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TEC Models

Andrew J. Mazzella, Jr.
Kevin P. Larson
Peter Dickson

RDP Inc.
Waltham Office Center
486 Totten Pond Road
Waltham, MA 02154

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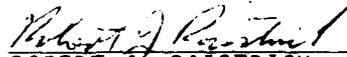
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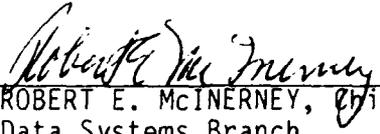
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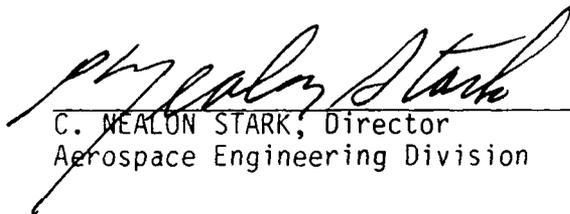
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ROBERT J. RAISTRICK
Contract Manager
Data Systems Branch
Aerospace Engineering Division


ROBERT E. McINERNEY, Chief
Data Systems Branch
Aerospace Engineering Division

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TEC Models

Introduction

The evaluation of Total Electron Content (TEC) for a radio transmission path through the ionosphere is of concern because of the associated phase lags for one-way satellite transmissions and also for ranging errors for two-way radar propagation. An earlier study attempted to derive TEC values from one-way phase lags, particularly for data from an earlier (1979) solar sunspot maximum period, but that effort was unsuccessful. The desired goal of that study was to develop an empirical description of the ionospheric disturbances in TEC, based on actual TEC variations, but a physical representation of the ionosphere, together with the numerical evaluation of TEC for a specified set of transmission conditions, was instead developed to accomplish this goal.

The physical representation of the ionosphere was based on data from a set of observations of the ionospheric structure conducted in 1982. This was a period of declining solar activity, and is thus not representative of the solar maximum conditions that were originally required. However, the flexibility allowed in the implementation of the modelling software is expected to be sufficient to represent the projections to solar maximum conditions. Additionally, the implementation of the software for the representation of the time variation of the transmission path through the ionosphere is expected to portray the essentials of the actual observational conditions.

Ionospheric Cloud Model

The ionospheric cloud model is a three-dimensional ionospheric electron density model consisting of a background altitude-dependent electron density and a superimposed "cloud" electron density which varies with altitude, latitude, and longitude. The background density is modelled according to the Chapman ionospheric profile¹, and provisions for up to three clouds are incorporated, although it would not be difficult to extend the model to accommodate a larger number of clouds. The ionosphere model is considered to have sharp boundaries in altitude, with a lower altitude limit of 200 kilometers and an upper altitude limit of 700 kilometers, but these are also parameters which can be easily modified.

The Chapman model is parametrized by a scale height for the electron density profile, a reference altitude at which the peak electron density occurs, the value of the peak electron density, and a parameter which influences the shape of the altitude density profile. Explicitly:

¹ Rishbeth, H., and Garriot, O.K. (1969) Introduction to Ionospheric Physics, Academic Press, New York

$$\eta(h) = \eta_0 \exp((1+G)(1-z-e^{-z})/2)$$

where

- η is the electron density at the altitude h ,
- η_0 is the electron density at the reference altitude h_0 ,
- G is the Chapman parameter,
- $z = (1/G) \ln(1 + G(h - h_0)/H)$ is an auxiliary altitude variable, such that $z = (h - h_0)/H$ for $G = 0$,
- H is the scale height.

This density profile is displayed in Figure 1 for a Chapman parameter value of $G = 0.05$, and a contour plot for the same density distribution is displayed in Figure 2.

The individual clouds are represented by ellipsoidal Gaussian electron density distributions, with principal axes in the altitude, latitude, and longitude directions. This formulation implies some curvature of the clouds along lines of latitude, but this feature has been of no consequence for the initial studies with the cloud models, because the transmission paths have been defined to lie along the local meridian plane.

For each of the three clouds, the following parameters can be specified:

- h_i central altitude, in kilometers [CloudHt];
- L_i central latitude, in degrees (positive North) [CloudLat];
- Γ_i central longitude, in degrees (positive East) [CloudLon];
- η_i central density, as number of electrons per cubic meter [CloudDens];
- H_i altitude scale length, in kilometers [ScLenHt];
- Φ_i latitude scale length, in degrees [ScLenLat];
- Θ_i longitude scale length, in degrees [ScLenLon].

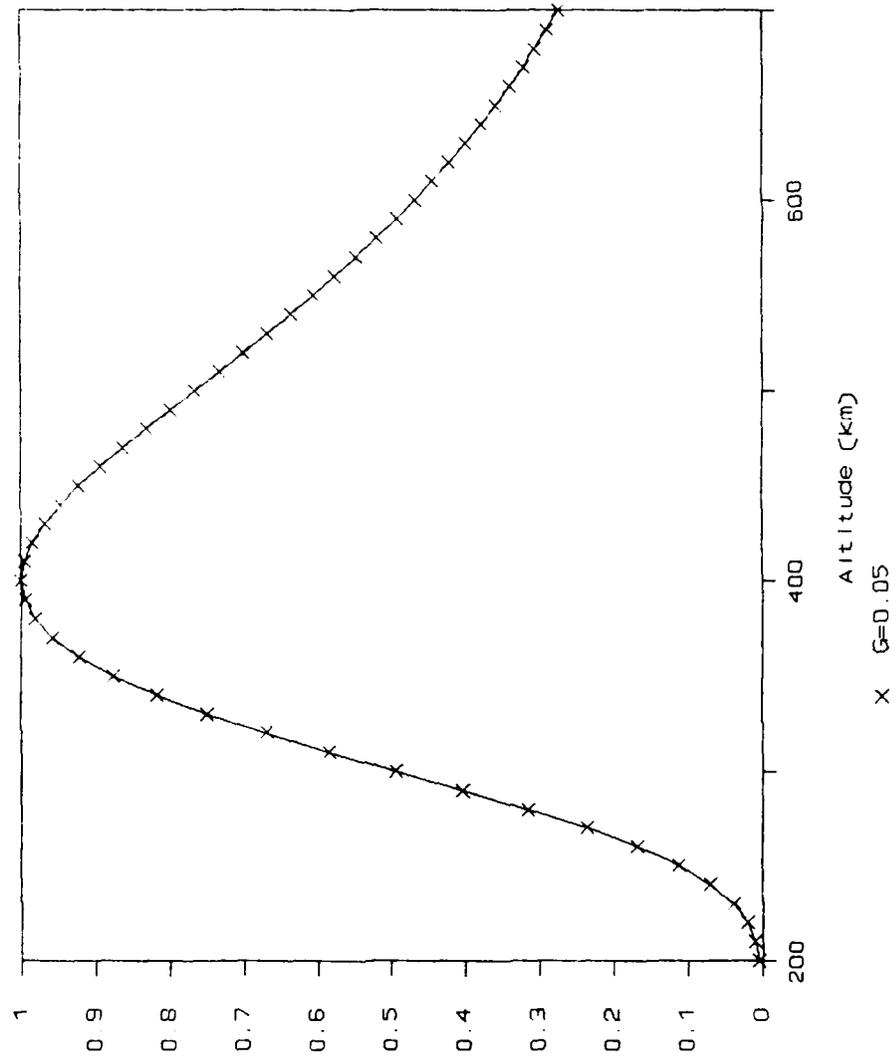
Additionally, a group drift velocity in latitude is associated with the clouds, through the program that implements the transmission path and TEC calculations. This drift velocity is specified in kilometers per second, with the positive direction being North, and is converted into a latitudinal rate based on the altitudes of the cloud centers. Drifts in longitude and altitude were not incorporated into the current representation. The density distribution associated with a single cloud is then given by:

$$\eta = \eta_i \exp(-[(h - h_i)/H_i]^2 - [(L - L_i)/\Phi_i]^2 - [(\Gamma - \Gamma_i)/\Theta_i]^2)$$

A contour display of the electron density in the ionosphere as a function of altitude and latitude was developed, using the NCAR (version 2) software library². This cross-section of the electron density is displayed for a selectable longitudinal plane through the ionosphere.

² Clare, F., Kennison, D., and Lackman, R. (1987) NCAR Graphics User's Guide, NCAR/TN-283+IA, National Center for Atmospheric Research, Scientific Computing Division, Boulder, Colorado 80307

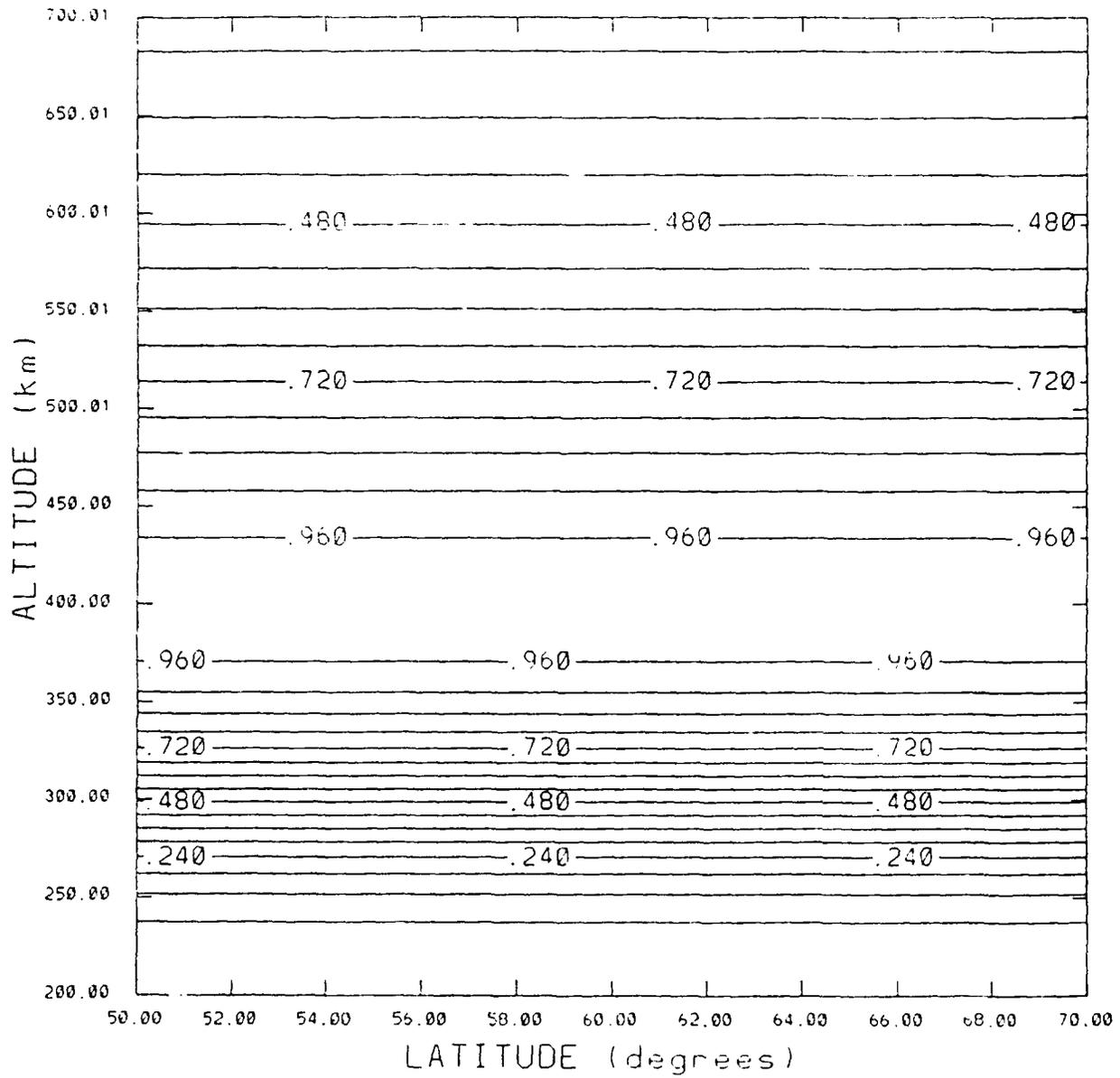
Chapman Ionosphere Profile



Relative Density

Figure 1

IONOSPHERIC ELECTRON DENSITY (10^{15} PER CC)



Contour Plot for Ionospheric Background
Figure 2

The contour routine utilizes the same model subroutine as the program which evaluates the transmission path through the ionosphere, but care must be taken that the model parameters are specified identically for the two programs when trying to obtain corresponding results.

The contour display routine can also optionally display the transmission path through the ionosphere, for a specified location for the observer and for up to ten elevation angles for the transmission path. This display can be extremely useful when investigations of features in the TEC profile are being conducted. (See Figure 3.)

An auxiliary program has been developed which will generate a VAX/VMS procedure, and the associated input parameters, to display a sequence of contour plots for a particular cloud model, at specified reference elevations for the cloud group. This sequence can be regarded as a series of "snapshots" of the cloud motion, particularly when the transmission paths are also displayed. (See Figure 4.)

Calculation of Total Electron Content

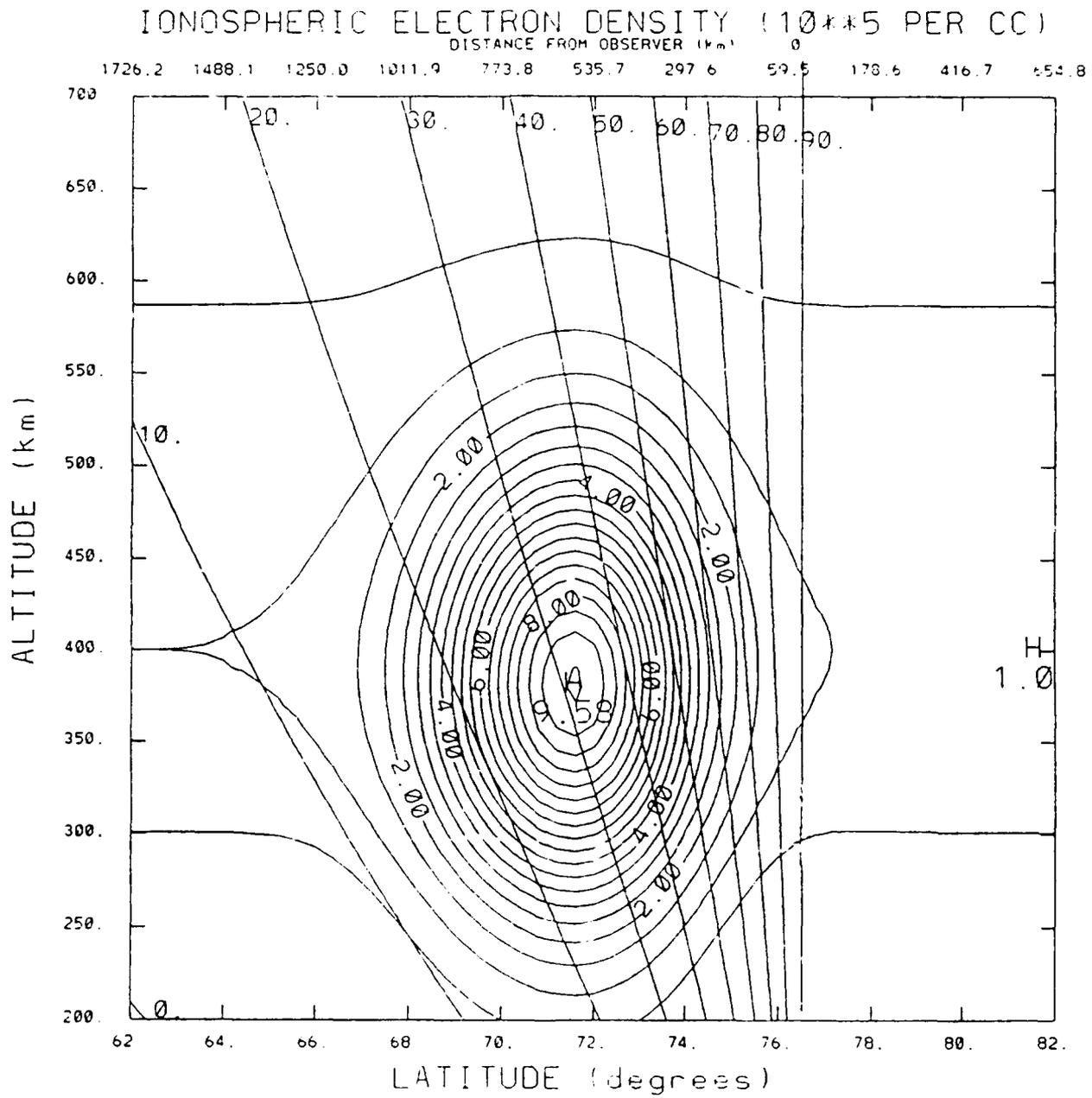
The Total Electron Content (TEC) for a transmission path is the integral of the electron density along the path, and thus has the dimensions of number of electrons per unit area. This integration was implemented as a discrete summation along the geometric straight-line path through the ionosphere. Thus, refraction effects on the transmission path are neglected. An Eulerian summation was used to represent the integral, for simplicity, but the step size for the summation is a parameter which can be specified when the program is invoked. This will improve the accuracy of the calculation for ionospheric models with a rapid spatial variability, at the cost of a larger amount of computational effort.

Fundamental trigonometric relations are used within the program to determine a location in latitude, longitude, and altitude above the earth, based on the quantities defining the position along the transmission path. These quantities are:

- the latitude and longitude of the ground-based observation station;
- the elevation angle of the transmission path;
- the distance along the transmission path from the observation station.

The ground-based station is considered to be at sea level, and the oblateness of the earth is also neglected. Once the position above the earth is determined, the ionospheric model can be utilized to evaluate the electron density at that position, and this density is then used in the Eulerian summation for TEC. The summation is considered complete when the calculated position is above the highest altitude defined for the ionosphere.

For each elevation angle for which TEC is calculated, the program tabulates the time associated with the observation, the elevation angle of the transmission path, and the calculated TEC value. This information is written to a listing for reference, and also to a data file for utilization by other programs.



Ionospheric Electron Density Contours with Transmission Paths
Figure 3

Transmission Path Scans

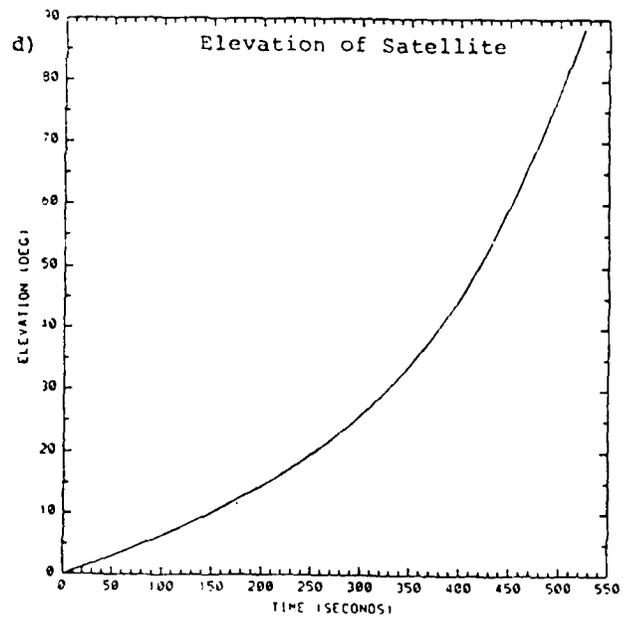
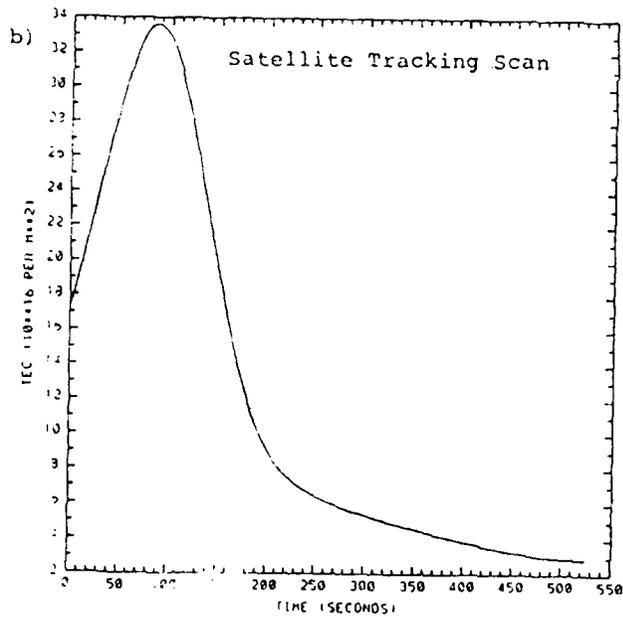
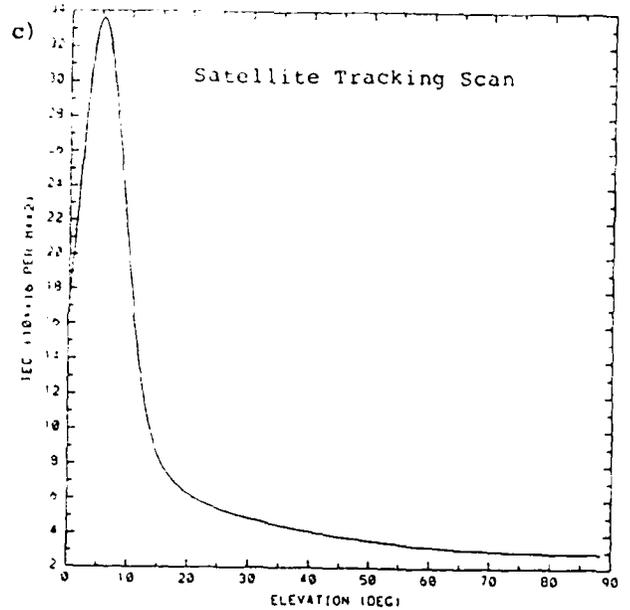
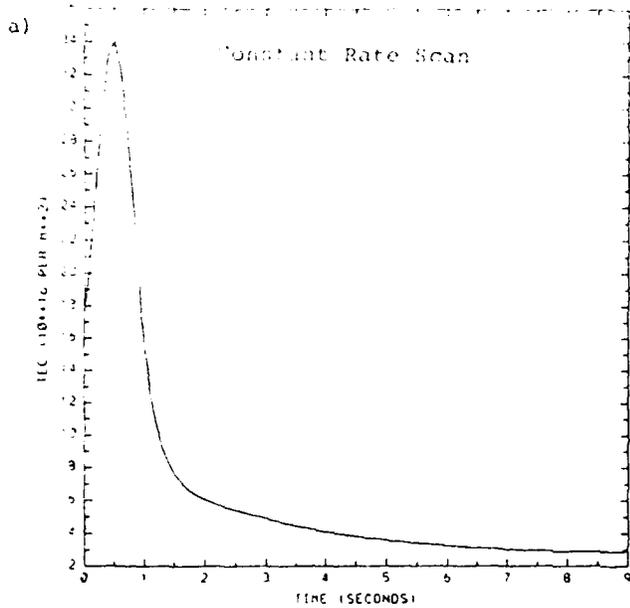
The ionospheric model was utilized in conjunction with a program designed to calculate the Total Electron Content along a specified transmission path and to represent the effects of variations in the elevation angle of the transmission path and the drift motion of the ionospheric clouds. The implementation of this program allowed only for scans within the local meridian plane, although a scan could cover the entire 180 degrees from horizon to horizon in the meridian plane. Additionally, the transmission path could be fixed at a particular elevation angle, so that the TEC variation is produced solely by the motion of the clouds.

Two different types of elevation angle scans could be performed. The first type is a simple scan in elevation at a constant rate, which can be terminated at a specified elevation angle. The second type incorporates a variable elevation rate, corresponding to that required to track a satellite in a circular orbit at a specified altitude. These tracking scans can also be terminated based on the elevation angle, but the time origin is considered to be the rising time for the satellite. Drift motion of the clouds during the course of the scan is also incorporated.

These two types of scans are illustrated in Figure 5, with a constant rate scan, at 10° per second, in Figure 5a, and a tracking scan, for a satellite in a 1000 km high circular orbit, in Figure 5b, versus time, and Figure 5c, versus elevation angle. The slight differences in the two TEC profiles with respect to elevation angle are a consequence of the drift motion of the cloud group, which is 500 m/sec for this particular model. Figure 5d displays the elevation angle for the tracking scan versus time.

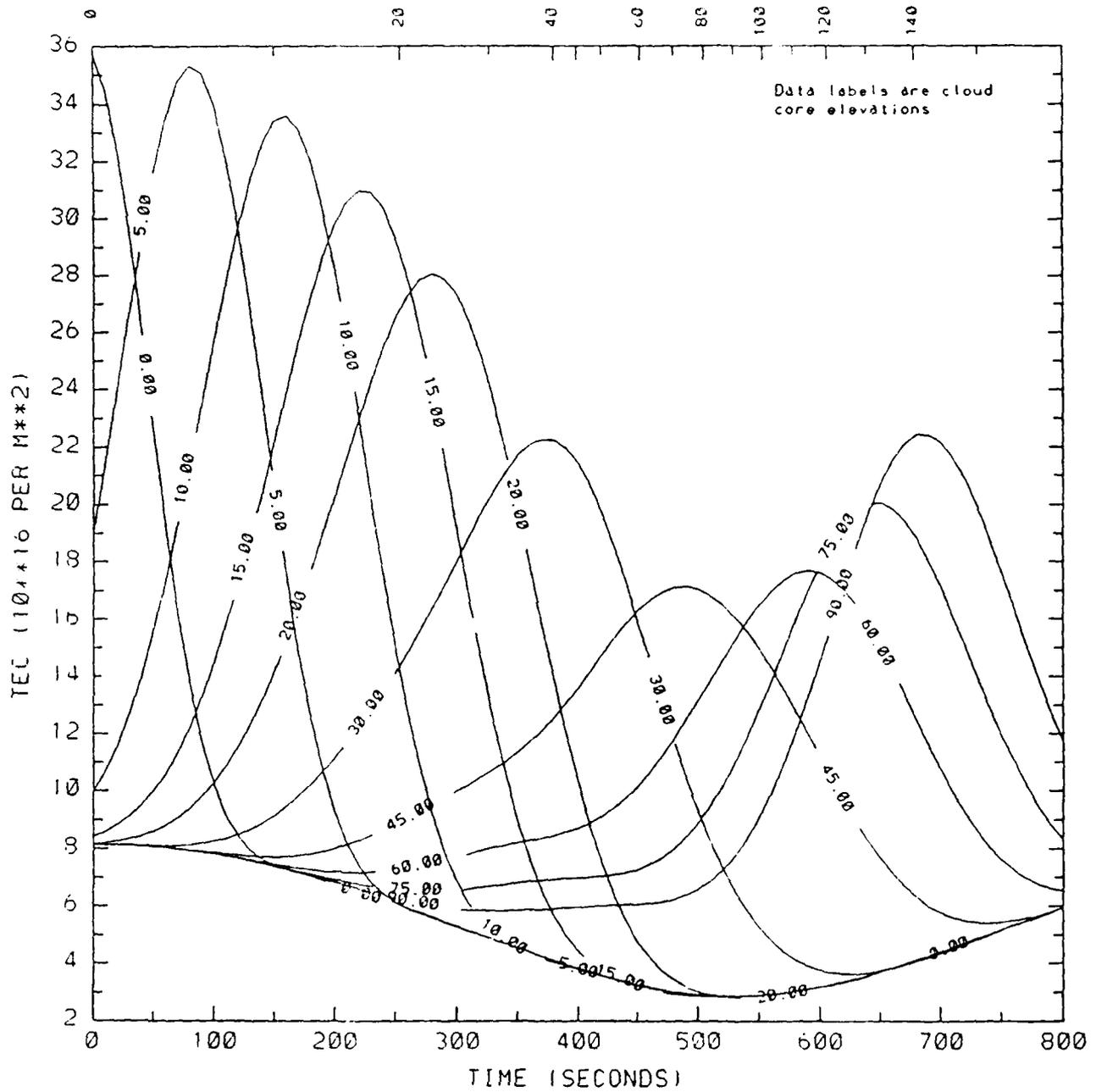
In a manner similar to that used to generate a contour plot sequence, an auxiliary program was developed to generate a sequence of scans, each spanning the same elevation and time ranges, but corresponding to different initial elevation angles for the cloud group. This set of scans could be interpreted as a repeated set of scans through the same cloud group at different times, based on the drift motion of the clouds in latitude. These are illustrated in Figure 6.

The TEC calculations for a transmission path at a fixed elevation angle are specified in a different manner from the scans in elevation angle, but the integration along the transmission path is performed in the same manner. Procedures have been developed so that concurrent observations at different elevation angles of a cloud group drifting in latitude can be simulated. In this case, the entire drifting motion of the cloud group is treated from within the transmission path program, and no auxiliary program is used, as for the contours or the elevation scans. A set of such scans, displaying the passage of one cloud group to higher elevations, is displayed in Figure 7.



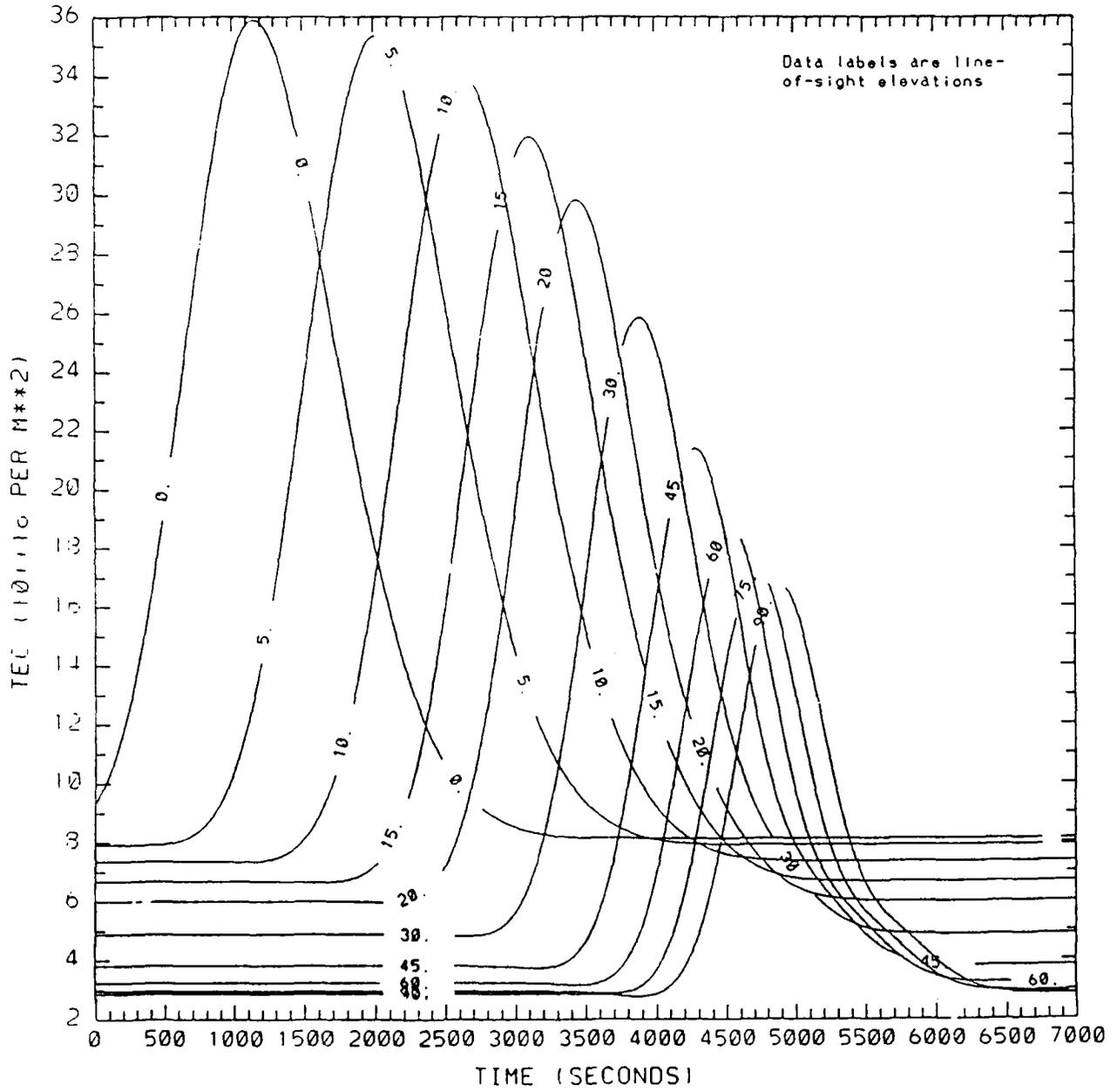
Constant Rate Scan and Tracking Scan
Figure 5

Total Electron Content Profile



Tracking Scan Set
Figure 6

Total Electron Content Profile



Scan Set at Fixed Elevation Angles
Figure 7

Display of the TEC Results

A number of graphical displays of the TEC results were developed, to complement the contour display of the ionospheric model electron densities. The TEC values can be displayed as functions of time or elevation angle, and the time rate of change of TEC can also be displayed as functions of the same two variables. In addition, the elevation angle for a scan can be displayed as a function of time. This is particularly useful for scans which simulate satellite tracking.

Provisions have also been incorporated to display multiple TEC profiles together in one frame. The set of TEC profiles would either be the simultaneous TEC values for a set of fixed elevation angles, or an associated set of scans with the cloud group at different specified initial elevations. For the fixed elevation angle sets, the TEC profiles are labelled by the elevation angle of the transmission path, while for the sets of associated scans in elevation angle, the TEC profiles are labelled by the initial central elevation angle of the primary cloud.

Results From Cloud Models

The baseline ionospheric model, without clouds, was defined using available information to serve as both a reference for the evaluation of the cloud effects and also as a background electron density upon which the clouds were superimposed³. The parameter values for the baseline ionosphere were the following:

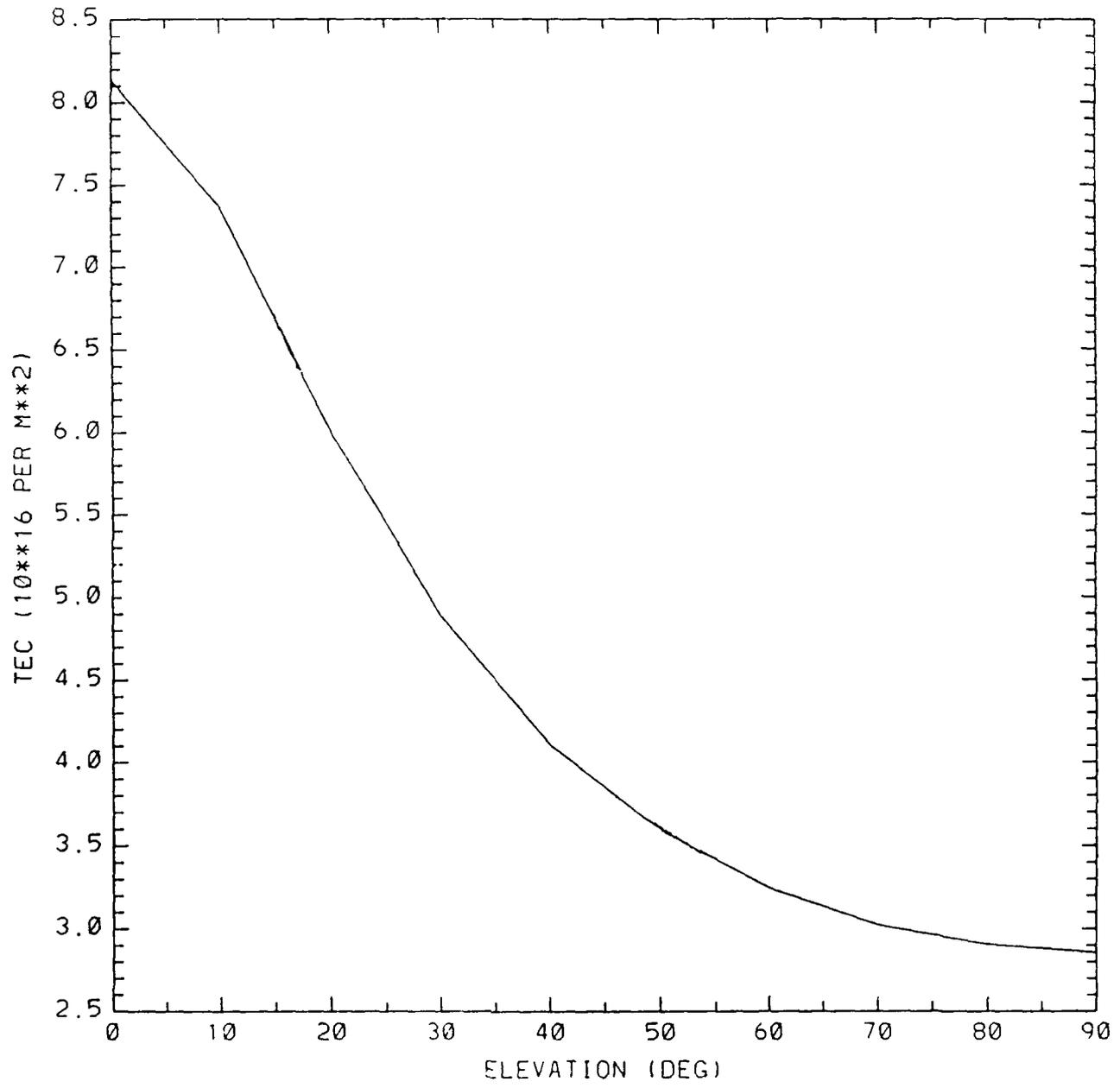
- peak electron density;
- altitude of peak electron density;
- scale height for density distribution;
- Chapman parameter.

The electron density profile for this background model is displayed in Figure 1, and the corresponding contour plot is displayed in Figure 2. An elevation scan showing TEC versus elevation angle is displayed in Figure 8. This profile can often be detected within a set of TEC profiles for multiple scans of a cloud model, as a composite of those scan segments for which the cloud contribution is not present. (An example of this effect can be seen in Figure 6.)

Following a series of general cloud models, the task of modelling a specific ionospheric electron density profile was undertaken. This profile was derived from sounder data taken on January 22, 1982, during a coordinated study of the ionosphere, and is displayed in Figure 9. The representation of the electron density distribution from the lower edge of the ionosphere up to the altitude of the peak electron density is derived from the sounder data, but the representation of the electron density distribution above this altitude is less certain.

³ J. Klobuchar, AFGL/LYC, private communication

Total Electron Content Profile



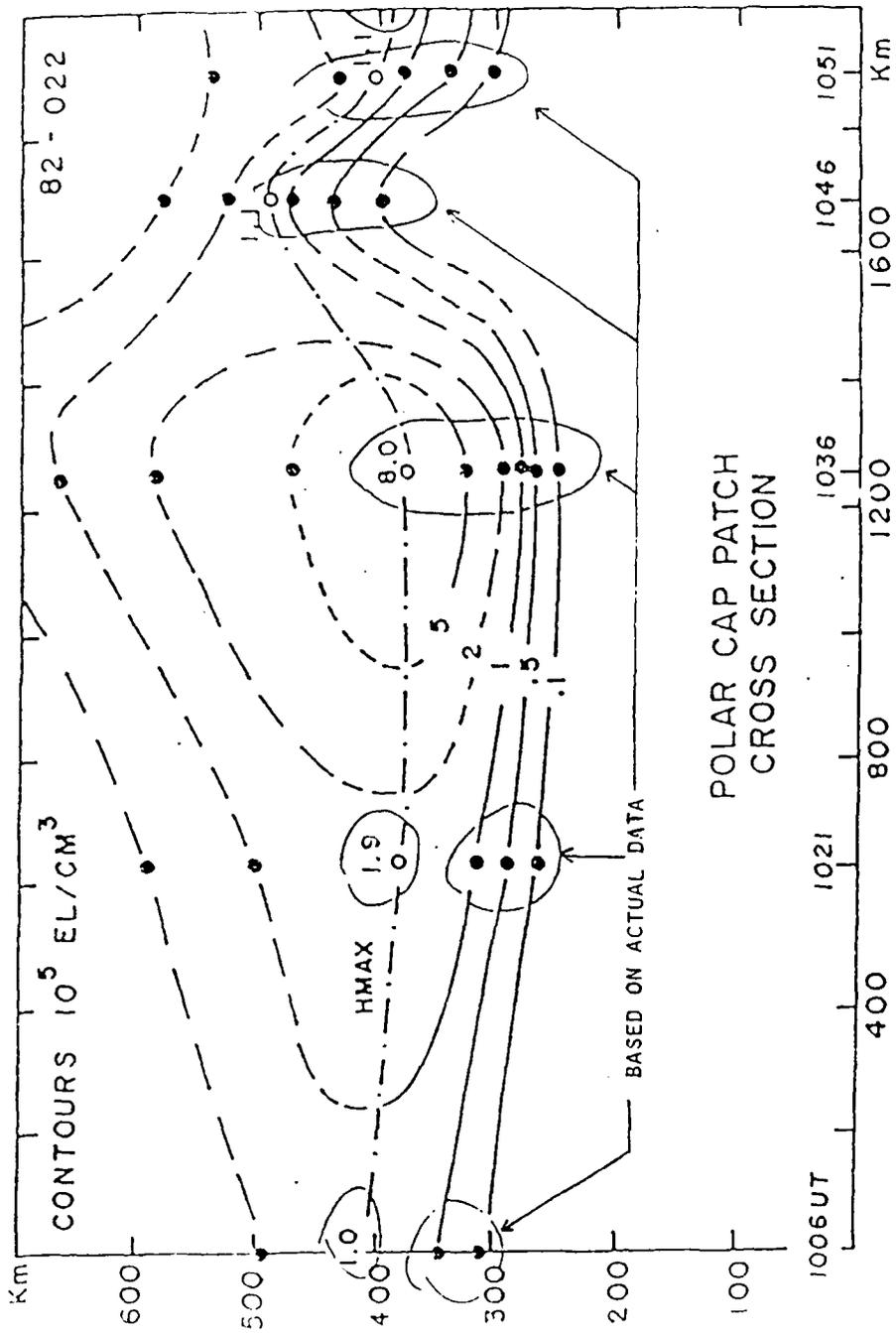
TEC Profile for Background Ionosphere
Figure 8

Nevertheless, the structure of this upper region is significant for low-elevation transmission paths when the cloud structure is at lower elevations, as evidenced in Figure 10 for the 10 degree elevation path, where only the upper structure is observed and the main portion of the cloud is missed by the transmission path.

For greater facility in comparing the sounder data to the existing format for the contour plots, the sounder density contours were roughly transcribed onto the same scales as the ionospheric model contours, producing Figure 11. The first cloud model to achieve reasonable agreement with the sounder densities was designated "Model 5", which is displayed as a contour plot in Figure 12. The parameter values for this model are given in Table 1, and sets of TEC profiles are displayed in Figure 6 and Figure 7.

It was decided that some improvements could be made for the modelling of the sounder density data, particularly with regard to the representation of the relative depletion region at the northern edge of the cloud structure. These changes were incorporated into a model designated "Model 6", which is displayed as a contour plot in Figure 10. The parameter values for this model are given in Table 2, and sets of TEC profiles are displayed in Figure 13 and Figure 14. Particular care was taken in the construction of this model, to assure that the electron densities are always positive throughout the ionospheric region.

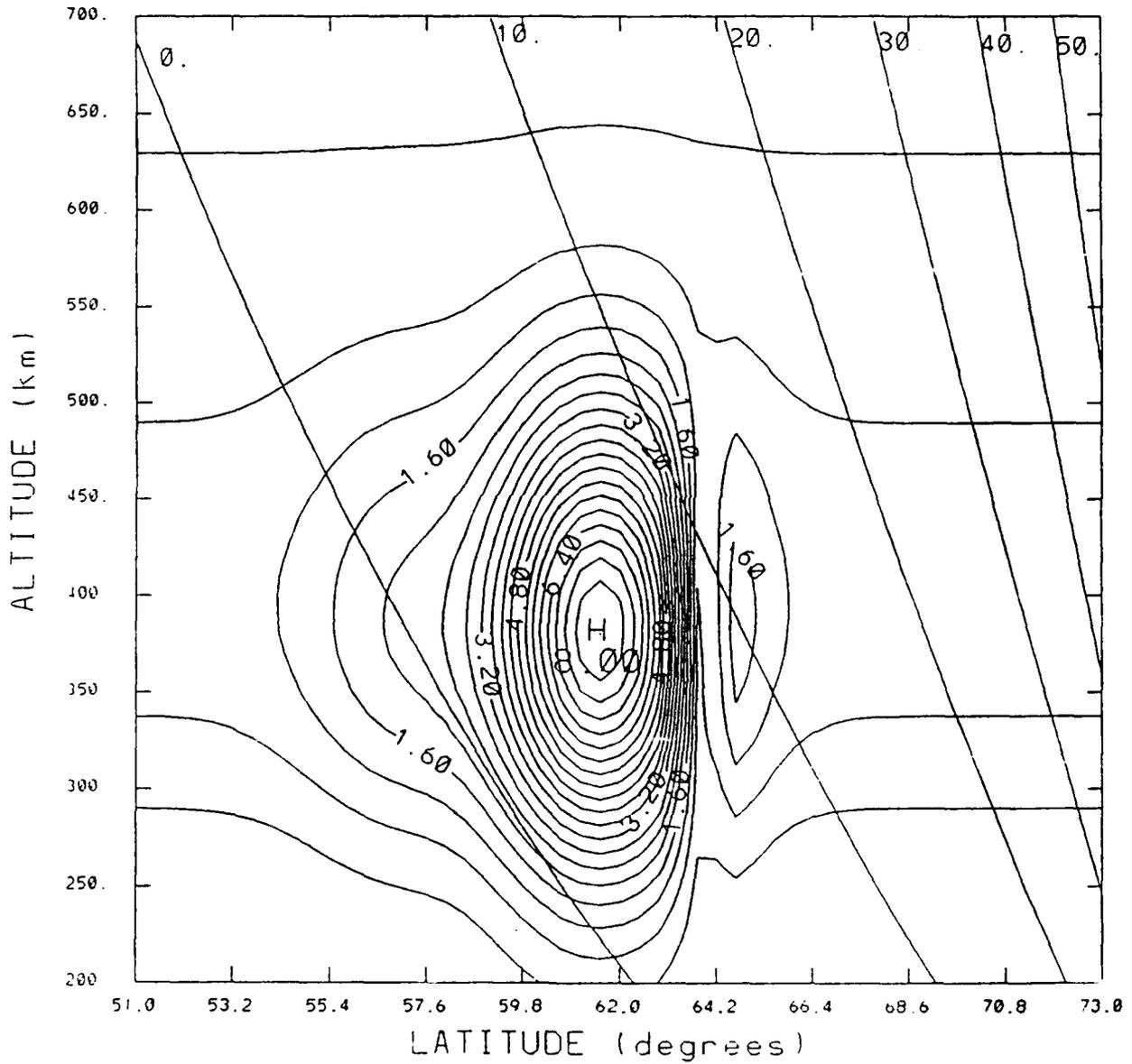
Noticeable distinctions between Model 5 and Model 6 are that the enhanced depletion region for Model 6 introduces TEC values that are even below those for the baseline ionosphere, and that considerably steeper gradients in TEC are present. These gradients are more apparent for the high-elevation transmission paths rather than the low-elevation transmission paths, but such an appearance is strongly associated with the actual geometric structure of the cloud group, and the predominance of high or low elevation gradients will depend on the detailed structure of the cloud group.



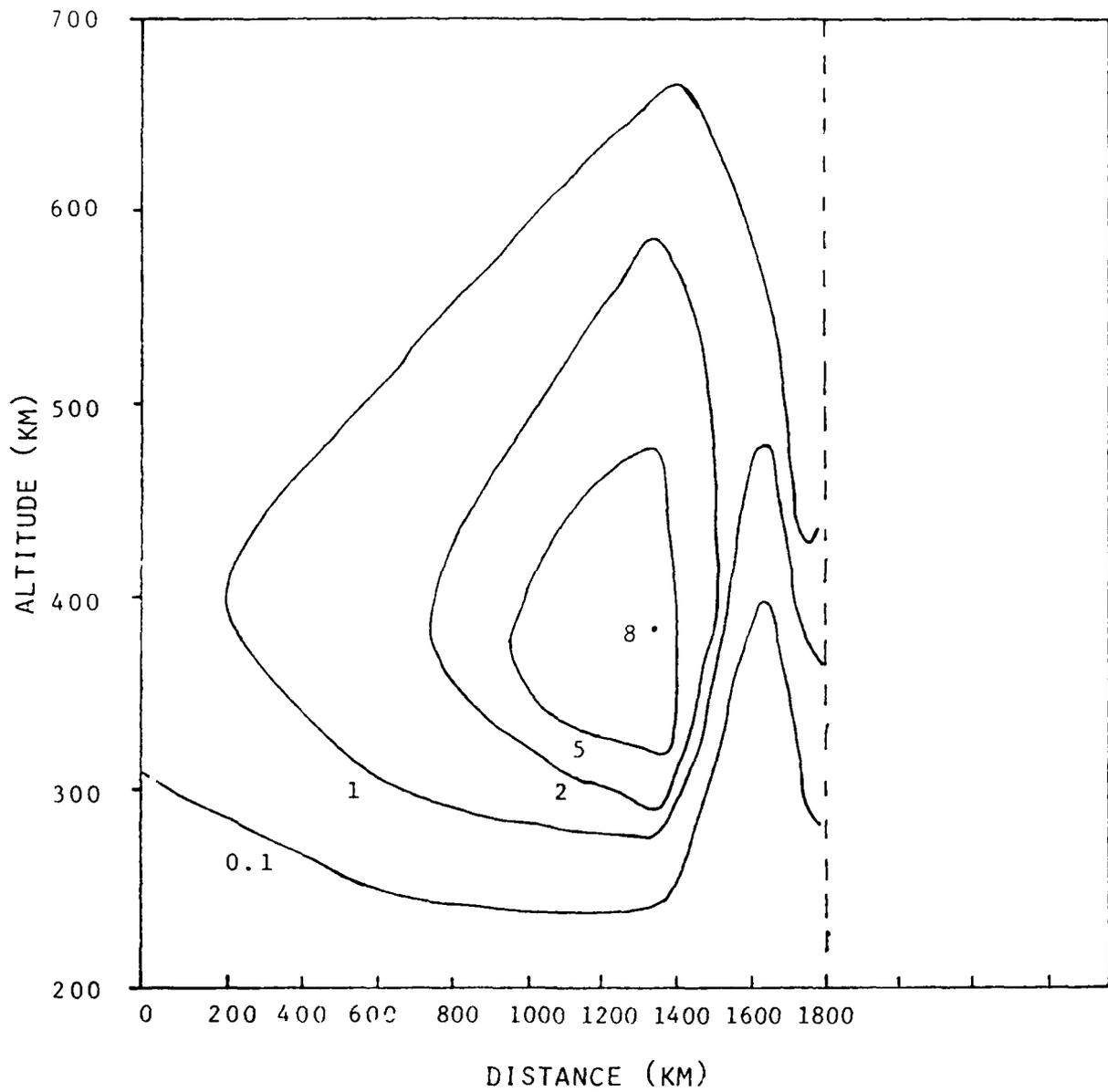
Polar Cap Patch
Figure 9

IONOSPHERIC ELECTRON DENSITY (10^{15} PER CC)
DISTANCE FROM OBSERVER (km)

3035.7 2773.8 2511.9 2250.0 1988.1 1726.2 1464.3 1202.4 940.5 678.6 416.7



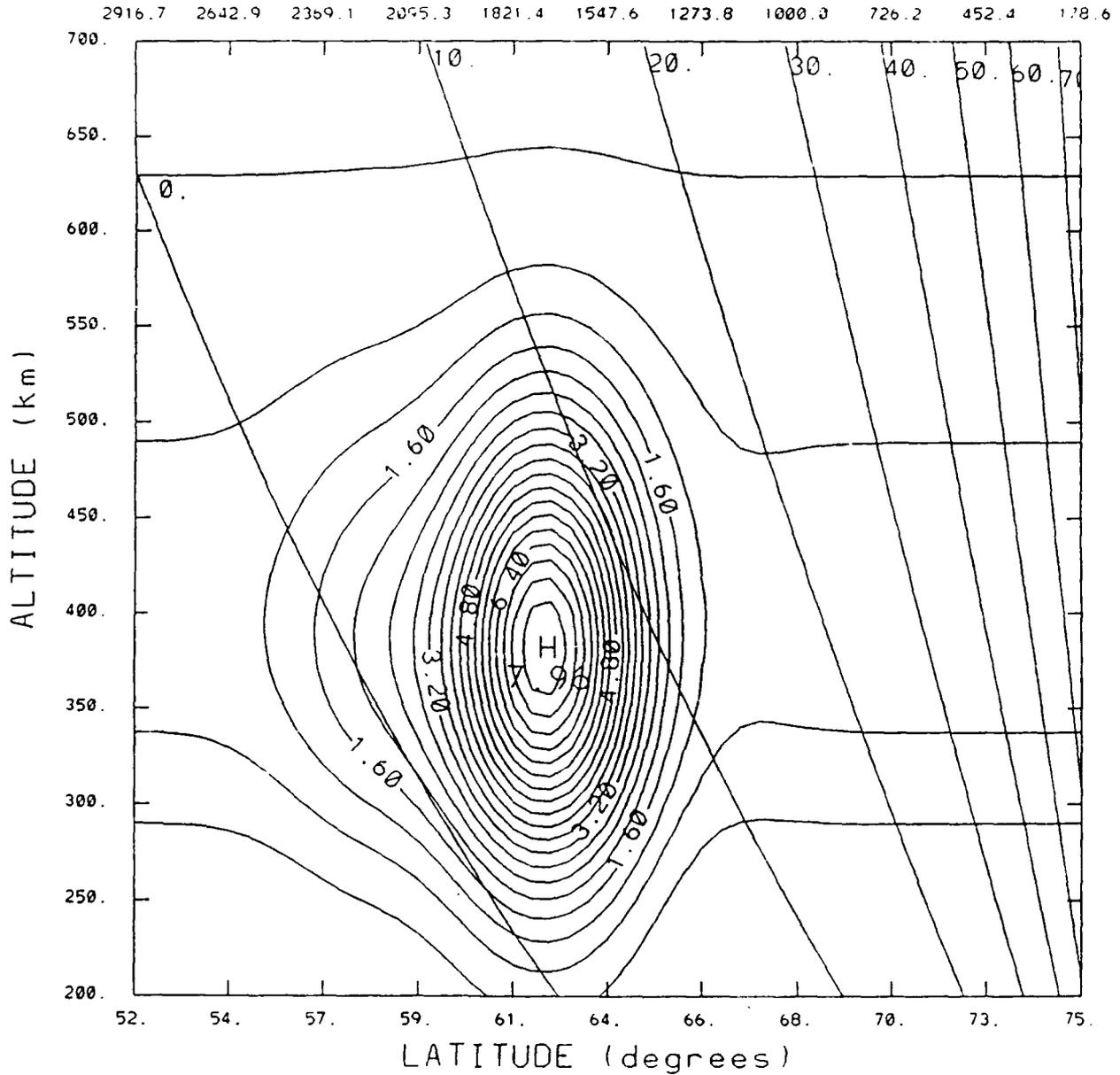
Model 6 with 10° Transmission Path
Figure 10



Transcribed Polar Cap
Figure 11

IONOSPHERIC ELECTRON DENSITY (10^{15} PER CC)

DISTANCE FROM OBSERVER (km)



Model 5 Contours
Figure 12

Three-cloud models: Model 5

Observer:

Fixed, at default location (Thule: latitude = 76.5 degrees (North), longitude = -69.0 degrees (West))

Ionosphere:

Background parameters:

Background density = 1.0×10^{11} electrons per cubic meter;

Background scale height = 80 km;

Background reference height = 400 km;

Chapman parameter = 0.05;

Default ionospheric extent: (200, 700) km;

Cloud Parameters

Cloud index	1	2	3
CloudDens	7.0×10^{11}	1.0×10^{11}	-0.2×10^{11}
CloudHt	380	380	380
CloudLat	62	58	65
CloudLon	-69	-69	-69
ScLnLat	1.6	1.6	1.6
ScLnHt	80	80	80
ScLnLon	400	400	400

Cloud velocity = 0.6 km/sec.

NOTES

At 380 km: 1 degree equal 117.83 km; 100 km equals 0.849 degrees (for horizontal variations).

Table 1

Three-cloud models: Model 6

Observer:

Fixed, at default location (Thule: latitude = 76.5 degrees (North), longitude = -69.0 degrees (West))

Ionosphere:

Background parameters:

Background density = 1.0×10^{11} electrons per cubic meter;

Background scale height = 80 km;

Background reference height = 400 km;

Chapman parameter = 0.05;

Default ionospheric extent: (200, 700) km;

Cloud Parameters

Cloud index	1	2	3
CloudDens	7.0×10^{11}	1.0×10^{11}	-3.0×10^{11}
CloudHt	380	380	380
CloudLat	62	57.5	64.2
CloudLon	-69	-69	-69
ScLnLat	1.6	1.6	0.4
ScLnHt	80	80	80
ScLnLon	400	400	400

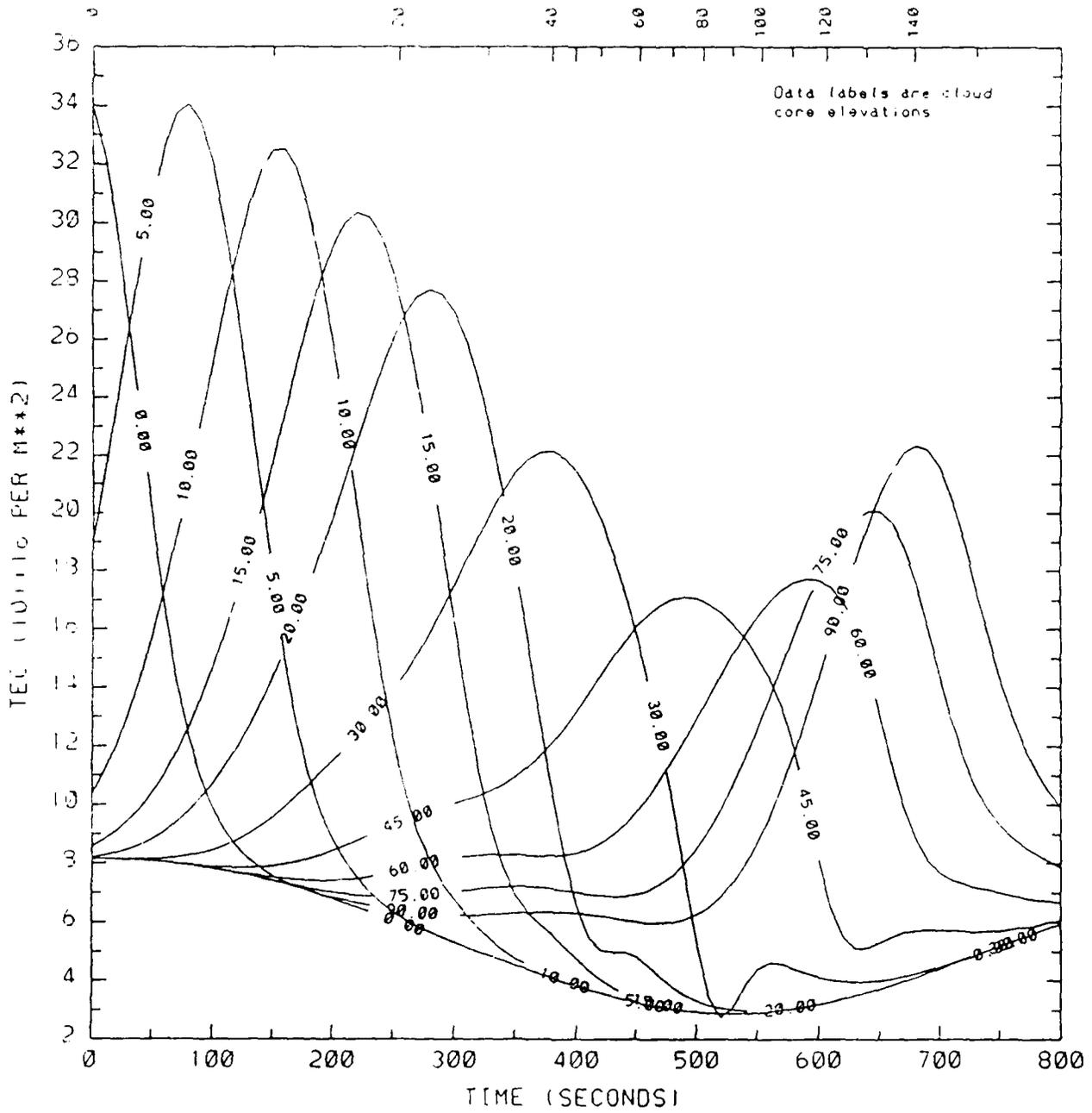
Cloud velocity = 0.5 km/sec.

NOTES

At 380 km: 1 degree equal 117.83 km; 100 km equals 0.849 degrees (for horizontal variations).

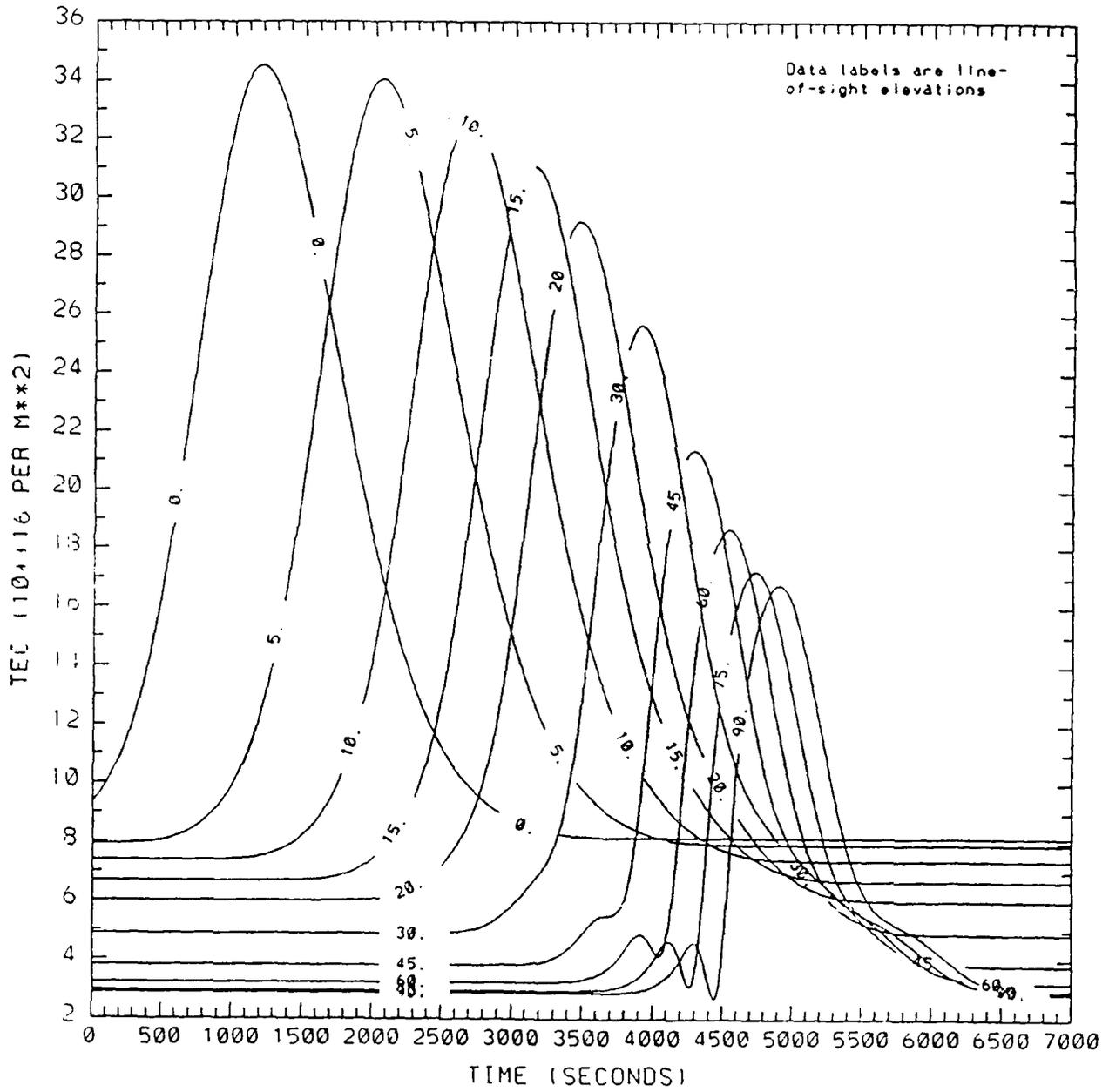
Table 2

Total Electron Content Profile



Tracking Scan Set for Model 6
Figure 13

Total Electron Content Profile



Scan Set at Fixed Elevation Angles for Model 6
Figure 14