is the lack of a good description of both neutral density and electron density throughout the upper atmosphere). It is also our opinion that the development of the model has provided several insights into the linking of the ionosphere with the upper atmosphere and magnetosphere and that the availability of such a model should hasten the development of a more sophisticated second generation quantitative description of ionospheric electron density. Through the development of this model we have been in contact with NRL, NELC, AFGWC, AFWL, and Aerospace Corporation. These groups will be among the first users of the model. We hope to have a large amount of feedback from them. We have found with our other models, especially the MDAC magnetospheric magnetic field model (developed with ONR funding), that this interaction with model users is vital. It has in the case of the magnetic field model led to a much more accurate second generation model that has just recently been completed.

We are proceeding as planned. The program plan for the past year called for determining N_e for the several global ionospheric features we planned to represent, combine those features to form the global model, and choose provisional inputs for the model. These three tasks have been completed and the resulting model is described in the next section. The important task of "model calibration" remains and it is planned that this work will be initiated in 1977. It is this calibration that will tie the model to the satellite data sets and make it, we hope, a very useful tool for specifying and predicting global features of N_e.

Details of the form of the model are presented in the following section. We plan to present a paper on this model at the Spring American Geophysical Union Meeting and at other meetings as appropriate. We further plan, once the calibration is completed, to test the model against several observed structures in N_e and finally to publish papers describing its construction, form, and uses.

2.0 MODEL DESCRIPTION

We report here the construction of the model in terms of its primary and secondary constants and parameters (see Section 1). The model specifically includes: the structure of the E, F_1, and F_2 layers, the equatorial anomaly, the winter anomaly, polar cap structure, semiannual and seasonal dependences, and the mid-latitude trough.

The input parameters to the model are chosen such that satellite data can be used together with the model to specify N_e in real time. Hopefully, with data from the HELIOCENTRIC satellite, the model can be used to predict those features controlled by magnetic fields and solar charged particles. In part, the predictive capability of the model stems from its dependence on inputs from other quantitative environmental models. For example, the location of the mid-latitude trough is largely controlled by the locations (L values) of the plasmapause and the auroral oval. Coupling of the model to the MDAC magnetic field model provides the necessary input on the dayside cusp position. More important, the model relies heavily on the MDAC model of upper atmospheric neutral density, N. Several ionospheric structures and temporal dependences are found to tie directly to variations in atmospheric density. This is illustrated in Figure 1 where the semiannual variation in N_e at the F_2 peak is shown. This variation in N_e is produced entirely by the semiannual variation in N described in the MDAC neutral density model. In addition, the structures of the E and F_1 layers are determined by calculating the absorption of solar electromagnetic radiation in the neutral density model.

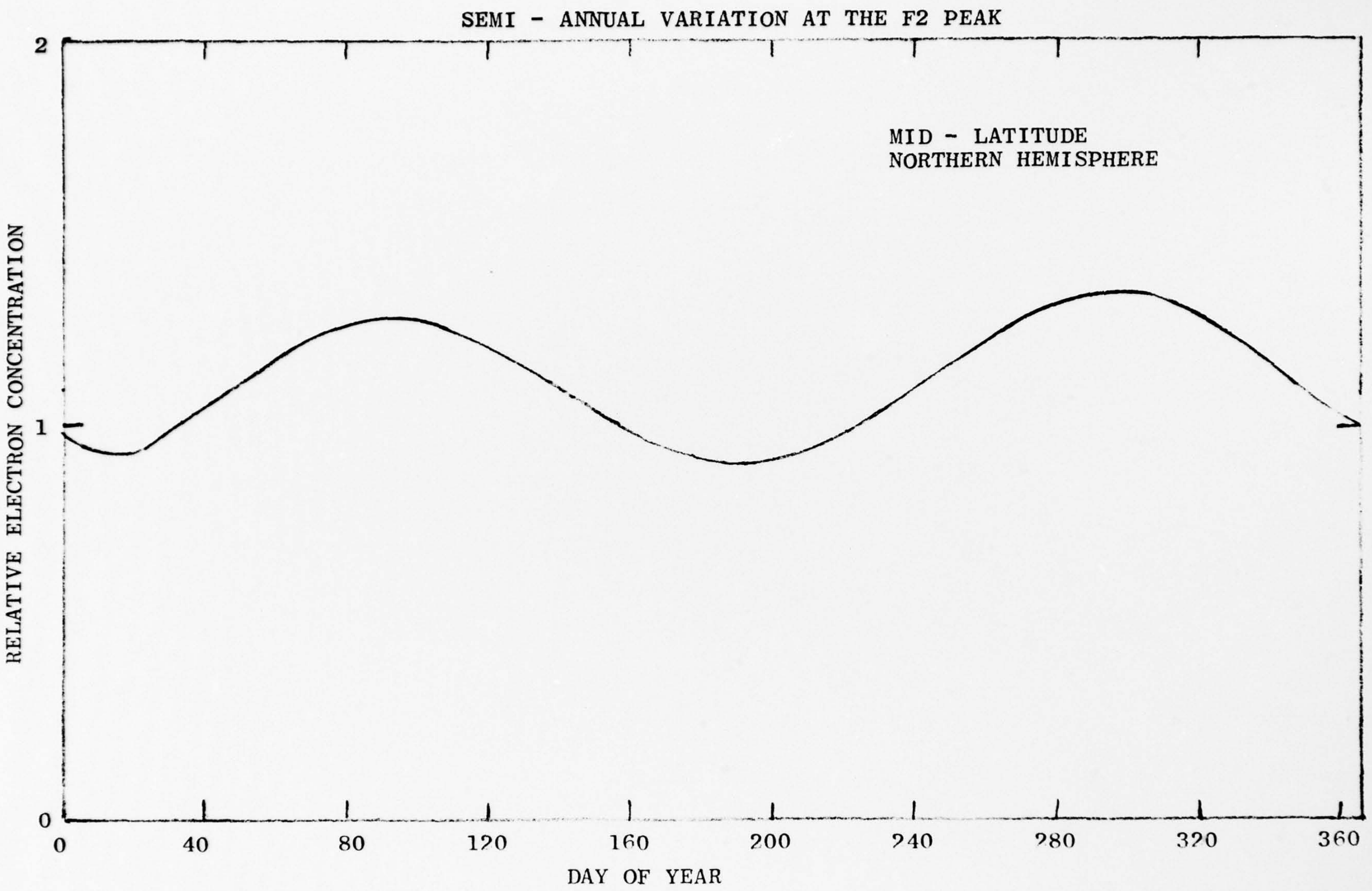

SEMI - ANNUAL VARIATION AT THE F2 PEAK
MID - LATITUDE
NORTHERN HEMISPHERE
RELATIVE ELECTRON CONCENTRATION
2
1
0
0
40
80
120
160
200
240
280
320
360
DAY OF YEAR

Figure 1.

The semiempirical formulation of the model is discussed below with emphasis on layer formation and anomalies.

2.1 Layer Formation

Let S be the energy flux at location ℓ and S + dS the flux at location ℓ + dℓ. Let σ be the absorption cross section of the atoms of the gas and N their number density (the neutral density of the upper atmosphere). The energy absorbed, dS, in a cylinder of unit cross section and axis parallel to the direction of the incident beam is given by

$$dS = S\sigma N\, d\ell$$

$$\frac{dS}{S} = \sigma \int_{\infty}^{\ell_0} N d\ell = -\tau$$

where τ is the optical thickness of the atmosphere at location ℓ_0 along the path to the sun. As $S \to S_\infty$ (its value above the atmosphere) $\tau \to 0$.

Thus $\quad S = S_\infty \exp(-\tau)$,

and the energy absorbed per unit volume is

$$\frac{ds}{d\ell} = N\sigma S = N\sigma S_\infty \exp(-\tau).$$

If η is the production efficiency per unit energy, then q (the number if ion/electron pairs produced per unit volume) is given by

$$q(\ell) = N\sigma\eta S_\infty \exp(-\tau).$$

The above equation gives the production of electrons. The two predominant loss mechanisms for ion/electron pairs are recombination and attachment. For recombination then

$$\frac{dN_e}{dt} = -\alpha N_e N^+$$

where N_e is the electron density N^+ the positive ion density and α the recombination coefficient.

Thus, at equilibrium

$$\frac{dN_e}{dt} = q - \alpha N_e N^+ = 0$$

Then, assuming that $N^+ \approx N_e$,

$$N\sigma\eta S_\infty \exp(-\tau) - \alpha N_e^2 = 0$$

Therefore, $N_e = [\frac{N\sigma\eta S_\infty}{\alpha} \exp(-\tau)]^{1/2}$

For attachment the loss equation is

$$\frac{dN_e}{dt} = -b N_e N$$

In discussing attachment processes in the ionosphere it is generally assumed that the number of neutrals is much greater than the ions so that when ionization occurs the neutral density does not change significantly. Thus

$$\frac{dN_e}{dt} = -\beta N_e$$

is generally used, where β is the attachment coefficient.

Then, at equilibrium

$$\frac{dN_e}{dt} = q - \beta N_e = 0 \quad \text{and}$$

$$N_e = \frac{N\sigma\eta_\infty}{\beta} \exp(-\tau)$$

In general α and β may vary with height because the reactions usually involve three bodies instead of two.

2.1.1 The E and F_1 Layers

It has been observed that the E and the F_1 layers of the ionosphere can be explained quite well using the recombination equation. Thus, for the E and F_1 layers

$$N_e^E = [N S_E \alpha_E \exp(-\tau_E)]^{1/2}$$

$$N_e^{F_1} = [N S_{F_1} \alpha_{F_1} \exp(-\tau_{F_1})]^{1/2}$$

where N_e^E and $N_e^{F_1}$ are the electron concentrations for the E and F_1 layers, S^E and S^{F_1} are the solar U.V. flux affecting the E and F_1 layers, α_E and α_F are the recombination coefficients, N the neutral density, and τ_E given by

$$\tau_E = \int_{\infty}^{\ell_o} \sigma_E \, N \, d\ell \approx \sigma_E \int_{\infty}^{\ell} N \, d\ell$$

where $T \equiv \int_{\infty}^{\ell} N \, d\ell$ is the total atmospheric cross section between the observation point and the sun. The MDAC atmospheric density model (which is analytic and computationally very fast) is used in the evaluation of the above integral.

Then $\qquad \tau_E = \sigma_E \, T$

and $\qquad \tau_{F_1} = \sigma_{F_1} \, T$

where σ_E and σ_{F_1} are the absorption coefficients for the wavelengths affecting the E and F_1 layers.

These equations describe the observed structures in the E and F_1 layers. Changes in T depend on the neutral density and the location of the sun. Thus, by using the MDAC neutral density model (which contains most of the variations observed in the neutral atmosphere) and a simple sun-position program, the variations observed in the E and F_1 layers can be accurately described.

The F_1 layer is essentially turned off at local sunset but the E layer is maintained through the night. Thus

$$N_e^E \text{ (night)} = [N\, S_E^{'}\, \alpha_E \exp(-\tau_E^{'})]^{1/2}$$

where $S_E^{'}$ is the intensity of scattered light and

$$\tau_E^{'} = \sigma_E \int_{\infty}^{\ell_0} N\, d\ell$$

where $\int N\, d\ell$ is the optical thickness (integrated vertically - not toward the sun).

Contours of N_e at noon and midnight are shown at the equator and mid latitudes in Figure 2. These results are obtained simply by integrating the solar flux through the neutral density model. The model is constructed so that as parameters describing the solar flux vary in time (for example, as observed by SOLRAD-HI) the input parameters will vary such that the output, N_e, will exhibit the proper temporal variation.

2.1.2 The F_2 Layer

The structure and variability in the F_2 layer is not so directly controlled by the neutral atmosphere. All attempts to treat the F_2 layer using U.V. generated ionization and electron losses which are a function only of density ended in failure. It is generally agreed that the bottom of the F_2 layer is defined as the region where electron loss rates change dramatically (from the order of seconds to the order of hours). Several studies were undertaken with neutral constituents and electron density dependent attachment and recombination coefficients. In none of these attempts was it possible to reproduce the observed seasonal, semi-annual or solar cycle dependencies.

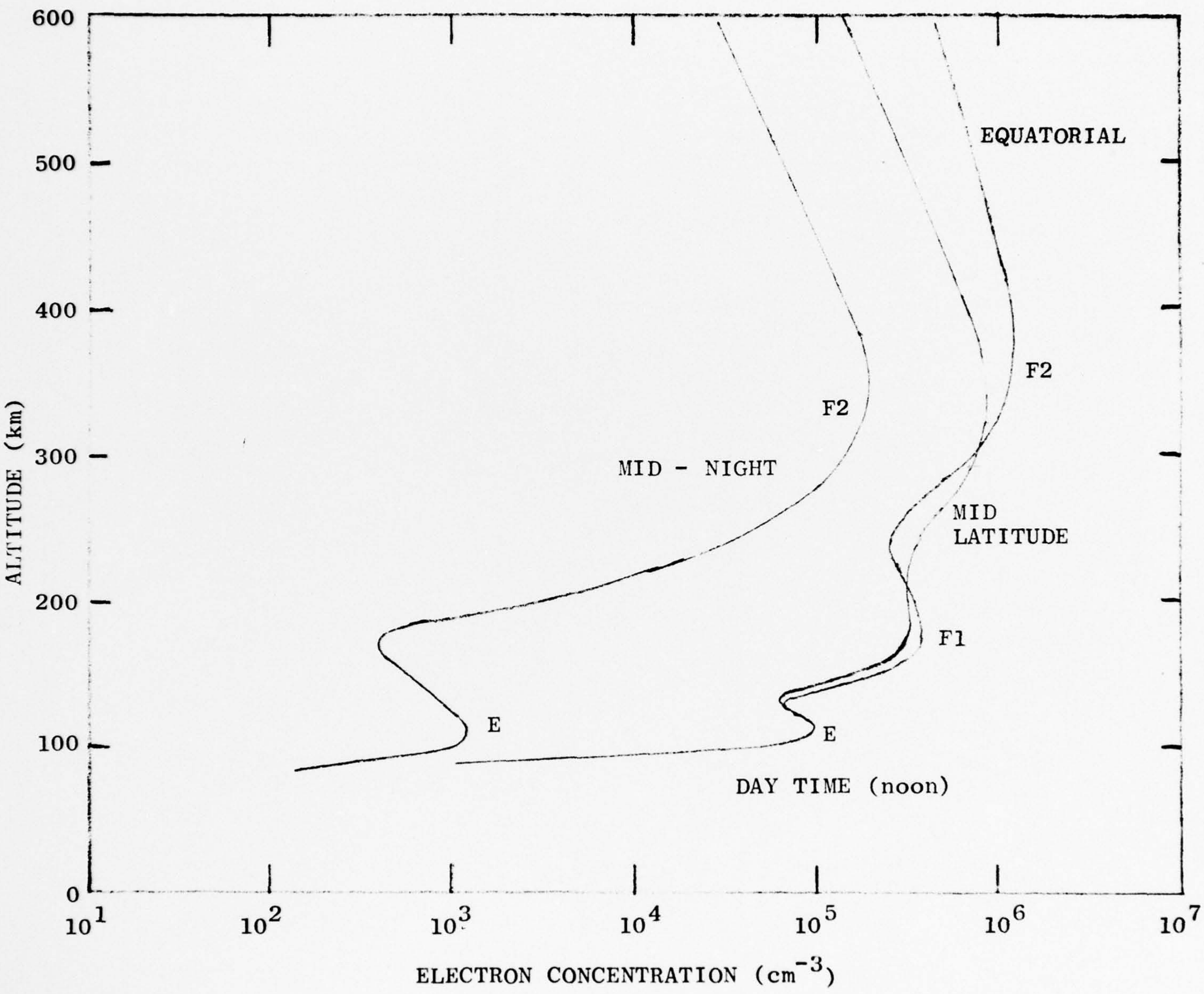

600
500
400
300
200
100
0
ALTITUDE (km)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
ELECTRON CONCENTRATION (cm^{-3})
EQUATORIAL
F2
MID LATITUDE
F1
E
DAY TIME (noon)
F2
MID - NIGHT
E

Figure 2.

An empirical function was therefore developed which arbitrarily (adjusted to provide a best fit at some point in time) defines a loss term varying with height and an ionization term depending only on the ambient density. Further empirical observations suggested that the normal F_2 layer was limited to the region equatorward of the latitude of the plasmasphere. Thus, a function was introduced which limits the F_2 layer (except for the winter anomaly peak) to L values $\lesssim$ 4-6. (The L value can roughly be thought of as the equatorial extent of magnetic field lines measured from the center of the earth in earth radii. Thus at the equator $L = 1$.) That is, the neutral density dependent F_2 electron values are multiplied by the function

$$L(\Lambda) = \exp\left(-\gamma\, \Lambda^3\right)$$

where $\Lambda = \cos^{-1}\left[\sqrt{\frac{1}{L}}\right]$ is the magnetic invariant latitude. The parameter γ was adjusted to give a best fit to the midnight equatorward edge of the mid latitude trough. Thus, the parameter γ is a primary parameter, since it is derived from the size of the plasmasphere. To properly calibrate the parameter γ simultaneous satellite measurements of the plasmapause and location of the equatorward edge of the trough are required.

The F_2 layer is essentially independent of direct solar zenith angle control, and depends instead on the density of the neutral atmosphere and the latitude extent of the plasmasphere. The winter anomaly however is observed to be under direct solar control. It appears at sunrise and rapidly disappears at sunset. Much of the average structure of the F_2 region as given by the model, including the F_2 peak, is shown in Figures 3 and 4 in terms of the critical frequency (which relates directly to N_e). Note that on the noon meridian some of the structure is produced by the equatorial anomaly (around the 12 Mhz contour). The magnetic latitude dependence of the equatorial anomaly is included in the model and discussed below.

2.2 Equatorial Anomaly

The equatorial anomaly which is thought to be caused by an upwelling in the equatorial region produced by electric fields may be organized around a central L value, L_0. The functional form of the anomaly term is

$$d \cdot \exp\left[-\delta(L-L_0)^2\right]$$

where the amplitude, d, is dependent on solar cycle as well as local time and δ, which defines the width of the anomaly peaks, has a local time and solar cycle dependence and a latitude dependence. The anomaly is strongest along the magnetic field line with the L value, L_0. The anomaly dependence on altitude and magnetic latitude as given by the model are shown in Figure 5.

2.3 Winter Anomaly

In this model the winter anomaly is treated as a completely separate source and loss mechanism and its contribution to the electron content is additive to all other electron sources. The formalism developed for the F_1 layer was used for electrons associated with the winter anomaly. The winter anomaly's contribution

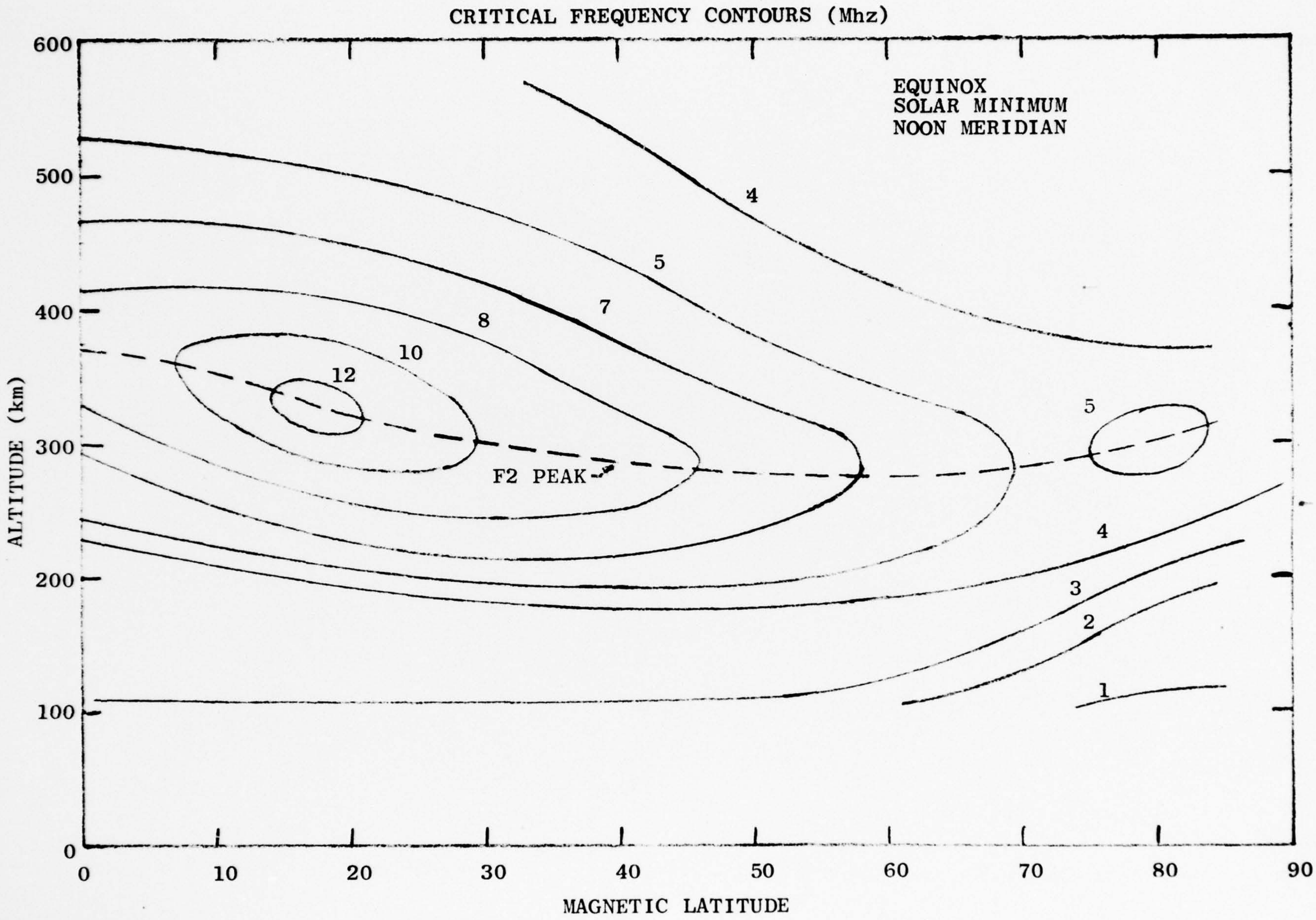
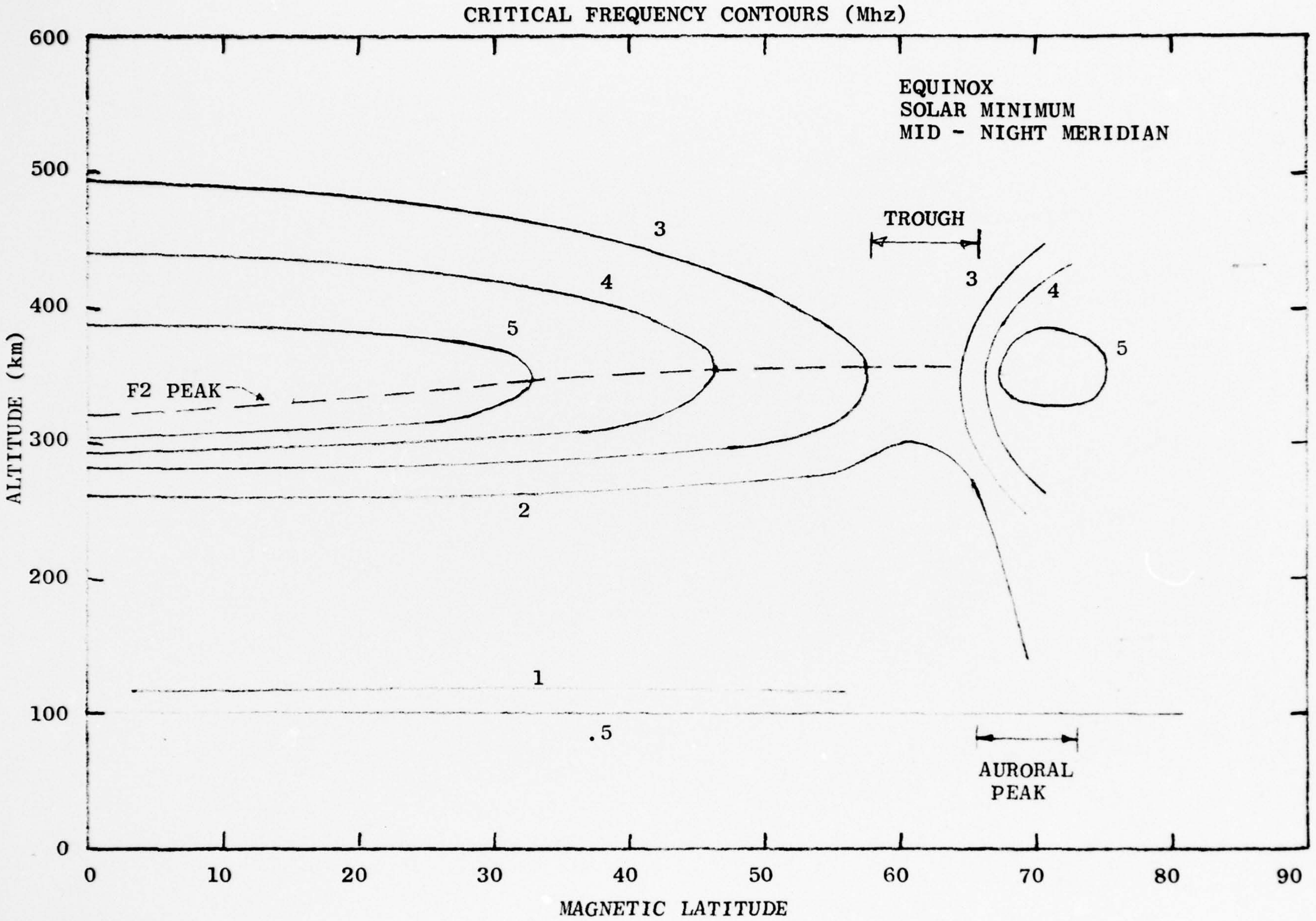
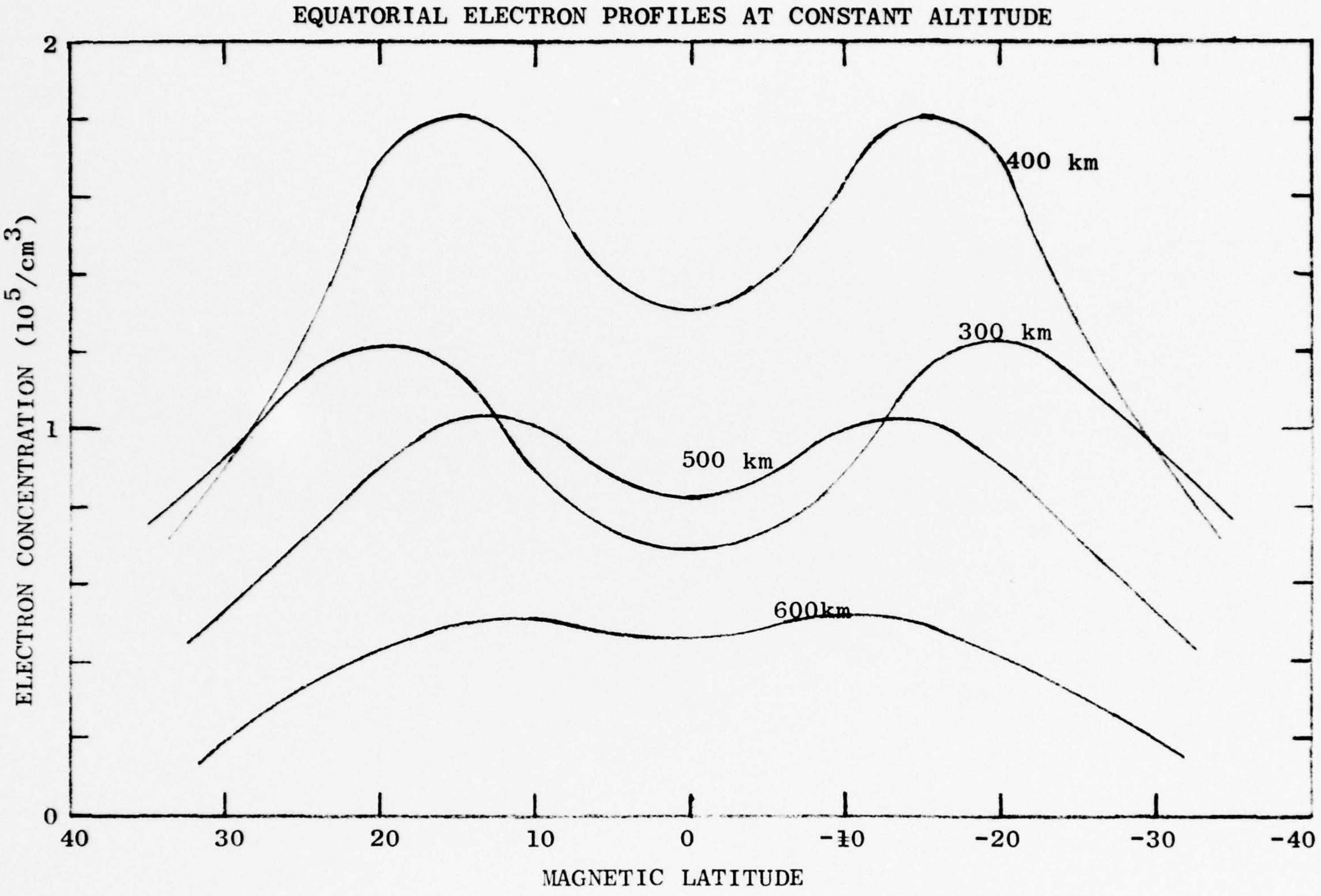

CRITICAL FREQUENCY CONTOURS (Mhz)
EQUINOX
SOLAR MINIMUM
NOON MERIDIAN
ALTITUDE (km)
0
100
200
300
400
500
600
MAGNETIC LATITUDE
0
10
20
30
40
50
60
70
80
90
4
5
7
8
10
12
F2 PEAK
5
4
3
2
1

Figure 3.



CRITICAL FREQUENCY CONTOURS (Mhz)
EQUINOX
SOLAR MINIMUM
MID - NIGHT MERIDIAN
TROUGH
AURORAL PEAK
F2 PEAK
3
4
5
3
4
5
2
1
.5
ALTITUDE (km)
600
500
400
300
200
100
0
MAGNETIC LATITUDE
0
10
20
30
40
50
60
70
80
90

Figure 4.



EQUATORIAL ELECTRON PROFILES AT CONSTANT ALTITUDE

Figure 5.

to the F_2 layer, $N_e^{F_{2W}}$, during the winter months near solar maximum is therefore written as

$$N_e^{F_{2W}} = g(\lambda,\rho)\ [NS_{F_{2W}}\ \alpha_{F_{2W}}\ \exp(-\tau_{F_{2W}})]^{1/2}$$

where $g(\lambda,\rho)$ is a latitude and solar cycle dependent function which determines the extent and amplitude of the winter anomaly. N is the neutral density, $S_{F_{2W}}$ is the solar flux responsible for the ionization, $\alpha_{F_{2W}}$ is the ionization efficiency, and $\tau_{F_{2W}} = \sigma_{F_{2W}}\ T$, where $\sigma_{F_{2W}}$ is the absorption coefficient and T the optical density to the sun.

In general there is no F_2 layer over the polar cap in the above formulation (except for the winter anomaly which at times extends into the polar cap). The F_1 layer, however, extends to higher and higher altitudes as the light-dark terminator is reached.

2.4 Polar Cap Structure and Mid-Latitude Trough

To complete the polar cap structure the charged particle source must be included. These high latitude sources appear most often at auroral latitudes (at L values greater than 8.5-9). At night the particles originate from the tail and are more energetic than the particles which enter through the dayside cusp regions.

The configurations of the auroral E and F layers vary extensively in amplitude and location. For sake of simplicity a simple Gaussian has been used centered at L = 10.5 with a low latitude edge of 8.5 at midnight. During daylight hours the low latitude edge moves to slightly higher latitudes and is centered on the dayside cusp field line.

The disappearance of the F_2 plasmasphere associated electron density together with the corpuscular generated auroral electron layer forms the midlatitude trough. During daylight hours, especially during the winter, the U.V. produced electron concentration may "fill in" the trough. The variation in the F_2 peak through the trough region is shown for the "average" model in Figure 6. Note that the important feature in N_e is largely under magnetic control. That is, as the plasmasphere expands or contracts, the low latitude edge of the trough moves respectively to higher or lower latitudes. Likewise the field lines along which the dayside cusp particles precipitate can also change their latitude and simultaneously the latitude of the poleward edge of the trough.

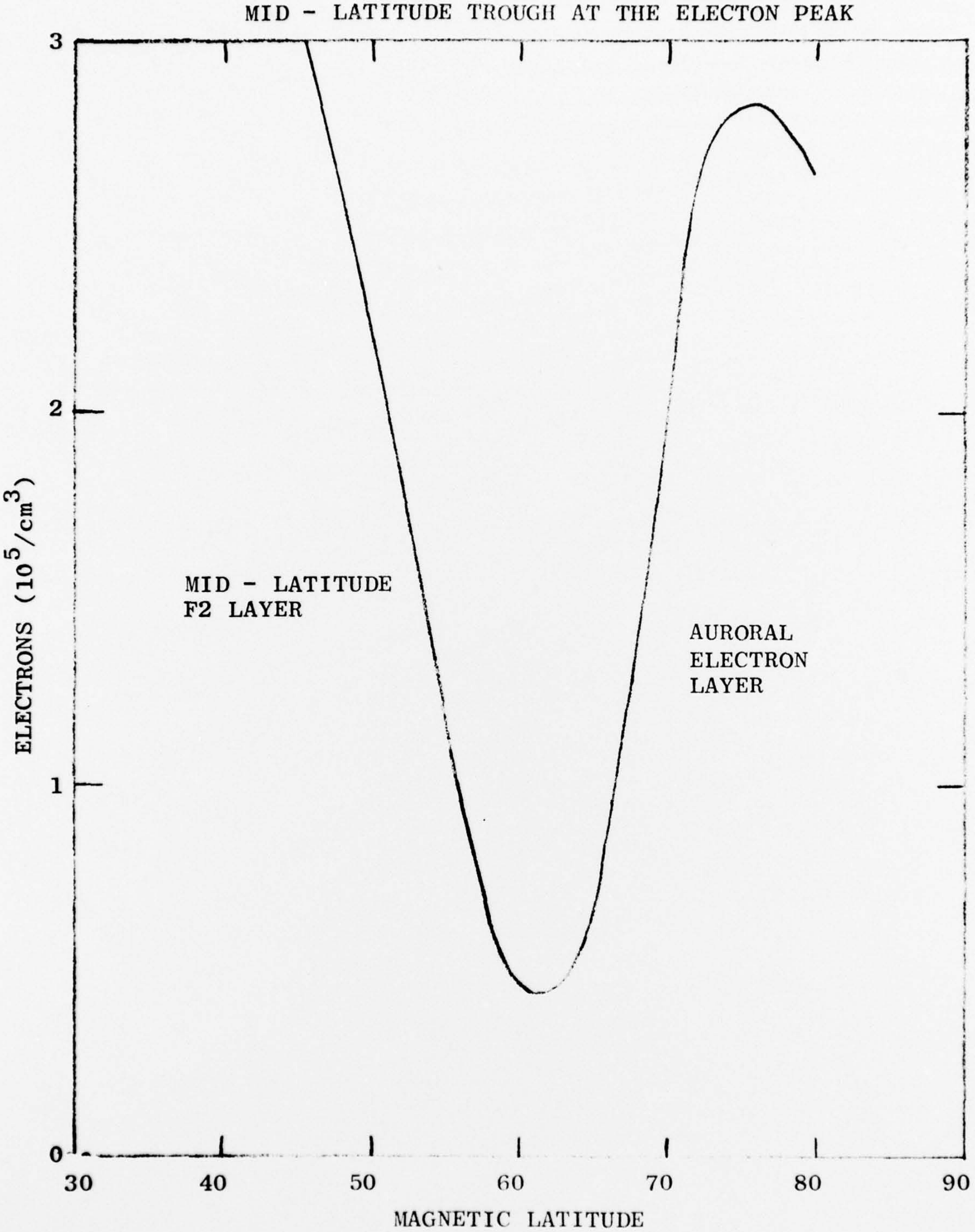

MID - LATITUDE TROUGH AT THE ELECTON PEAK
ELECTRONS ($10^5/cm^3$)
3
2
1
0
30
40
50
60
70
80
90
MAGNETIC LATITUDE
MID - LATITUDE
F2 LAYER
AURORAL
ELECTRON
LAYER

Figure 6.

3.0 COMMENTS AND SUMMARY

In the above description little was said concerning the primary and secondary parameters. This is primarily because the parameters will be determined by satellite and other real time data sets. The values of these parameters will be listed later when an "average" model is published. For example, the value of L_o (used to organize the equatorial anomaly information) currently is set at 1.12. During the next year, when the model calibration is being performed, this value may be changed. More important, the primary parameters associated with the equatorial anomaly determination will be determined. They will provide the model with its predictive capability.

It is emphasized again that the model is not statistical and that when the calibration is completed, it will be possible to use it in real time to specify and in some cases predict temporal and spatial variations in N_e. It is intended that this model be used with satellite data sets (although some provision may be made for its use with magnetic indices) and other quantitative models of the near earth environment such as those developed by the MDAC group. Further it is our hope that this model will be of use to both systems groups and research people. The immediate model uses with communications problems are obvious. It is hoped that the model will also be used for such research endeavors as the determination and understanding of the global upper atmospheric wind system.