AURORAL/POLAR CAP ENVIRONMENT AND ITS IMPACT ON SPACECRAFT PLASMA INTERACTIONS*

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As space systems become more complex, they have demonstrated an increasing sensitivity to the space environment. Although the shuttle will not in general be in orbit long enough to suffer severe radiation exposure nor normally experience the "hot" particle fluxes responsible for geosynchronous spacecraft charging, deleterious environmental effects are anticipated at shuttle altitudes. The high density of the plasma at shuttle altitudes is, for example, likely to increase greatly the possibility of arcing and shorting of exposed high voltage surfaces. For military missions over the polar caps and through the auroral zones, the added hazards of high energy auroral particle fluxes or solar flares will further increase the hazard to shuttle, its crew, and its mission. The purpose of this presentation is to review the role that the auroral and polar cap environment play in causing these interactions. A simple, though comprehensive attempt at modelling the shuttle environment at 400 km will be described that can be used to evaluate the importance of the interactions. The results of this evaluation are then used to define areas where adequate environmental measurements will be necessary if a true spacecraft interactions technology is to be developed for the shuttle.

INTRODUCTION

As the pace of space activities increases with the advent of the "shuttle era", the concern of engineering and scientific communities over possible adverse interactions between the space environment and spacecraft systems has grown proportionally. In particular, with the desire for large, high voltage structures, cost, complexity, and sensitivity of spacecraft have increased greatly. The necessity for long (10 years or more) mission durations in order to recoup expensive development costs has further intensified the concern for "endurable" or "survivable" spacecraft. Although much experience has been gained in these matters over the last 25 years, the fact is that there are still major gaps in our knowledge of how systems affect and are affected by the environment. After the geosynchronous environment, which has been studied extensively over the last decade, the earth's polar and auroral environments at shuttle altitudes pose the greatest risks to future space systems. The objective of this study is to review the capabilities that currently exist to predict the shuttle auroral/polar environments and to compare these predictions

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with similar ones for the equatorial environment. In order to limit the analysis, this study will only consider the environment at 400 km over the northern hemisphere during winter. Even with this limitation, the amount of information covered is still enormous. As a result, we have further restricted the study to periods of high solar (sunspot number, R, of 100) and geomagnetic activity (geomagnetic activity level, Kp, of 6_0). The emphasis will not be on the accuracy, but rather on the models necessary to adequately specify the shuttle environment. Listings of the actual models, data for other locations and conditions, and references to models not covered in the report can be obtained directly from the author.

The secondary object of the study is to determine the relative importance and sensitivity of different types of environmental interactions as a function of the environment. To accomplish this, where possible, the modelled environments have been used to predict the level of the anticipated interaction. Although this has proven to be a valuable output from the study, the interactions models employed were by necessity quite simplistic so that the absolute levels predicted are not intended to be accurate. Rather, the results demonstrate potential parameter sensitivities and areas where the environmental models need to be improved.

The report is organized into 4 sections dependent on the environment being considered. In this study, only the natural atmosphere, geomagnetic field, ionosphere, and auroral environment at shuttle altitudes were considered. Models of the cosmic ray flux, radiation level, solar electromagnetic flux, ambient electric field, gravity field, and debris environment will be presented at a later time. For each of the environments studied, an interaction is modelled. For the neutral environment, the drag is computed. For the geomagnetic field, the induced vxB electric field is estimated. For the ionosphere and auroral environments, the vehicle to space potential is estimated. The results of this analysis demonstrate, as would be anticipated, that there are indeed major differences in the environment between the equatorial and auroral/polar environments that are reflected in the interactions.

THE NEUTRAL ATMOSPHERE

By far the major environmental factor at shuttle altitudes is the earth's ambient neutral atmosphere. Whether it be through drag or the recently discovered interactions with atomic oxygen, the effect of the neutral atmosphere (predominately the neutral atomic oxygen) on spacecraft dynamics and surfaces greatly exceeds any of the other effects that will be considered in this report. Currently there exist a number of models of the earth's neutral atmosphere. These models are based on differing ratios of data and theory. The 3 main sources of data at shuttle altitudes have been neutral mass spectrometers, accelerometers, and orbital drag calculations. Without going into detail, most models attempt to fit the observations with some form of an algorithm that includes the exponential fall off of the neutral density, the effects of increasing solar activity (particularly in the ultraviolet), the local time, and geomagnetic activity. Of these, the large variations associated with increasing geomagnetic activity (and subsequent heating of the atmosphere) have eluded adequate modelling by this fitting process. Unfortunately, it is clear from many sources (see, for example, ref. 1) that these variations, particularly in density, over the auroral zone often dominate the neutral environment and that to date no adequate method of including these effects in the models has been devised (some recent very sophisticated theoretical computer models do hold promise, however).

With the preceding caveat in mind, 2 models were used to compute the variations in drag due to the neutral atmosphere at 400 km. These are the Jacchia 1972 model (ref. 2) and the MSIS model (refs. 3 and 4). These models are readily available in computer format and have been well developed over the last decade. For the purposes of this study, the Jacchia 1972 model results are presented (the MSIS model results deviate by about 20% from the Jacchia values on the average—a relatively small value given the much larger average uncertainties in the models themselves). Figure 1 illustrates the type of output that can be obtained. As stated earlier, the results are for the northern hemisphere (the reader is looking down on the north pole with the projection in terms of equal latitude intervals) and 400 km. The geomagnetic conditions for the model are for $F10.7 = 2.2 \times 10^{-20}$ $W\text{-}m^{2}\text{-}Hz^{-1}$ (the solar radio flux at 10.7 cm; believed to be proportional to the extreme ultraviolet flux) and $Kp=6_0$. These give an exospheric temperature of about 1500 °K.

Several features are apparent in the figure. First is the two-fold increase in density from midnight to noon. Further, there is the pronounced shift by 2 hours of the peak in the density and temperature maxima away from local noon. This well know phenomena results from the rotation of the earth and causes the peak in atmospheric heating to occur after local noon. The figure shows no clear feature associated with the auroral zone. This is directly due to the averaging techniques used in deriving models of this type which smooth out the density waves actually observed over the auroral zone. Even so, the model results are useful in estimating the levels of atmospheric drag and, when the processes are better known, the levels of shuttle "glow" and surface degradation.

The major effects of the neutral atmosphere at 400 km result from the impact of neutral particles on spacecraft surfaces. This causes drag and surface damage. The standard expression for the drag force is:

$$F(drag) = 1/2\, pV^2\, CD\, A = \sim(300 - 5000)\ \text{dynes} \qquad (1)$$

where:

$p = 10^{-15}$ g/cm^3 at 400 km
CD = drag coefficient = 2.2 - 4.0
A = cross-sectional area of spacecraft
= ~50 m^2 (Frontal) for shuttle
= ~400 m^2 (Base) for shuttle
V = spacecraft velocity
= 7.6 km/s

Comparing these values with Figure 1, it is evident that uncertainties in the orientation of the shuttle and lack of knowledge in the drag coefficient are equal to or greater than variations in the neutral environment at these altitudes. Given, however, the very real uncertainty

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in the effects of auroral heating, it is also apparent that these variations, if they are greater than a factor of 10 (which they can be), will be the major contributor to uncertainties in neutral drag calculations.

MAGNETIC FIELD

Aside from the gravitational field of the earth, the geomagnetic field at shuttle altitudes is the most accurately known. It can be crudely modelled in terms of a tilted (~11° from geographic north) magnetic dipole of magnitude 8×10^{25} G-cm^3. Numerous accurate models of this field exist. Here we have used the POGO model (refs. 5 and 6) as it is the basis of the International Reference Ionosphere (IRI) model employed in the next section. This model is a straight forward expansion of fits to the earth's magnetic field in terms of spherical harmonics. The total magnetic field magnitude at 400 km according to this model is presented in Figure 2. The surface field is seen to vary from a minimum of 0.25 G near the equator to 0.5 G over the polar caps. The existence of 2 peaks in the magnitude is real and reflects the true complexity of the magnetic field in the auroral/polar cap regions (note: if vector components had been included in this figure, it would have been obvious that the maximum at 270° east longitude is the true "dip" magnetic pole). Geomagnetic storm variations are typically less that .01 G so that even during a severe geomagnetic storm, magnetic fluctuations would be small compared to the average field—a marked contrast with the atmospheric and ionospheric environments! Even so, the great complexity of the magnetic field over the poles makes it difficult to use magnetic guidance systems in these regions—a fact long known to navigators.

Besides magnetic torques (which are very system dependent), the earth's magnetic field can induce an electric field in a large body by the vxB effect:

$$E = 0.1\ (v \times B)\ \text{V/m} = 0.3\ \text{V/m} \qquad (2)$$

where:

v = spacecraft velocty =
= 7.6 km/s
B = 0.3 G

Since the shuttle is roughly 15 m x 24 m x 33m, potentials of 10 V could be induced by this effect. As systems grow to km or large dimensions, the induced fields will grow accordingly.

In Figure 2, the induced electric field for a vehicle of ~90° inclination has been calculated. As would be anticipated, the largest electric fields are seen over the polar caps. The ambient environment can also produce strong electric fields in the auroral/polar regions. Although not shown here, these fields can reach values of nearly 100 mV/m (see ref. 7)—a sizable fraction of the induced field. These fields are also comparable to the fields necessary to deflect charged particles in this environment as the particles have ambient energies of typically 0.1 eV (ram energies for the ions like oxygen can reach several eV, however) and thus must be taken into account when studying ionospheric fluxes.

IONOSPHERE

Given the importance of the ionosphere to radio and radar propagation, it is surprising to find that relatively few models are available for the ionosphere. Less surprising is the fact that most of these models only predict electron densities--the most readily measureable quantity by ground means and the most important to radio propagation. The principle ionospheric model available based on observations is the International Reference Ionosphere (ref. 8). This is the only readily available computer model that gives the electron and ion composition and temperature as a function of longitude, latitude, altitude (65 to 1000 km), solar activity (by means of the sunspot number, R), and time (year and local). Although the model is obviously limited (it is confined to R values of 100 or less whereas R values of 200 or greater may occur during solar maximum), it nonetheless is the "best" available comprehensive model of the ionosphere.

In Figures 3 and 4, for the northern hemisphere, are presented several examples of the output from the IRI model. Figure 3 presents the electron number density and temperature at 400 km for R=100 in December. Unlike the neutral temperature, the electron temperature increases by a factor of 2 in going from the equator to the pole. Like the neutral density, however, the peak in the electron density again is shifted by about 2 hours from local noon.

At 400 km, the ionosphere, primarily because of the corresponding high level of neutral oxygen, is dominated by oxygen ions (45% near local midnight and below 30^0 latitude to 97% over the pole). Values for oxygen are presented in Figure 4. The temperature is assumed to be the same for all ion species in this model (i.e., for O^+, H^+, He^+, $O_2{}^+$, and NO^+) and can not for physical reasons ever exceed the electron temperature. Unfortunately, at 400 km for R=100 or larger, the IRI model will occasionally predict ion temperatures far in excess of the electron temperature. This reflects the fact that the model is based on a limited set of data (R<100) and needs improvement. Theoretical models exist that avoid this problem but these models are still too cumbersome to be useable on all but the largest computers.

In Figure 5, using a simple 1-dimensional, "thin sheath" ram model for ion collection (described in ref. 9), potentials for the case of no secondary emission and no photoelectron current were calculated based on Figures 3 and 4. The spacecraft to space potential varied from -0.2 V at the equator to -0.7 V at the pole--in rough agreement with observations (ref. 9). Thus, based on the IRI model environment alone, spacecraft charging should not be a concern (note: the high plasma density will, however, encourage plasma interactions with exposed high potential surfaces as discussed elsewhere in this book).

AURORAL ENVIRONMENT

The most dramatic changes in the earth's environment at shuttle altitudes are brought about by geomagnetic substorms. These changes are reflected in visible auroral displays and in intense particle and field variations in the auroral region at shuttle altitudes. In this section, a simple auroral flux model based on data provided by the Air Force Geophysics Laboratory (courtesy M. Smiddy and D. Hardy; see papers by Smiddy and Hardy, this volume) is presented in order to estimate these effects. The data were provided in the form of 7 sets of color contour plots of the electron number flux and energy flux in intervals of Kp from 0 to 6. The plots were crudely approximated by a simple analytic function in geomagnetic local time and latitude and the geomagnetic Kp index. Although, the AFGL data were for about 800 km, no attempt has been made to correct for altitude in this model.

The crude model developed from the AFGL data was used to estimate the auroral/polar cap electron temperature and number densities. These results for the northern winter hemisphere and a Kp of 6_0 are shown in Figure 6. They imply that there is a peak in the density of the auroral electron flux of about 1000 cm^{-3} in the noon sector while the auroral electron temperature is 1 keV in the post-midnight sector. Although the validity of this crude result will need to be compared with the actual AFGL data when they become available, the range of values should at least be indicative of the characteristics of the average auroral fluxes (comparisons with other data sources bear this out).

The results in Figure 6 can be used in conjunction with the IRI data at 400 km to estimate the expected variations in spacecraft potential in the auroral zone and over the polar caps (note: the auroral ion fluxes should not contribute significantly to the ambient ion current so that their exclusion should not seriously alter the results). When this calculation was carried out, there was little or no change from the results in Figure 5. This is not surprising as it is generally believed that the average auroral flux levels seldom exceed the ambient ion and electron ionospheric fluxes.

In order to estimate what auroral flux levels are in fact necessary to bring about significant increases in the spacecraft potential in the auroral/polar cap regions, the electron density and temperature in Figure 6 were increased by varying factors. Changes of a factor of 10 in either the temperature or density had little effect on the potential. A factor of 10 in both the electron density and temperature did, however, bring about a significant increase in the potential--raising it from a few tenths of a volt negative to several thousands of volts in the early afternoon sector. These results are illustrated in Figure 7. Such a large increase in the auroral flux may seem unrealistic but a careful review of auroral data does imply that occassionally intense fluxes 10 to 100 times that of the average flux may indeed occur over narrow regions in the auroral zone (see, for example, Burke, this conference).

In carrying out the potential analysis, it was found that the details of the assumed charging model greatly affected the results. Specifically, if a 1-dimensional, thin sheath model was assumed, the auroral potentials could reach -6000 V when the ion return current was equated to the cold ambient ion current. If the ion return current was assumed to be the ram current, as was done here, the potential was about -1200 V maximum (this is probably the more "realistic" assumption). If on the other hand the ion return current in the charging model was assumed to be for the thick sheath, orbit-limited case such as normally assumed at geosynchronous orbit, the potential was only -1 to -2 V! This sensitivity to the details of the amount of return current is to be expected given the simplicity of the charging model and its resolution will need to await the development of more accurate charging models for the conditions at shuttle altitudes.

CONCLUSIONS

This paper has brought together most of the elements needed to form a complete model of the ambient shuttle environment for the purpose of studying spacecraft interactions. Emphasis has been on modelling the interactions in the auroral/polar cap regions where it was demonstrated that, although models of the average ambient environment (neutral particles, fields, ionospheric particles, and auroral/polar cap fluxes) are probably satisfactory for many interaction study purposes, the intense variations in the auroral zone are not adequately modelled. These variations are known from in-situ observations to exist and to result in several orders of magnitude increase in the charged particle fluxes and atmospheric heating which can similarly alter the neutral compostion. It is only relatively recently that long term statistical studies and examples of extreme cases have become available. It is to be anticipated that, in the near future, models of the evironment will become increasingly sophisticated and capable of being used in modelling effects such as spacecraft charging much more accurtely than presented here. Even so, the results presented should assist current interaction studies in better assessing average levels of effects in the auroral/polar regions and in comparing equatorial and auroral/polar environments. The process of presenting the models has also clearly indicated where improvements need to be made in the existing models. This is particularly true in the case of the auroral model due to the varying sensitivity of the principle interaction to changes in the ambient environment (i.e., spacecraft potential calculations).

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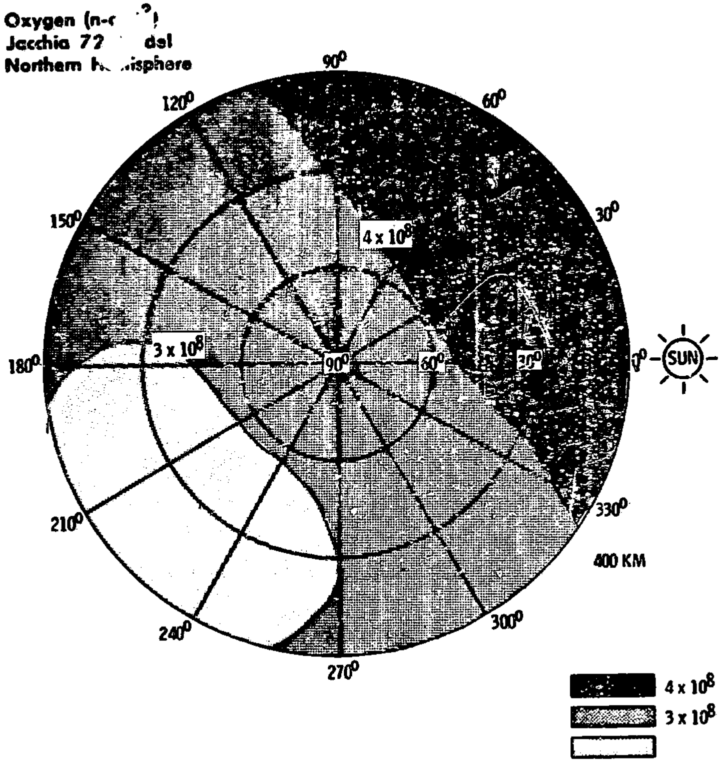
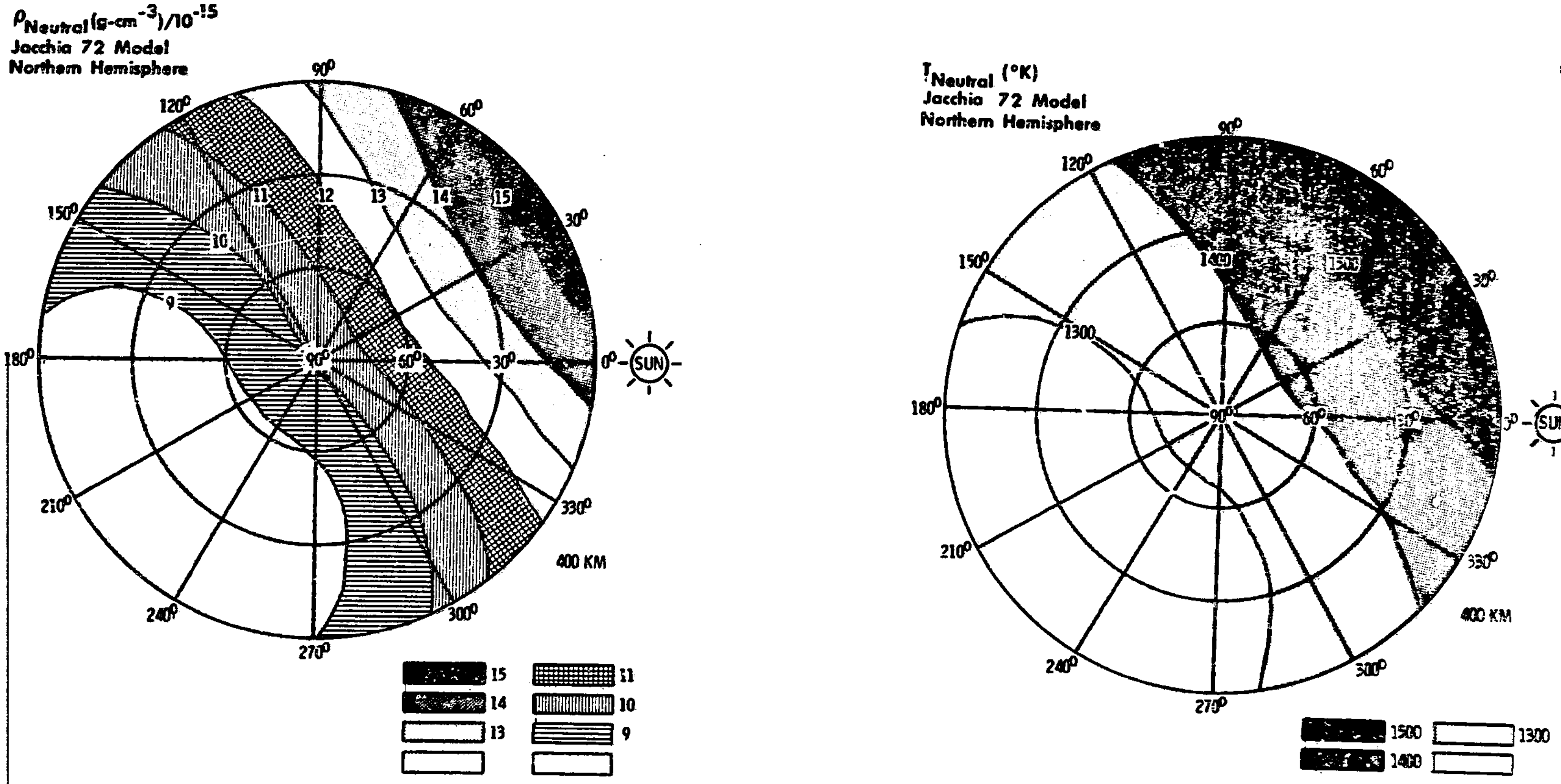


(c) Number density of oxygen.

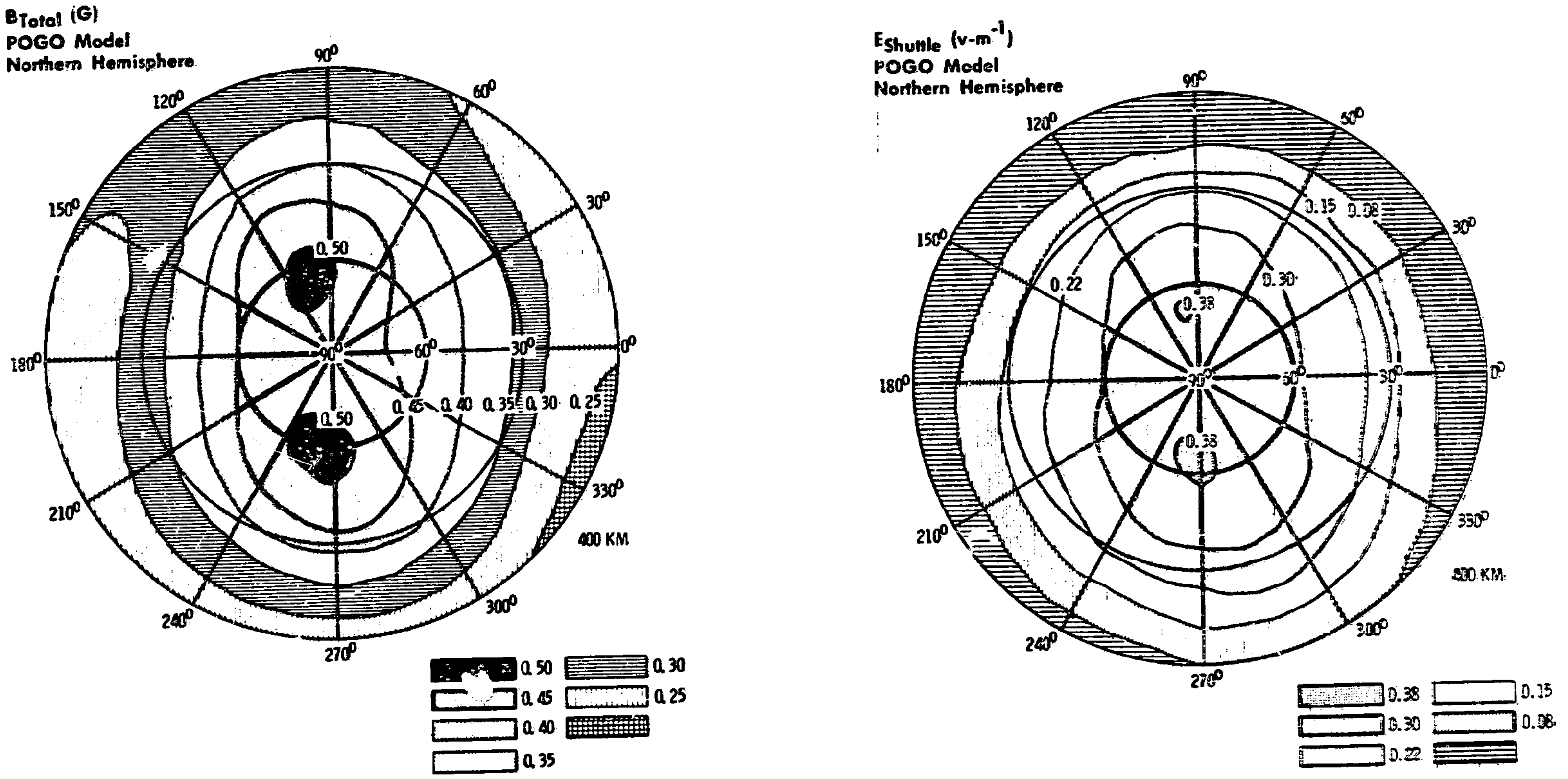
Figure 1. - Concluded.



(a) Neutral density.

(b) Neutral temperature.

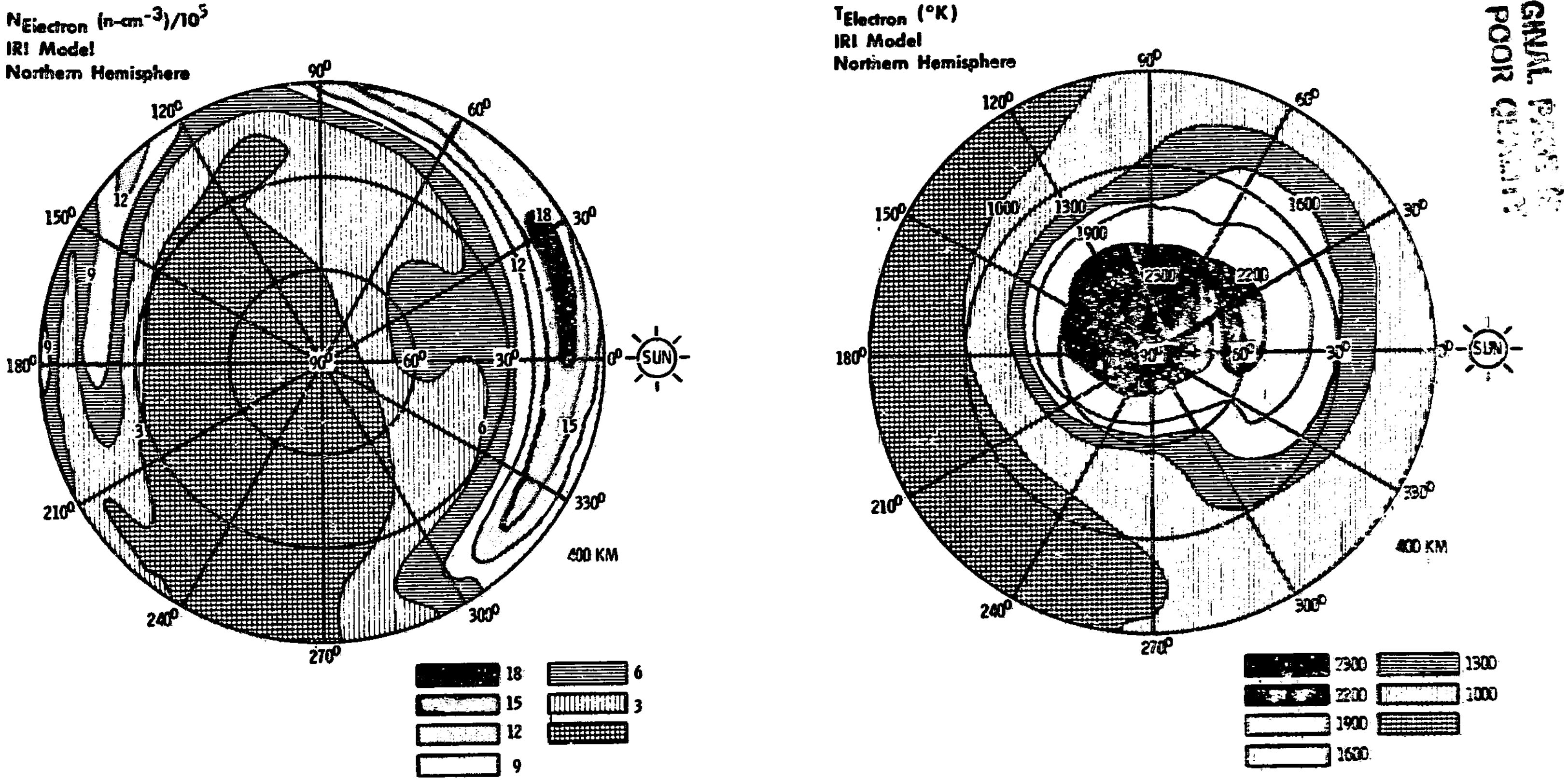
Figure 1. - Polar view of Northern Hemisphere. Polar coordinates are employed such that radial distance is in intervals of equal latitude (0° is the equator) while angular coordinate is east longitude. Neutral atmosphere conditions for $K_p=6_o$, F10.7=220, day 357.5, and altitude of 400 km as computed by the Jacchia 1972 model are shown.



(a) Total magnetic field at 400 km.

(b) Absolute value of vxB electric field induced on a body in a 90° inclination orbit for POGO model.

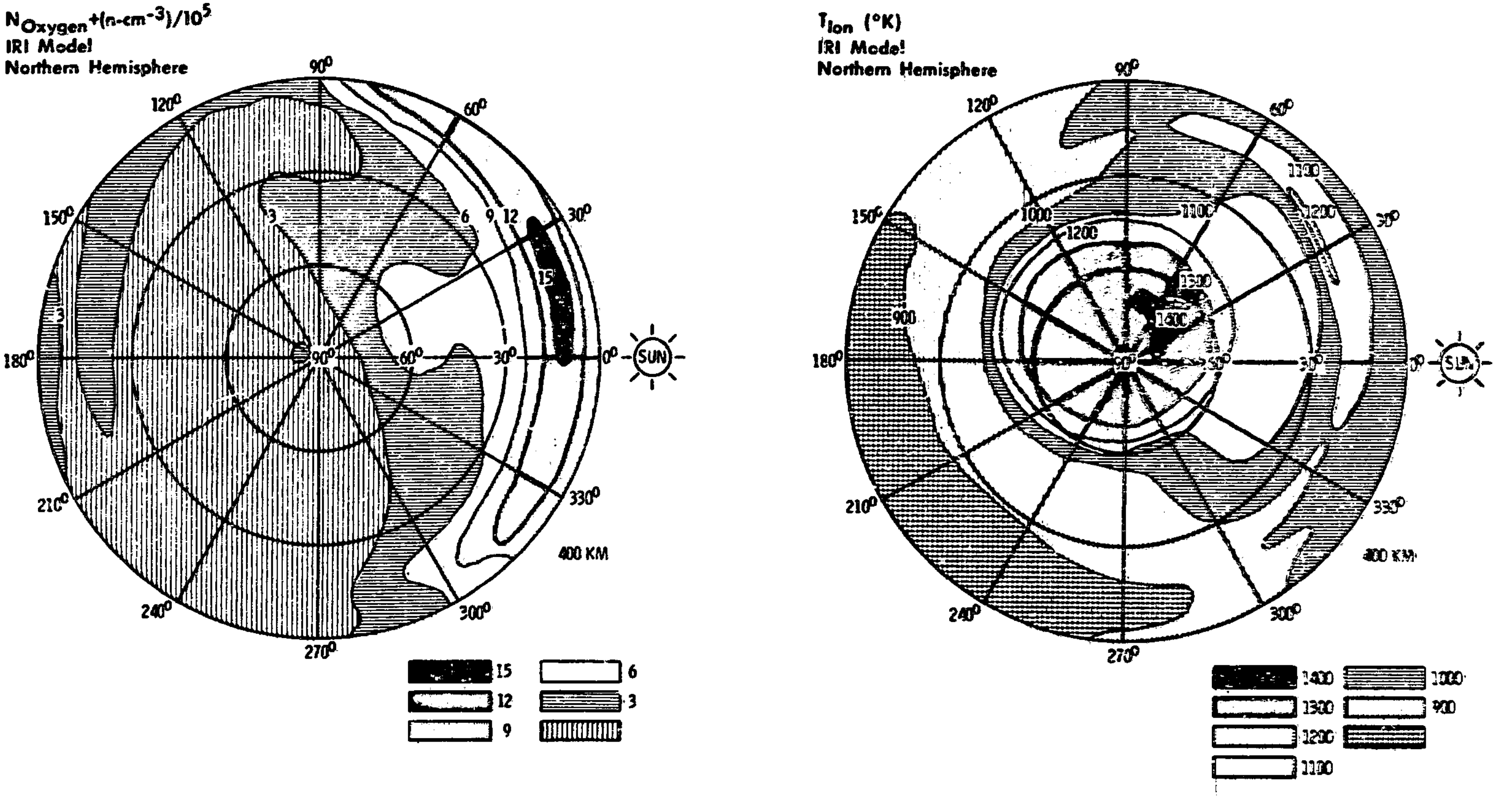
Figure 2. - Polar view as in figure 1 for POGO magnetic field model.



(a) Electron density at 400 km.

(b) Electron temperature at 400 km.

Figure 3. - Polar view of electron environment as in figure 1 for IRI model. Conditions are the same as in figure 1 with the additional constraint that R=100.



(a) Oxygen ion density at 400 km.

(b) Oxygen ion temperature at 400 km.

Figure 4. - Polar view of oxygen ion environment as in figure 1 for IRI model. Conditions are the same as in figure 1 with the additional constraint that R=100.

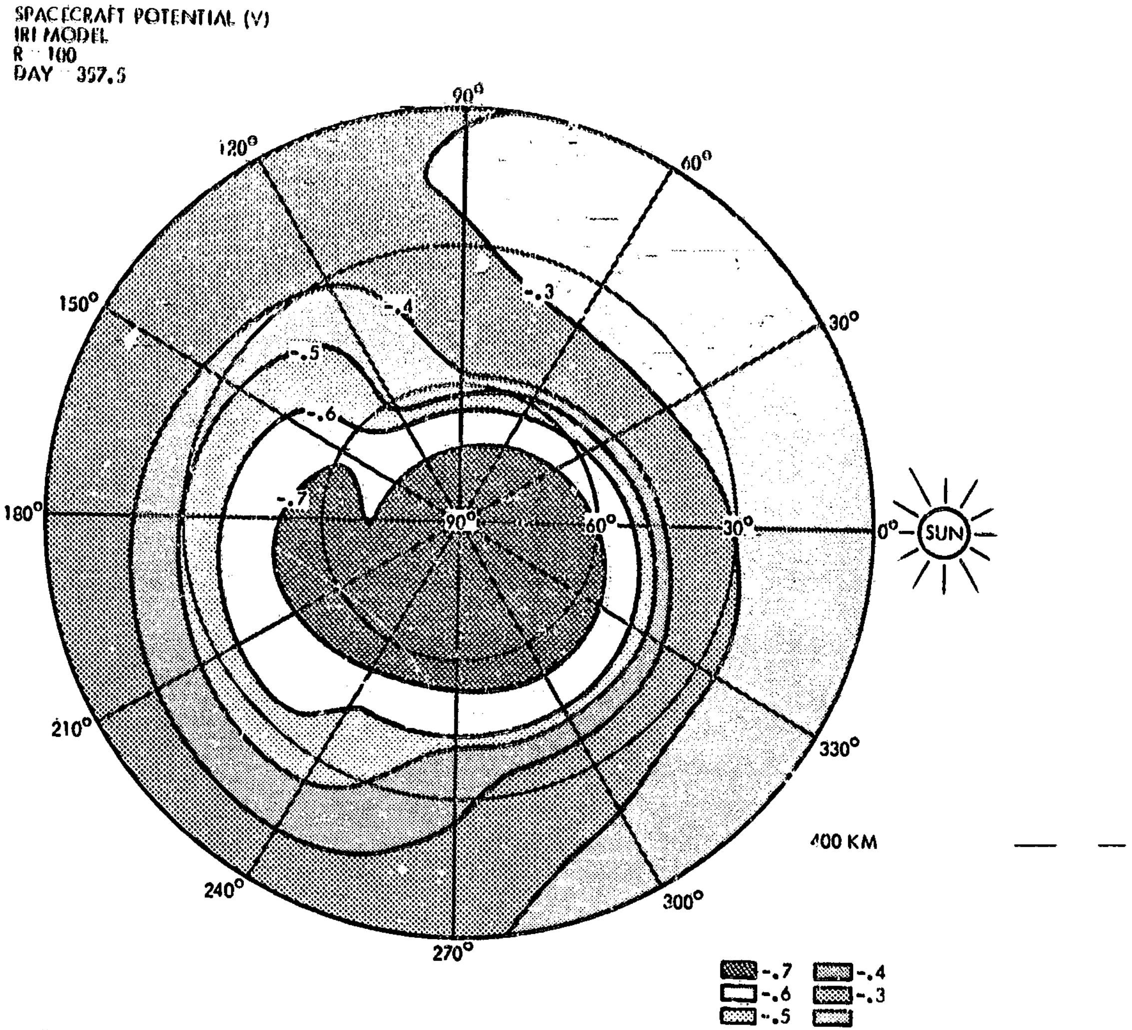
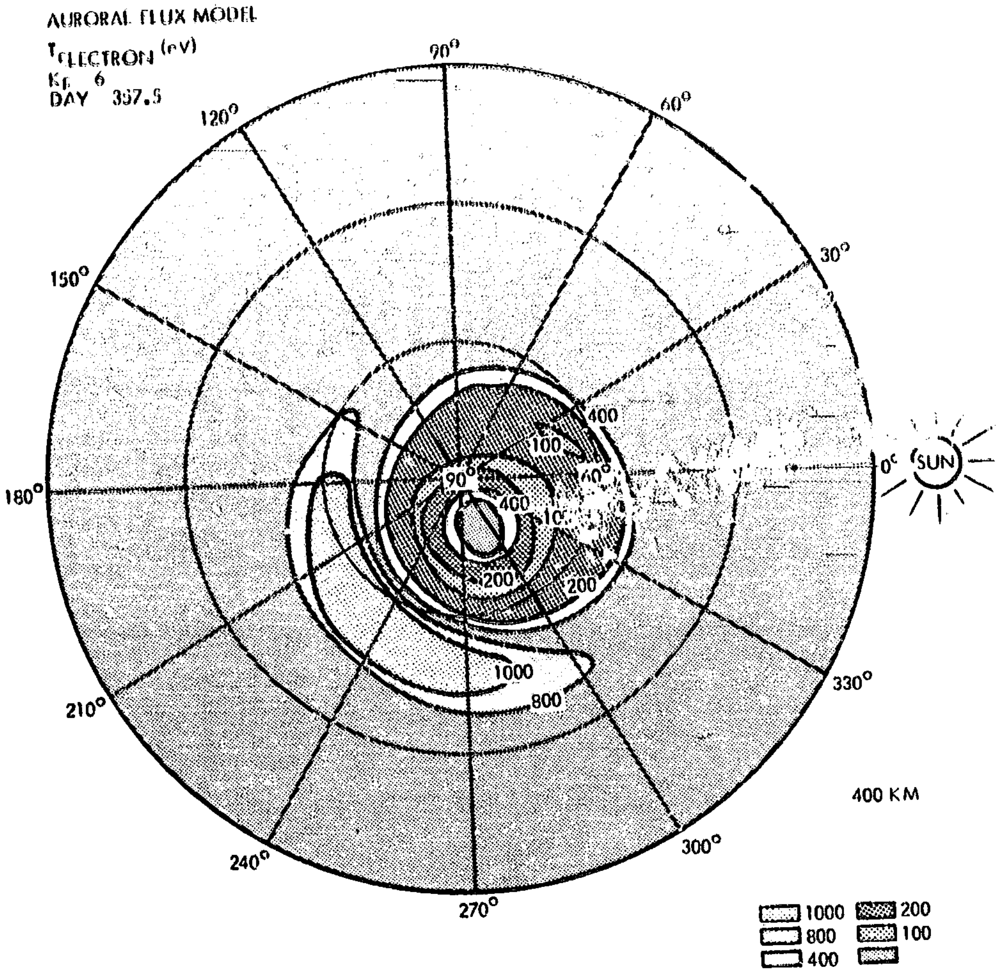
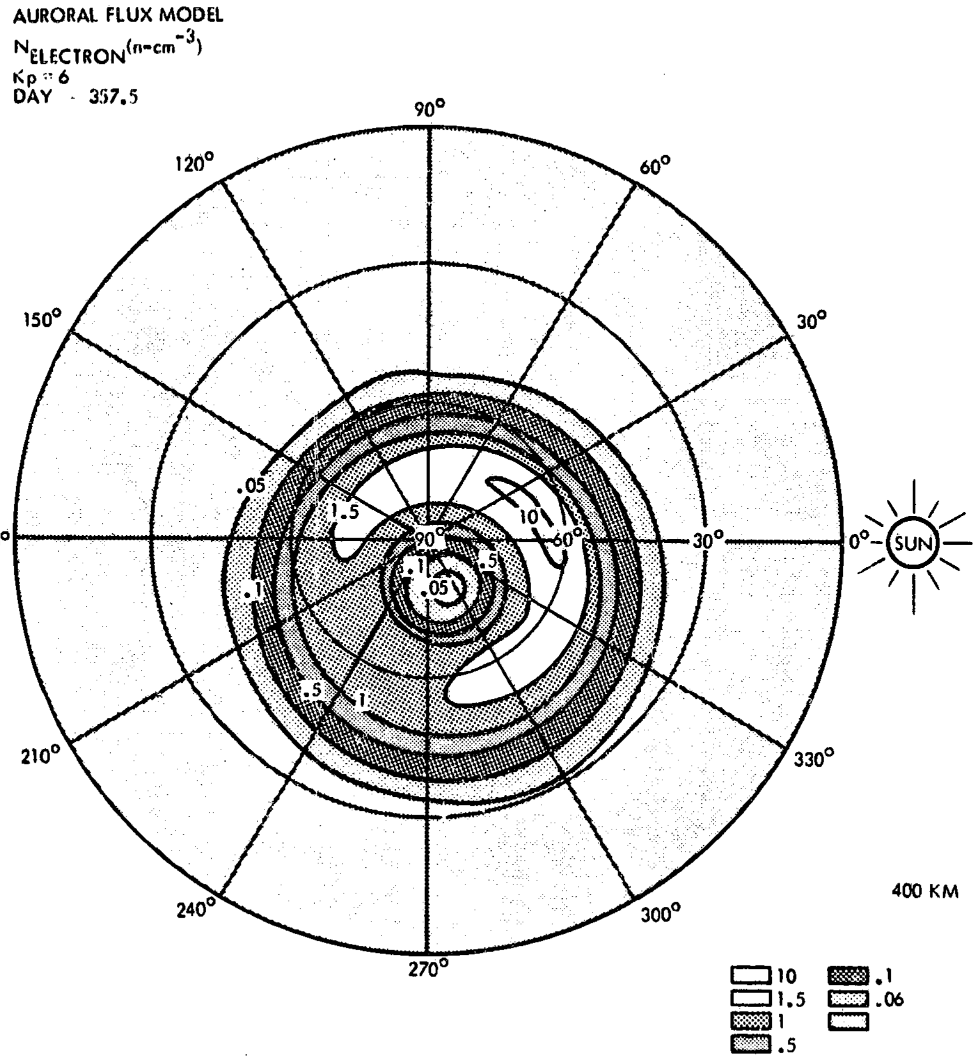


Figure 5. - Polar view as in figure 1 of spacecraft-to-space potentials predicted for IRI model. Potentials were computed assuming that the ion current was proportional to the ion ram flux (see text) and that there were no secondary or photoelectron currents.



(a) Density of auroral electron flux at 400 km.

Figure 6. - Polar view as in figure 1 of auroral flux model adapted from AFGL observations. Conditions correspond to $K_p=6_0$ and for day 357.5.



(b) Temperature of the auroral electron flux at 400 km. Units are °K.

Figure 6. - Concluded.

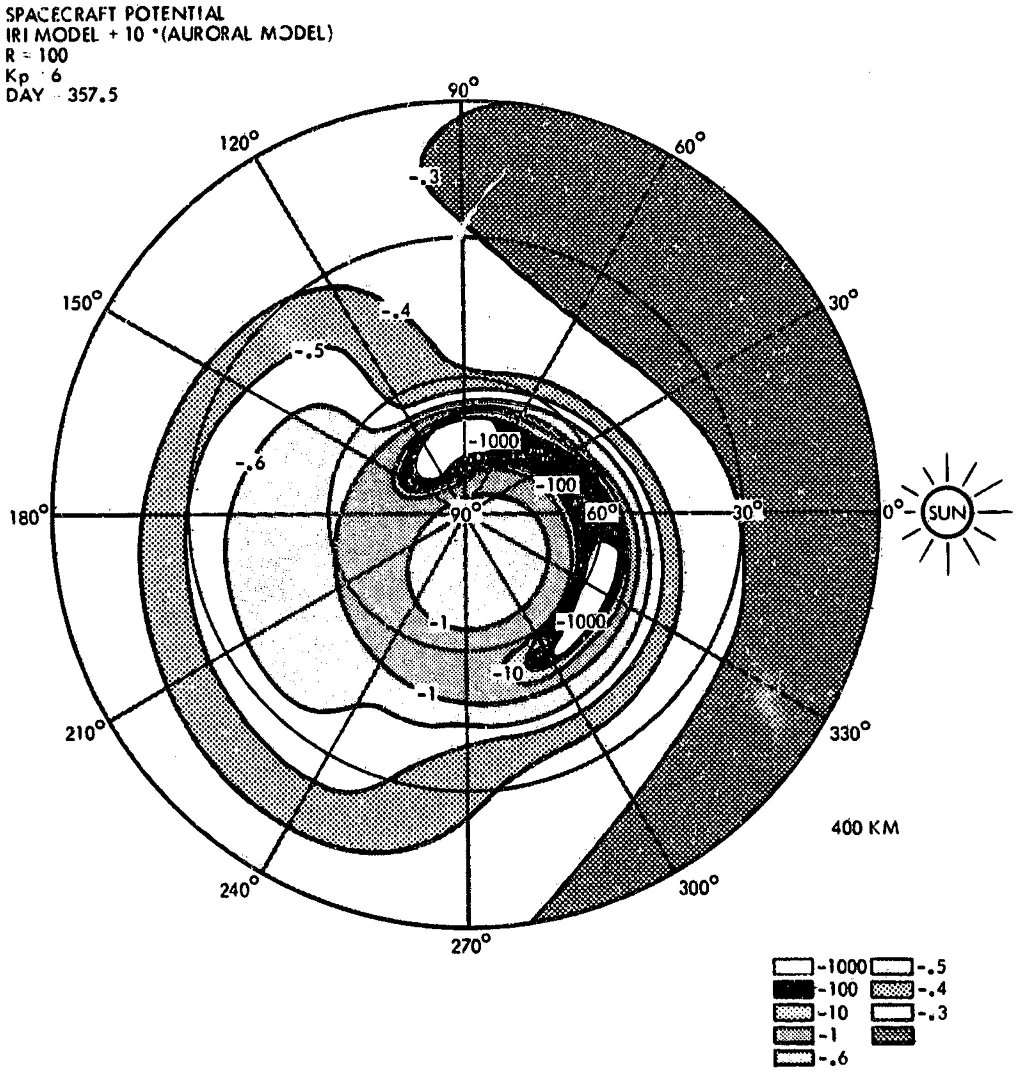


Figure 7. - Polar view as in figure 1 of spacecraft-to-space potentials predicted for combination of IRI and auroral models. Potentials were computed as in figure 5 except that the auroral density and temperature from figure 6 have both been multiplied by 10.