Final Project Report for
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Entitled

"Visualization of Space-Time Ambiguities to be Explored by the NASA GEC Mission with a Critique of Synthesized Measurements for Different GEC Mission Scenarios"

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Overview

The objective of this grant was to study how a multi-satellite mission configuration can be optimized for maximum exploratory scientific return. NASA's Solar Terrestrial Probe (STP) concept mission Geospace Electrodynamic Connections (GEC) was the target mission for this pilot study. GEC prime mission characteristics were two fold: (i) a series of three satellites in the same orbit plane with differential spacing, and (ii) a deep-dipping phase in which these satellites could dip to altitudes as low as 130 km to explore the lower ionosphere and thermosphere. Each satellite would carry a full suite of plasma and neutral in-situ sensors and have the same dipping capability. This latter aspect would be envisaged as a series, up to 10, of deep-dipping campaigns, each lasting 10 days during which the perigee would be lowered to the desired probing depth.

The challenge in optimization is to establish the scientific problems that can best be addressed by varying or selecting satellite spacing during a two-year mission while also interspersing, in this two year time frame, the deep-dipping campaigns. Although this sounds like a straightforward trade-off situation, it is complicated by the orbit precession in local time, the location of perigee, and that even the dipping campaigns will have preferred satellite spacing requirements.

Procedure

The GEC science technology design team has generated a report that outlines the prime science, hence this is not reviewed here. However, the findings are that exploratory science will be achieved at all points in the mission, and hence the recommendations for satellite spacing are from equally spaced around the orbit to spacings as small as possible without driving up the cost of the mission. With regard to deep-dipping, the most compelling conditions for deep dipping are across the auroral regions where the primary electrodynamic closure occurs and maximum energy deposition into the thermosphere occurs.

Based on these rather wide constraints, a physical modeling and diagnostic analysis procedure has been developed to study the mission under different geophysical and mission conditions. The following lists the resources brought together that form the computational basis for the study.

Ionospheric Model:

The Utah State University (USU) Time Dependent Ionospheric Model (TDIM) is the core of the ionospheric representation. This model generates the following state variables: O^+, NO^+, O_2^+, N_e, T_e, T_i, and $\mathbf{V}_{ion}$. Each of these is a GEC measurement. Because of the Lagrangian software architecture, the TDIM can be run in extremely high spatial resolution in specific regions, i.e., where the satellites will be deep-dipping or simply passing through the auroral electrodynamics closure regions.

Neutral Atmosphere:

The University of Colorado, Boulder, Coupled Thermosphere Ionosphere Model (CTIM) is the core of the thermospheric representation. Dr. Tim Fuller-Rowell, as a Co-I, ran this model for several conditions at several resolutions in both space and time, to provide a storm and non-storm thermosphere. The CTIM generates the following state-variables: density, T_n, composition, and **u**. Each of these is a GEC measurement.

Magnetosphere-Ionosphere (M-I) Electrodynamics:

The USU coupled MHD model of the M-I system at auroral and polar latitudes generates the M-I physics needed to simulate geomagnetic substorm conditions. Dr. Lie Zhu (USU) prepared the primary substorm event used to drive the ionosphere for the studies. The M-I model generates the following fields: **E**, **j**, Δ**B**, auroral precipitation, and integrated Hall and Pedersen conductivities. Again, these are parameters the GEC satellites will measure or infer.

GEC Mission:

Software development was carried out to simulate the satellites traversing the simulated TDIM-CTIM-"M-I" database. Software was also developed to display these synthetic measurement streams; this is the crucial part of the development. It is based on a movie format that captures the entire constellation of satellites as they probe the regions of interest. The next two sections provide details of this software as well as movies on a CD that are available from the author.

GEC Environment Simulation:

The three environmental models are run in a specific sequence. Geomagnetic and solar conditions are first defined via selection of solar and geophysical indices; these are used to drive a CTIM simulation. The M-I substorm model is then run to simulate the electrodynamics and auroral precipitation. Output from both these models is then used to drive the TDIM, which creates the ionospheric response.

Visualization Software

The visualization in the context of the geospace being explored, as well as in the mission-satellite configuration, are equally important. The final product is a set of panels, on a single screen, which evolve in time showing different aspects of both the mission and the geoscience observed by the satellites. For the purposes of this report, a scenario that includes three satellites in a high inclination orbit passing at perigee through a winter northern hemisphere was selected. The auroral conditions were arranged to be a moderate substorm as the satellites dipped and traversed the evening sector auroral oval.

Figure 1 is a frame from this simulation movie. In all, there are seven panels that each evolve in time. The three panels on the left provide the mission geometry in terrestrial representations. In the bottom left panel, a set of white crosses on the sea-land rendering of the Earth represent the locations of the satellite footprints. The corresponding altitude of these three satellites is shown in the top left panel, in which the three are identified sequentially with satellite 1 always leading the constellation. This becomes evident when the movie is run, i.e., the three white crosses in the lower left panel follow each other around their orbit and no further annotation is needed. The third panel, the globe of the Earth, represents the three-dimensional reconstruction of the orbits from a selected vantage point. This vantage point has been selected to emphasize the satellites traversal of the region of greatest scientific interest for this simulation.

Hence, the orientation of the Earth, as seen in Figure 1 in this panel, is changeable. In this panel, the satellites are identified by large yellow blobs!

The relationship of satellite location to the ionosphere is shown in the polar diagram on the right. This is a magnetic latitude-magnetic local time display of the electron density at 160 km. The color-coding is such that blues are low densities and yellows and reds are the highest densities. The location of the satellite footprints are shown as circles with the corresponding satellite sequence number. This number, together with the top left altitude panel, provides information about which ionospheric layer the satellite is actually in. This panel can be reconfigured to show different state variables, at different heights. However, the electron density at 160 km does provide excellent representation of solar ionization, the mid-latitude, the auroral, and the polar boundaries. Also, this altitude is very sensitive to geomagnetic auroral evolution. In the panel, the substorm activity that the satellites have passed through is evident in the pre-midnight sector.

The remaining three square panels represent a satellite's "view" of the geographic terrain the satellite is crossing. For example, the top panel shows the coastline of Scandanavia, while the second satellite, middle panel, shows Iceland and part of Greenland. This enables the viewer to mentally coordinate ground-based resources, which may be crucial to a coordinated campaign. This is especially important for deep-dipping campaigns. Not shown in these three panels is the additional capability that the user can select to display in color a particular state parameter, i.e., a density or a temperature. The satellite location is at the middle of the square; the center of the square represents the parameter that is being measured, i.e., at the in-situ location. The purpose of showing the parameter as a 2-D constant altitude slice is that it provides context on gradients in the parameter as well as an indication of the region into which the satellite will move. This latter attribute is deduced from the region to the right of the center of the panel, i.e., the panel is organized such that the satellite direction is horizontal to the right of each panel.

The available CD provides three examples of this software being exercised for the same conditions, with different measurable parameters being emphasized, specifically, the plasma parameters N_e, T_e, and T_i. Note the movie deliberately runs slowly. This is to enable the viewer time to compare panels in order to assimilate what the satellite constellation is traversing.

Figure 2 is identical to the snapshot presentation of Figure 1 with the addition of the electron density at satellite altitude being displayed. The horizontal electron density distribution surrounding each satellite is shown in the three vertical square panels located as the second from the right side panels. The color-coding is logarithmic with highest densities being red. Figure 3 shows the same format again, but in this instance the parameter being displayed is the electron temperature. In this case, the color-coding is linear with red as the highest temperatures. In the figure, the right panel is also changed to show the electron temperature at 160 km altitude as a reference.

Measurement Reconstruction

As the satellites move through the modeled environment, measurements are being simulated and hence a pseudo data stream is created. This aspect of the study is more conventional, i.e., it emulates what scientists usually analyze. Figure 4 shows an example plot of the conventional time series type of the GEC constellation passing through the auroral zone during a substorm. It is clear that the three satellites, with an eight minute separation, see different ionospheric conditions. The variability between these satellite simulations provides a means of statistically evaluating space and time scales for different measurements.

Figure 5a shows the same simulated observations replotted in a magnetic latitude coordinate system. In this figure, the three satellite N_e data streams are superimposed and at low latitudes they are, in fact, equal. The largest variability is found in the evening sector. The second enhanced density region is caused by the satellites gaining altitude as they pass into the pre-noon sunlit F-layer; this demonstrates a "resolution"-interpolation limitation of the existing TDIM simulation. The saw-tooth pattern is removable by running the TDIM with higher resolution in this sector. Figure 5b shows the variation in the electron temperature for the same satellite orbit paths of Figure 5a, while figure 5c shows the ion temperature. The ion and electron temperatures have dramatically different space-time variability due to the fact that their respective drivers are so different.

A final example of the analysis software is shown in Figure 6. This presentation of the third satellite's electron density is given as a function of UT, altitude, magnetic latitude, and magnetic local time. In this type of figure, the various coordinates that have geophysical significance are presented. Figure 6 simply highlights the fact that the synthetic satellite data files contain all the standard coordinate information. Such information is crucial when statistical analysis of space-time phenomena is to be carried out.

Summary

The major objective of this grant has been achieved, namely the creation of a scientific tool to study "what-if" geophysical scenarios that the GEC mission would encounter. That the GEC mission within the STP line has an uncertain future makes extensive further analysis of GEC-type scenarios less than fruitful. However, the development is of a type that it can be readily re-tooled for other multi-satellite missions in the ionosphere-thermosphere region. There is no requirement that the mission must be three satellites. However, the valid geophysical conditions are restricted to those of the CTIM-TDIM-"M-I" models.

A secondary pursuit was to investigate how successful the three-satellite approach would be at resolving or characterizing the space-time variability. In carrying out test scenarios like the one demonstrated with the earlier figures, the analysis indicates that the expected variability is present but that "three" in situ points do not resolve the scales. Specifically, variability is present on many scales, both in space and time, and worse yet the events do not generate the same response signatures in the thermosphere and ionosphere, or at different altitudes! The separation of space-based variability and time-based variability becomes extremely difficult when only three satellites are available. These comments are qualitative and express a negative view on how a three-point analysis will be sufficient for resolving space weather variability in the ionosphere. The stronger value of this configuration would be in determining rates of change or motion of boundaries in the I-T system. As an example, the propagation of thermospheric disturbances from high latitudes to the equator would readily be resolved by three satellites with 10s of minutes separation, if a fortuitous storm-orbit configuration occurs.

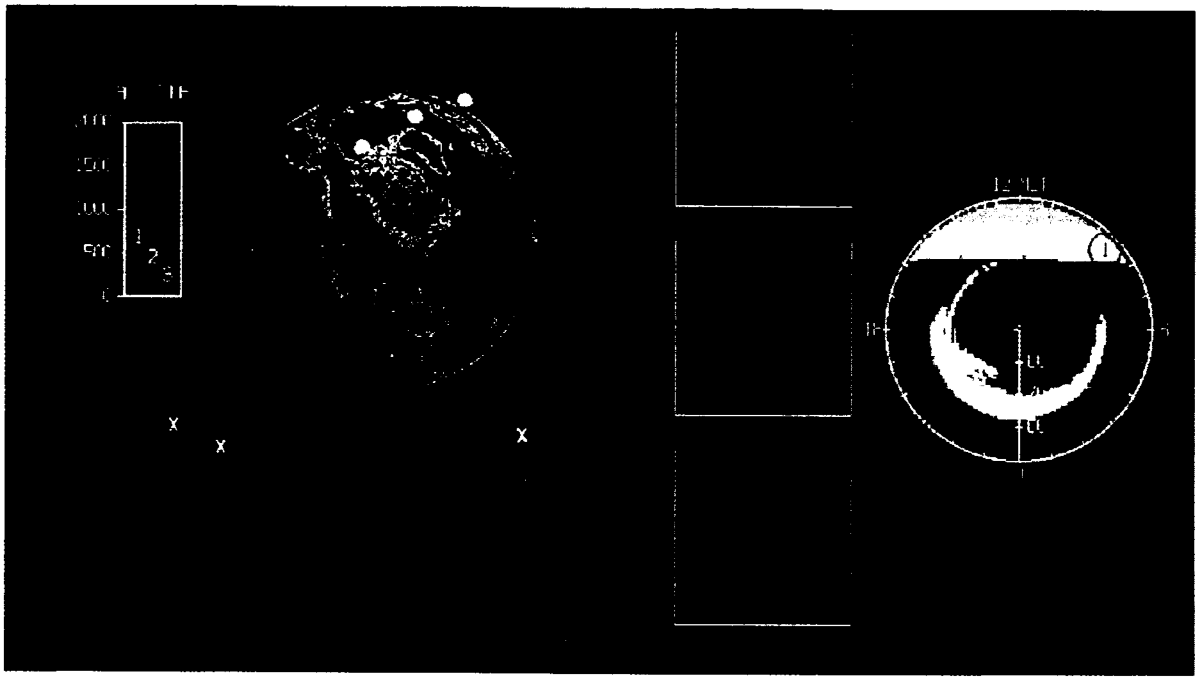

Figure 1. A snapshot from the visualization movie for a three satellite GEC configuration. Each panel is described in detail in the text.

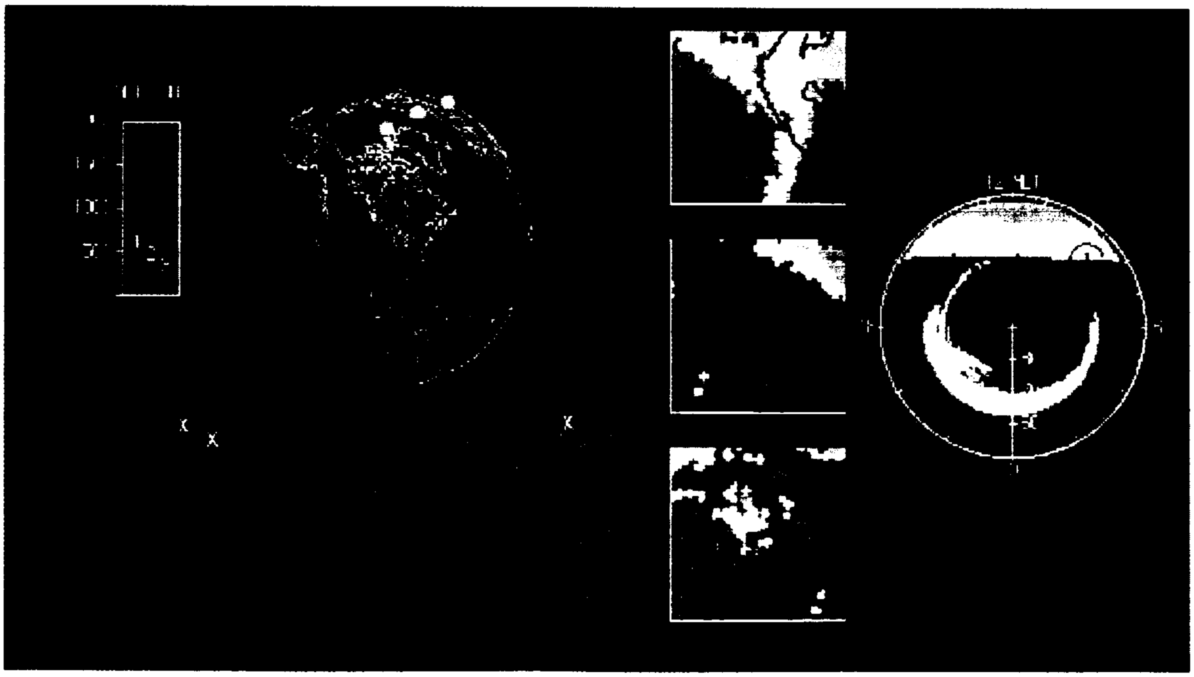

Figure 2. Same layout as in Figure 1, but the electron density distribution at satellite altitude is shown in each of the satellite views.

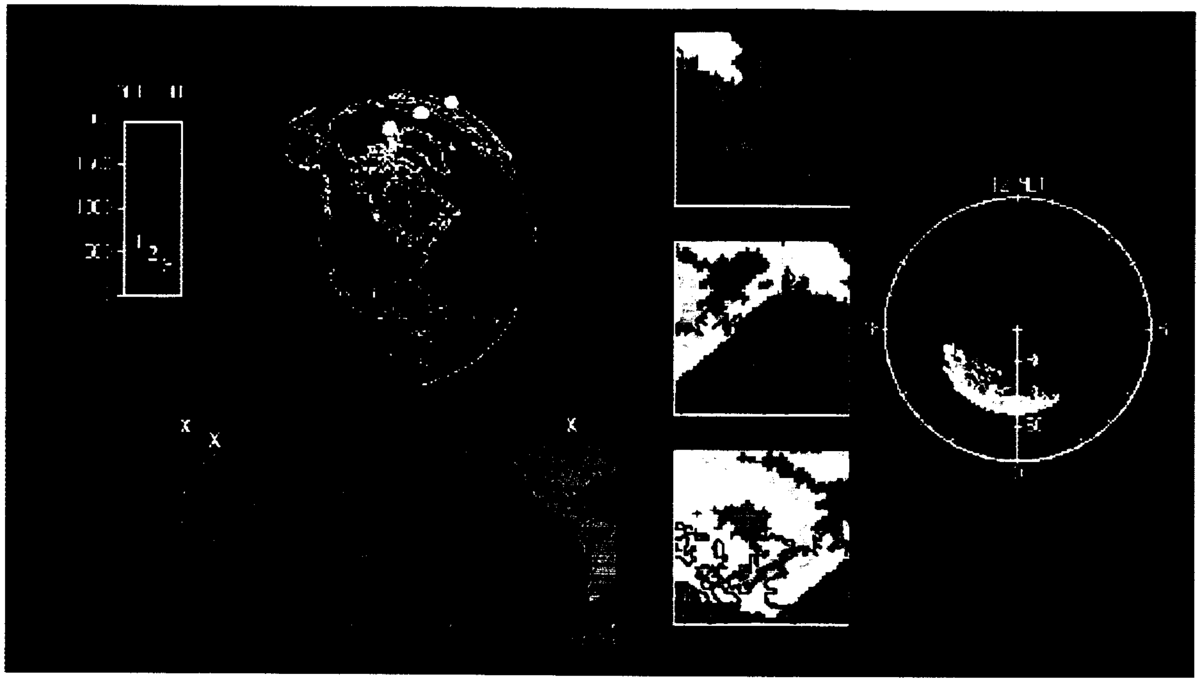

Figure 3. Same layout as in Figure 1, but the electron temperature distribution at satellite altitude is shown in each of the satellite views.

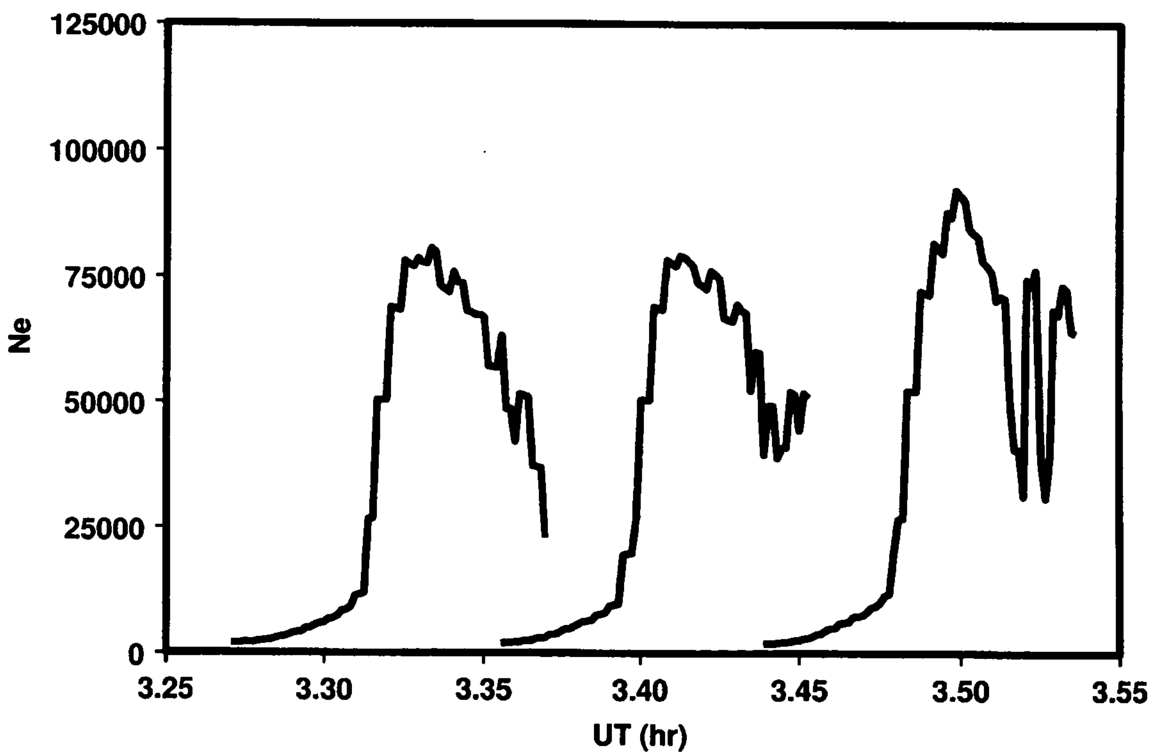

Figure 4. Electron density simulation from the three GEC satellites making a perigee pass through the northern auroral region in the pre-midnight sector.

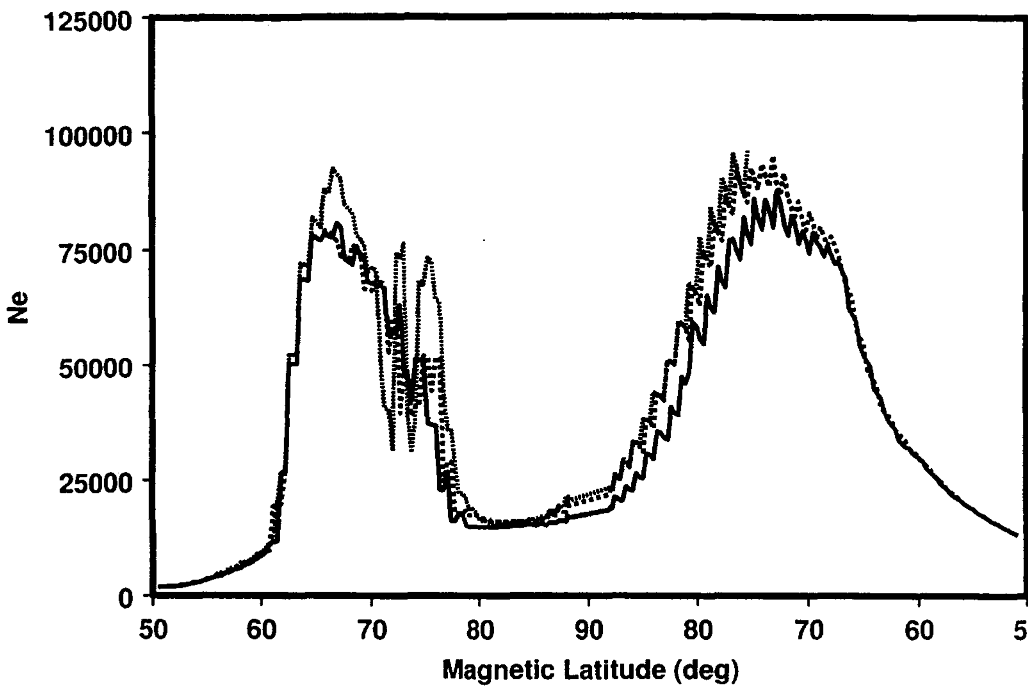

Figure 5a. The simulated electron density data has now been plotted as a function of magnetic latitude. The portion from 60° to 80° latitude is that which was plotted in Figure 4.

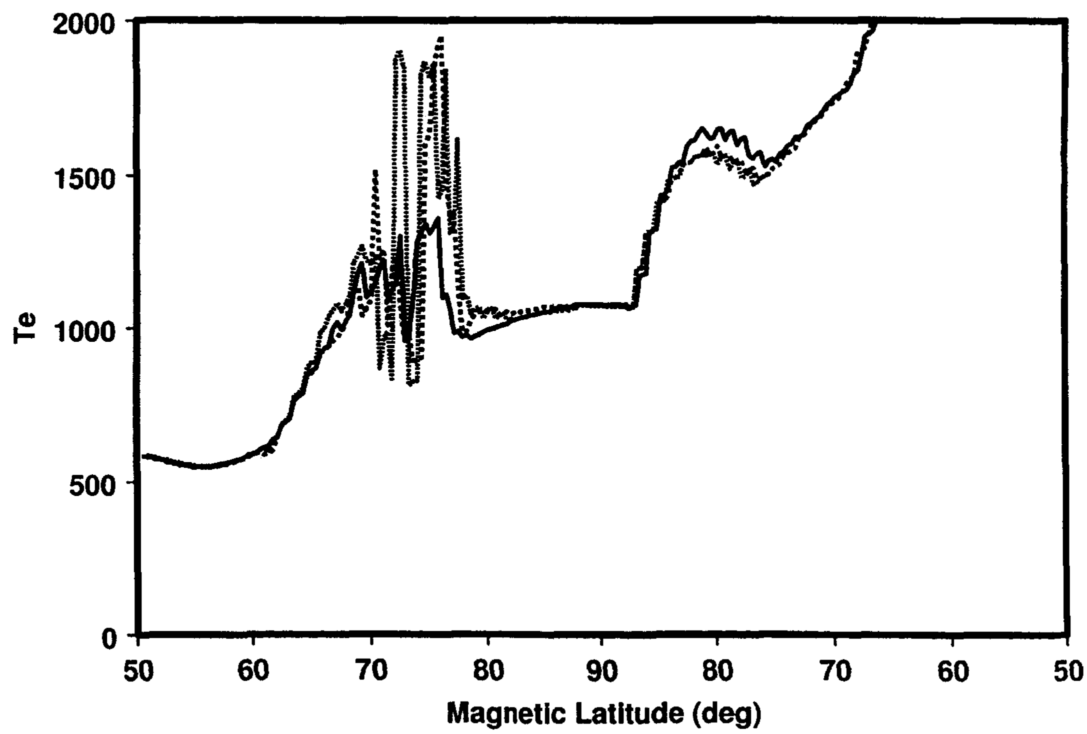

Figure 5b. The same layout as Figure 5a, but in this case the parameter displayed is the electron temperature.

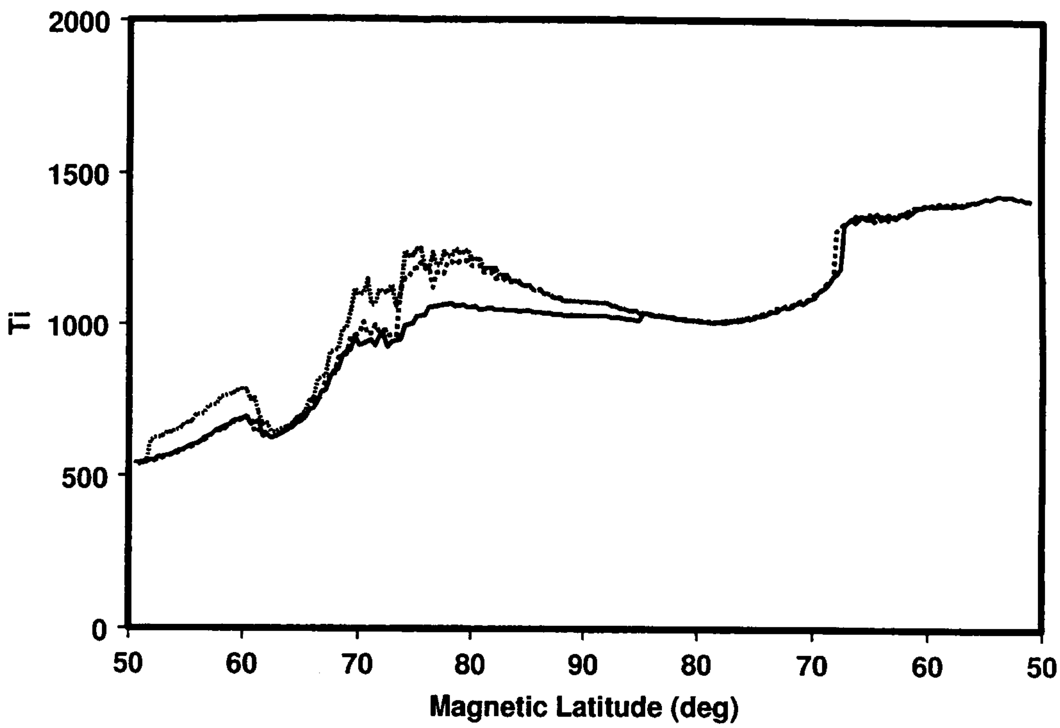

Figure 5c. The same layout as figure 5a, but in this case the parameter displayed is the ion temperature.

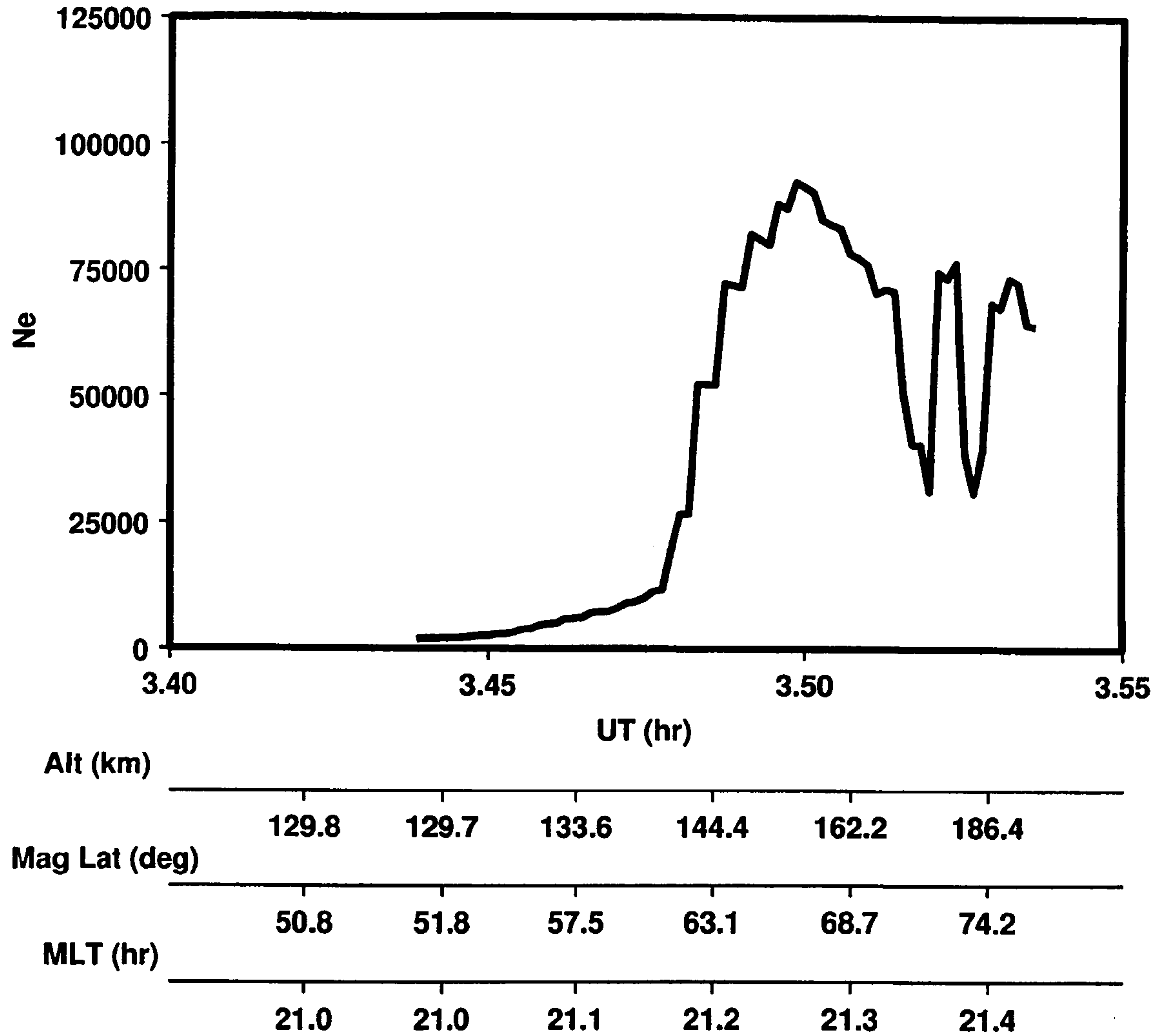

Figure 6. Shows the synthetic electron density of satellite #3 as a function of UT, altitude, magnetic latitude and magnetic local time.