SPECIFICATION OF ISS PLASMA ENVIRONMENT VARIABILITY

Joseph I. Minow
Jacobs Sverdrup, Marshall Space Flight Center Group
MSFC/ED44, Huntsville, AL 35812
Phone: (256) 544-2850
Fax: (256) 544-0242
E-mail: joseph.minow@msfc.nasa.gov

Linda F. Neergaard
Jacobs Sverdrup, Marshall Space Flight Center Group

Them H. Bui
Microcraft, Inc., MSFC Group

Ronald R. Mikatarian
H. Barsamian
The Boeing Company

Steven L. Koontz
NASA, Johnson Space Center

Abstract

Quantifying spacecraft charging risks and associated hazards for the International Space Station (ISS) requires a plasma environment specification for the natural variability of ionospheric temperature (Te) and density (Ne). Empirical ionospheric specification and forecast models such as the International Reference Ionosphere (IRI) model typically only provide long term (seasonal) mean Te and Ne values for the low Earth orbit environment. This paper describes a statistical analysis of historical ionospheric low Earth orbit plasma measurements from the AE-C, AE-D, and DE-2 satellites used to derive a model of deviations of observed data values from IRI-2001 estimates of Ne, Te parameters for each data point to provide a statistical basis for modeling the deviations of the plasma environment from the IRI model output. Application of the deviation model with the IRI-2001 output yields a method for estimating extreme environments for the ISS spacecraft charging analysis.

Introduction

Empirical ionosphere models are used in applications requiring electron and ion density (Ne, Ni) and temperature (Te, Ti) predictions for spacecraft design and mission analysis studies although the output of these models are typically limited to mean values. In many applications, however, knowledge of the electron temperature and density variations about the mean and the magnitude of extreme deviations are important parameters as well, particularly for spacecraft designers and operations support personnel conducting space environment analysis for low Earth orbit missions. Quantifying the spacecraft charging risks and corresponding hazards for the International Space Station (ISS) is such a case where the mean plasma environment is not

Table 1. Historical Satellite Records

Spacecraft	Records in Study
•AE-C	**[1973-12-16 to 1978-12-11]**
–Circular, 68.1 deg in	608,139 records
–Elliptical 150 km x 4300 km	
–68.1 deg inc	
•AE-D	**[1975-10-06 to 1976-01-29]**
–Circular, 90.1 deg inc	100,395 records
–Elliptical, 154 km x 3816 km	
–90.1 deg inc	
•AE-E	**[1975-12-01 to 1981-05-24]**
–Circular, 19.7 deg inc	464,690 records
–Elliptical, 156 km x 2983 km	
–90.1 deg inc	
•DE 2	**[1981-08-06 to 1983-02-15]**
–Elliptical, 300 km x 1000 km	693,112 records
–89.99 deg	

sufficient to determine the maximum range of spacecraft potentials that may be expected during the construction phase of the vehicle and after assembly complete. Specification of ionospheric Ne, Te conditions for a spacecraft charging analysis requires not only the mean environment for mean charging conditions but estimates of the extreme values as well to determine if the maximum spacecraft potentials anticipated for any configuration of the vehicle will remain within the –40 volt program requirement. This paper describes the development of a prototype empirical ionosphere variability model for the ISS program intended for use with the International Reference Ionosphere (IRI) to provide ionospheric mean Ne and Te values as well as predictions of the range of variations in Ne and Te about the IRI output values.

Database

Satellite observations of electron density and temperature measurements are used to provide the database in the portion of the study reported here (although current work is underway to include ground based incoherent scatter radar observations as well). Data sets used in the study were obtained from the National Space Science Data Center (NSSDC), Goddard Space Flight Center, and are listed in Table 1. Since many of the satellites included in the database are the same satellites used in constructing the IRI topside models (Bilitza, 1994, 1997, 2001) the data set is particularly useful for examining variations in Ne and Te about the IRI values. Analysis of spacecraft charging data from the Floating Potential Probe instrument onboard the ISS during the winter and spring of 2001 (Ferguson, 2001; Ferguson et al., 2001) demonstrated that the

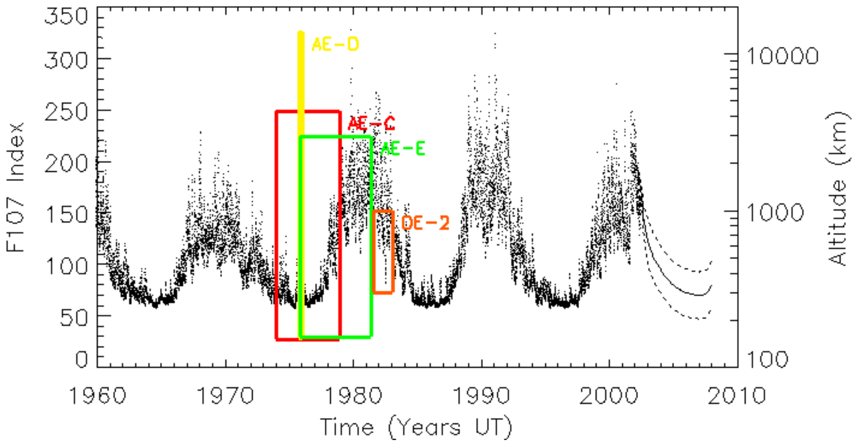


Figure 1. Altitude, solar cycle distribution of Ne, Te records. Altitude range and mission dates for the satellites are indicated by the colored boxes. The F107 EUV proxy index (in Solar Flux Units =10^{-22} W/m^2/Hz) is given to demonstrate phase in the solar cycle. Although the complete database covers nearly two solar cycles, only the AE-C, D, E and DE-2 data is included in the analysis (AE-E was removed) and results for this paper.

vehicle negative potential increases with increasing Ne and decreasing Te values and that the threat condition for maximum negative potential is high Ne, low Te values (Ferguson et al., 2001, 2003; Mikatarian et al. 2002, 2003). Since both Ne and Te parameters are required to determine the spacecraft potential, only data where simultaneous Ne and Te values are available are included in the study since these are required for estimates of spacecraft potential.

The data from the Atmosphere Explorer and Dynamics Explorer satellites, the subject of this paper, covers nearly a complete solar cycle. Electron density and temperature values were obtained from Langmuir probes on the Atmosphere Explorer series (Brace et al., 1973) and DE-2 (Krehbiel et al., 1981). Density values are available from the AE satellites over a range from $5.0\text{x}10^7$ to $1.0\text{x}10^{12}$ electrons/cm^3 and temperatures from 0.03 to 0.86 eV with an accuracy of approximately 10% to 20% (Brace, 1998). Additional data appropriate for the ISS study is currently being processed and incorporated into the database including the AEROS A satellite (~200 km to 800 km) and a large selection of incoherent scatter radar observations from Arecibo (Puerto Rico), Millstone Hill (Massachusetts), Jicamarca (Peru), and St. Santin (France). Finally, over three years of data from the Challenging Minisatellite Payload (CHAMP) satellite (circular orbit at ~400 km altitude) will also be available in the near future to include in the database. Results from the extended database will be provided elsewhere in a future report.

Data is available over a wide range of altitudes for low Earth orbit. All AE and DE-2 satellite data from 200 km to 1000 km is shown in Figure 2-a although only a restricted range of altitudes is useful for the ISS study. Figure 2-b are all data values (including both night and day) for the 350 km to 450 km altitude range appropriate for the ISS study. Night time data is not of interest to the ISS charging study since biased solar arrays are required for the electron collection process on the solar arrays to occur (Mikatarian et al., 2003; Gardner et al., this conference).

Further filtering of the data set by rejecting nighttime values finally yields the remaining data shown in Figure 2-c.

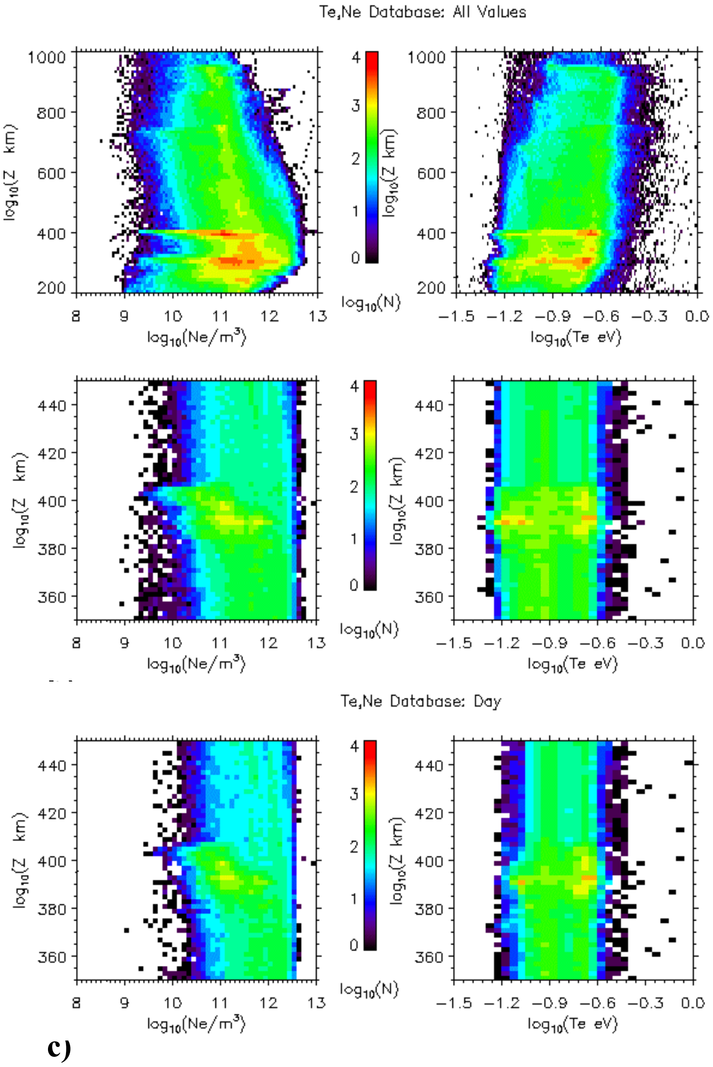


Figure 2. Distribution of Ne, Te values in database. Two-dimensional histograms of Ne-altitude (left panels) and Te-altitude (right panels) are shown for (a) all data from 200 km to 1000 km, (b) all data within 350 km to 450 km, and (c) only daytime data in 350 km to 450 km altitude range.

A two-dimensional histogram of the number of Ne, Te pairs is given in Figure 3 showing the number of values available in the ISS study set (350 km to 450 km) as a function of latitude and longitude. Coverage of the database is global since both polar and low inclination satellites are included in the database but only values with latitudes in the range -55° < λ < +55° are retained for the ISS study.

Although there are nearly two million individual records available in the original data sets obtained from NSSDC, not all records contain paired Ne and Te values. In addition, when specific application requires a subset of the complete database (for example, the ISS study), restricting latitude and altitude ranges further reduces the available data. For example, Table 2 demonstrates the impact of restricting the data to only those values appropriate to the ISS charging study. Of the original 1.96 million data records available from the NSSDC archives, only 1.89 million remain after removing records with missing latitude and longitude information, invalid Te or Ne values, and other data problems. Requiring coincident Te and Ne values further reduces the database to 1.17 million data records. Although this may seem like a large number of records, they are distributed over all latitudes and longitudes providing minimal statistics in localized regions. For example, there would be a few tens of values in a single 1° x 1° cell assuming a random distribution of data points distributed over a 200 km to 1000 km altitude range, not a very extensive database for deriving statistical variations in plasma parameters! If the geographical range is increased to a 5° x 5° cell then there would be approximately 700 values distributed over the altitude range. Restricting the database to the ISS altitude range and daytime conditions further reduces the amount of [Ne, Te] pairs to less than 100,000 records. Clearly the quality of any statistical analysis based on the database will benefit from a large amount of data and results are anticipated to improve with the introduction of additional satellite data and the incoherent scatter radar observations into the data set.

Scatter plots of Ne,Te values are shown in Figure 4-a for the complete historical dataset while Figure 4-b is a subset where the database has been filtered to retain only data available for the specialized application of determining the range of electron density and temperatures at sunrise and through the daytime period over the range of altitudes and latitudes available to the International Space Station. Filtering the data is required to obtain statistics appropriate for a very specific set of conditions but at the cost of reduced statistical quality of the results due to due to the reduction in the number of records in the database.

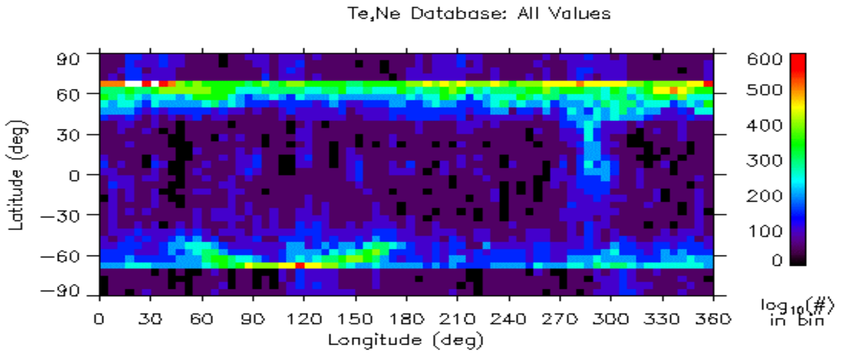


Figure 3. Latitude and Longitude Distribution of Ne, Te Data. The two-dimensional histogram shows the number of [Ne,Te] pairs of AE-C, AE-D, and DE-2 data values in 5 degree latitude/longitude bins. Only data within the 350 km to 450 km ISS study altitude range is included in the figure.

Table 2. Available Data

- **1,959,651 records in NSSDC data distribution**
- **1,894,008 remain after removing bad records**
  - –Missing lat/lon information
  - –zero or missing Ne, Te values
  - –other problems
- **1,173,581 records with coincident Ne, Te values**

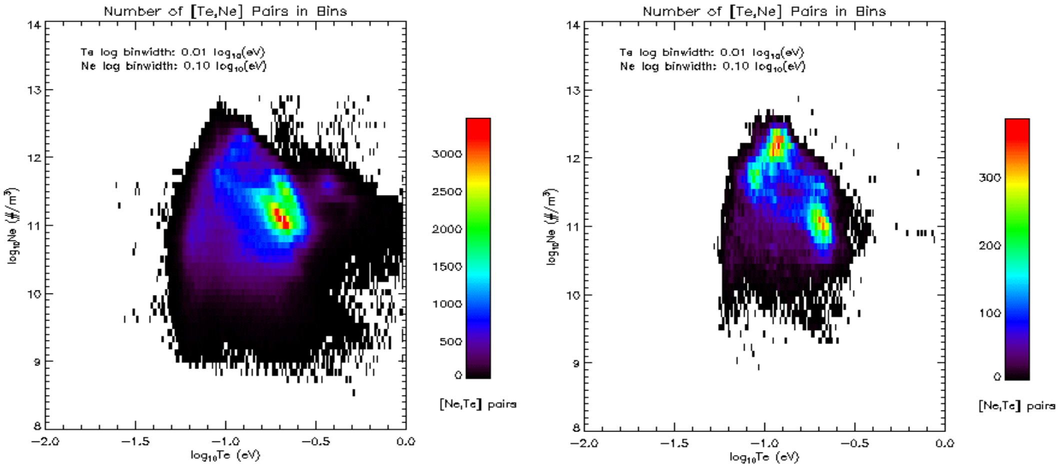
Distributed over all latitude, longitudes, altitudes:

~29 values/(1° x 1°)
~731 values/(5° x 5 °)

- **ISS specific application: 280,683 records**

350 km < z < 450 km -51.6° < latitude < 51.6°

~4 values/(1° x 1°)
~108 values/(5° x 5°)



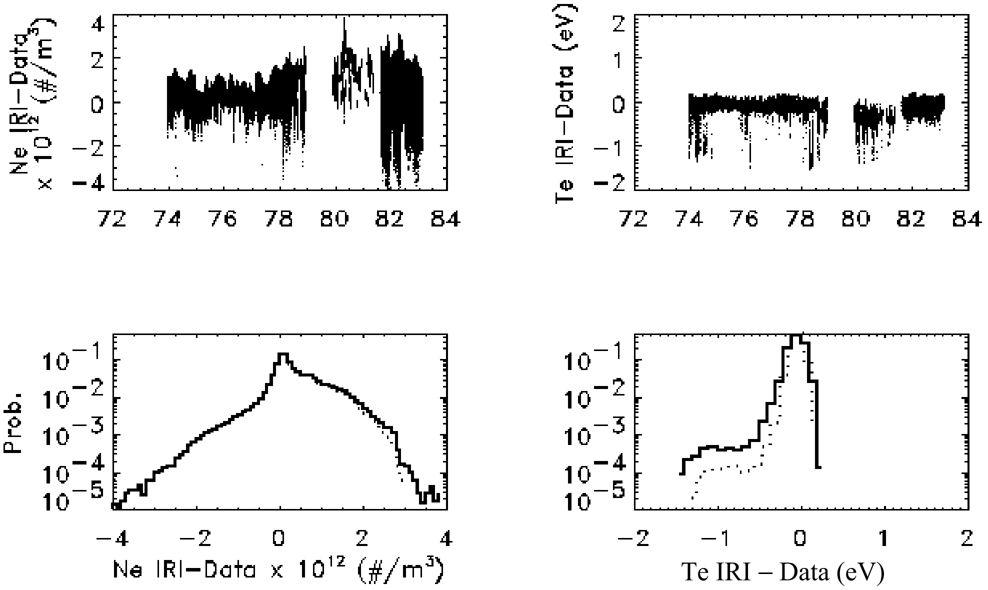
a) **b)**

Figure 4. Ne, Te scatter plots. (a) Historical database of all 1.07×10^6 values and (b) the subset of 0.88×10^6 values applicable for ISS orbit (±51.6° latitude, 350 km < z < 450 km) with solar zenith angles sza < 120°. Color coding provides the number of data values within each bin. The threat condition for ISS charging occurs in the high Ne, low Te sector of the scatter plots.

Implementation of the Variability Model

The variability model is derived from the variance of individual Ne, Te values from IRI-2001 model results. For each set of Ne, Te data values in the database, the corresponding IRI-2001 values are computed and compared to the data values. This requires using the IRI-2001 input parameters (latitude, longitude, altitude, time, and solar and/or geomagnetic conditions) for each Ne, Te pair in the historical database.Plots of differences between the data and model values are shown in the top panels of figure 5. Density values typically vary by orders of magnitude about the mean IRI output. There are numerous physical processes that result in plasma density variations that are not included in the climatological IRI model including equatorial plasma depletions associated with spread-f conditions during night in the equatorial regions, plasma depletions associated with sub-auroral enhanced plasma convection and stable auroral red arcs at mid latitudes, and plasma cavities associated with auroral arcs at high latitudes. Similarly, transient enhancements in electron temperatures due to auroral processes (particle and Joule heating) are not included in the IRI model and appear as deviations from the mean model output in the current analysis.

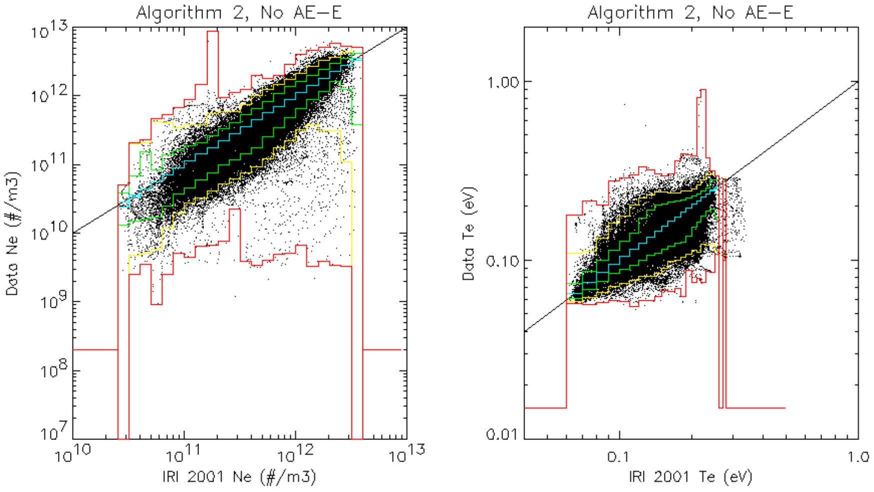
Histograms of differences between the IRI-2001 model and the data are provided in the bottom panels of Figure 5. The distributions are nearly Gaussian only for small deviations from the model but exhibit strongly non-Gaussian features for large deviations suggesting that simply computing mean and standard deviations of the differences will underestimate the extreme deviations in the database.



a) b)

Figure 5. IRI Model and Data Differences. Differences between the IRI-2001 values and the Ne, Te values in the database (top) and histograms of the differences (bottom) for electron number density (a) and electron temperature (b). The solid lines in the histogram include data from AE-C, AE-D, AE-E, and DE-2 spacecraft while the dotted line indicates histograms where the AE-E data has been removed. in the dotted line.

Te values from the AE-E satellite appeared biased to anomalously high Te values in comparison to the AE-C, AE-D, and DE-2 data, even during 1976 and 1977 when data is available from both satellites and direct comparison is possible. The AE-E values appeared to be spurious and were removed from the analysis for the ISS study. The histograms in Figure 5 include both the complete Atmosphere Explorer and Dynamics Explorer data sets for all latitudes and altitudes in the database (solid lines) as well as histograms with the AE-E data removed (dotted line). A set of high Te values is lost when removing the AE-E data although there does not appear to be a systematic bias in the measurements since the peak of the histograms with and without the AE-E data are at the same value. Since the threat condition for extreme ISS charging is low Te, loss of the high Te AE-E data is not important to the study.



a) **b)**

Figure 6. Comparison of historical Ne and Te database with IRI-2001. (a) Density values in the data are distributed about the IRI-2001 values. (b) Temperatures are similarly distributed. Lines drawn on each plots indicate bounds of 68%, 95%, and 99.9% of the data values for each bin (from Minow, 2002).

Scatter plots of data Ne and the corresponding IRI model Ne values are given in Figure 6a and data Te with corresponding IRI model Te values in Figure 6b. Density values in the database typically vary over an order of magnitude about the IRI values with extremes of approximately two orders of magnitude. Electron temperature variations in the historical database are typically within an order of magnitude of the corresponding IRI Te values.

Quantitative estimates of the variability are obtained by computing Ne and Te statistics for the historical database. For example, consider the process of obtaining electron density variability. The process begins with establishing Ne bins based on the IRI values then sorting the historical Ne database values into the appropriate density bins. Within each bin, statistical variation of the electron density is determined by finding the density values in the historical database that bound 50%, 68%, 95%, and 99% of the data values within each bin. Although the values are often referred to generically in this work as the “mean” and “1, 2, and 3 σ”variability estimates, the distributions within each bin are typically far from Gaussian and the technique is generally applicable in terms of the percentiles. Te variability is derived from a similar process using IRI Te bins and the historical Te database.

Results from the variability study can be applied to estimate potential threats to the ISS program in a very simple way by taking the greatest Ne and least Te values that appear in Figure 4-b and Figure 6 and use them as a "worst case" ionosphere for the ISS orbit. This technique was used by Mikatarian et al. (2003) to demonstrate that the current ISS configuration will not exceed the –40 volt limit on the structure floating potential. Since the program limit is not exceeded even for a non-physical worst case (although Ne and Te values are typically anti-correlated in the daytime ionosphere it is not readily apparent that the highest Ne and lowest Te value in Figure 6 will ever occur at the same time). More detailed analysis of the correlations between the Ne, Te pairs will be required when the predicted potentials approach or exceed the limit of –40 volts, a possibility in future construction of the vehicle.

The second method of applying the variability statistics is to use the results of the statistical analysis to develop a computer model of Ne and Te variations. Computation of the percentiles shown in Figure 5 within a spatial range of altitudes, latitudes, and local times yields a database of deviations from the IRI-2001 model results that may be applied to IRI output to estimate deviations in Ne, Te that are not contained in the average IRI model. Figure 7 provides a schematic of a FORTRAN program written to automate the process. A user runs the variability model by providing the standard IRI-2001 model input (latitude, longitude, altitude, time, solar activity, etc.) to a "wrapper" program that drives the IRI-2001 subroutines and includes access to the variability database. Ne, Te values from the IRI-2001 model are used to select which set of

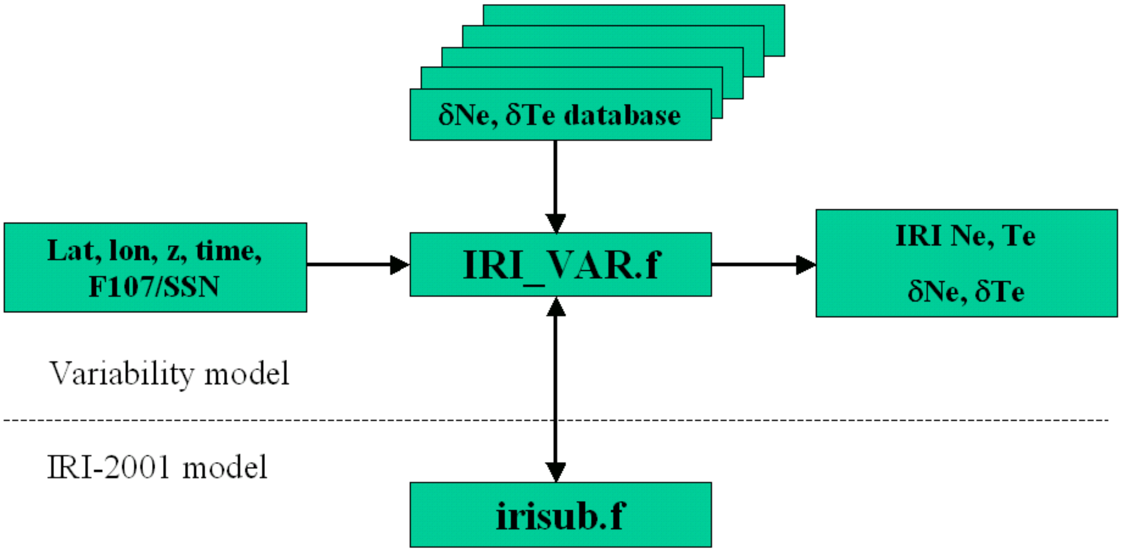


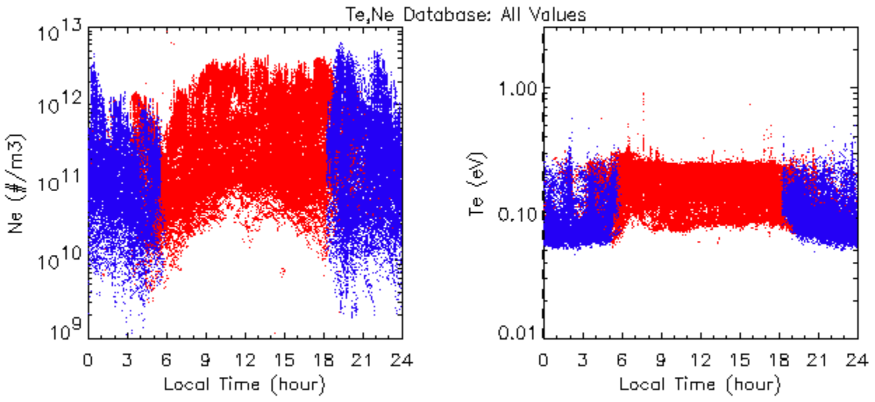
Figure 7. Schematic of Ne, Te Variability Model. The model takes the δNe, δTe results generated from the variability study to provide deviations from the IRI-2001 output for a given set of input parameters.

statistics to use from the variability study and the software then provides the appropriate offsets to add or subtract from the 50% values in the bin. Output from the "wrapper" program is both the standard IRI-2001 output as well as the deviations from the IRI-2001 values based on the historical database. This computer model is incorporated in the Plasma Interaction Model developed by Boeing and SAIC to predict ISS floating potentials (Gardner et al., this conference; Mikatarian et al., this conference).

Variations in solar and geomagnetic activity have not been included in the analysis described above. Simply collecting together all data within a given altitude and latitude range without sorting by geophysical conditions requires accepting wide deviation in Ne and Te values. For example, Figure 7 provides the distribution of Ne and Te values both day and night data in the ISS altitude range where daytime values are coded red and nighttime blue. The simple local time relation

$$LT = [UTC + longitude/15] \bmod 24$$

is used to organize the Ne, Te values and solar zenith angle is used to determine if the individual measurement was made in illuminated or night conditions (the modulus operation assures all local times are in the range of 0 hours to 24 hours). Overlap of day and night values near dawn



a) **b)**

Figure 8. Ne-LT and Te-LT scatter plots. Day (night) values are indicated by the red (blue) colors. The vertical dashed line is sunrise where SZA(z) of a data value is equal to the solar zenith angle of sunrise SZA_{SR} at altitude z of the [Ne, Te] data pair (SZA refers to the solar zenith angle, the angle between the satellite zenith-nadir axis and the direction of the Sun).

and dusk are due to variations in sunrise and sunset times over the latitude range from -55° to +55° included in the ISS study set. The typical ionospheric behavior is apparent with night density values decreasing until sunrise where they begin to rise. Midday Ne values in Figure 7-a are a maximum, ranging from $5x10^{10}$ #/m^3 to $5x10^{12}$ #/m^3, and Ne begins to decrease in the evening hours and into the night. Te values exhibit an abrupt increase at sunrise due to rapid heating of the electron gas by photoelectrons, decrease in midday when Ne is a maximum, increase in the late afternoon hours as Ne decreases, and finally decrease after sunset and into the night time hours as the ionosphere cools.

In addition to the typical diurnal behavior of the ionosphere, an obvious feature in Figure 8 is the large range of Ne and Te values at any given local time. Ne values in Figure 6-a vary approximately two orders of magnitude while the Te values vary by factors of two or three. Some of the wide range in the Ne and Te values can be attributed to the variations in solar activity. Pre-sunrise Ne and Te values obtained from incoherent scatter radar measurements at Arecibo (Puerto Rico) during ionosphere World Day observations over a complete solar cycle are given in Figure 9 as a function of the F107 proxy index for solar EUV activity. The figure demonstrates that the two order of magnitude variation in pre-sunrise Ne values in Figure 8-a is due to variations in solar activity. Current work on including both F107 and a geomagnetic proxy index (either Kp or Ap) to reprocess the database is underway to reduce the variations.

ISS Eclipse Exit and Daytime Ne, Te Environment

Mikatarian et al. [2002, 2003] describe the spacecraft charging analysis used to demonstrate the maximum values of ISS potentials for the current configuration are within the –40 volt limit even if the Plasma Contactor Units install to discharge excess electron current are not used. An important input to this work is an estimate of the mean and extreme Ne and Te values in the ISS orbit. Analysis of on-orbit ISS potential measurements showed that charge collection by the high voltage ISS solar arrays is linearly related to electron density and inversely proportional to electron temperature (Ferguson et al., 2001). The greatest negative potentials are found when the density is high and the temperature is low at eclipse exit (as the spacecraft enters sunlight) and prediction of extreme charging events requires an estimate of the maximum electron density and minimum electron temperatures in the ISS orbit.

A simple version of the statistical model was implemented for this work since it was sufficient to demonstrate that ISS potentials do not exceed the –40 volt limit anywhere over the range of altitudes and latitudes available to the ISS. In addition, since the extreme charging conditions require a bias on the solar arrays, it is only necessary to consider conditions where the spacecraft is illuminated by the Sun. Therefore, a variability model applicable over the 350 km to 450 km ISS altitude and within a latitude range of ±51.6° for daytime conditions satisfies the program requirements to determine a plausible worst case environment for input into the charging analysis.

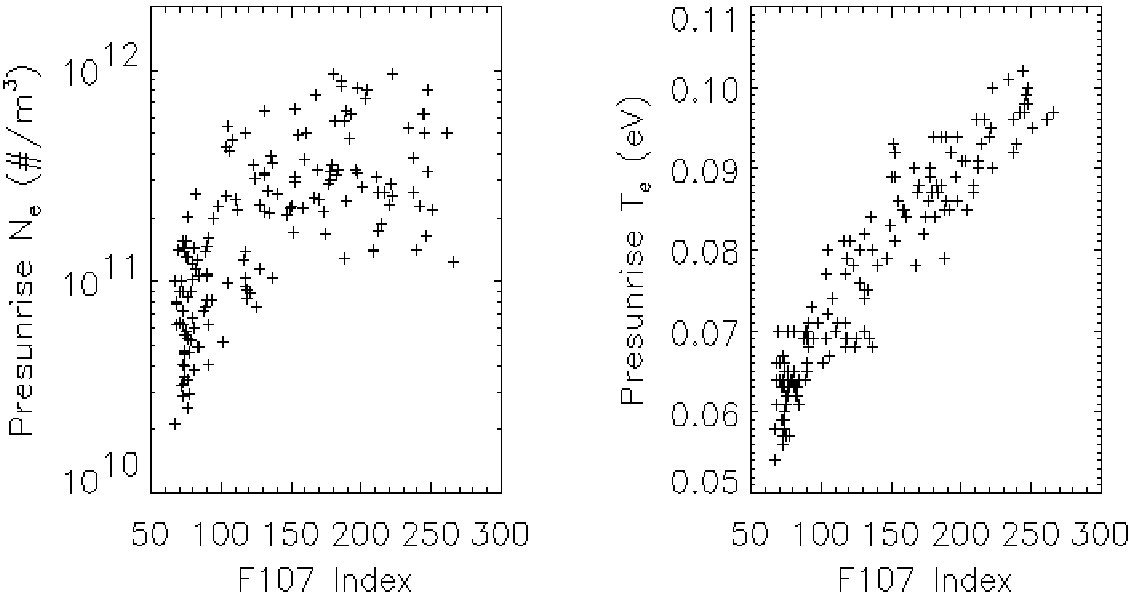


Figure 9. Pre-sunrise Ne, Te Measurements at Arecibo, Puerto Rico. (a) Ne and (b) Te values at ISS altitudes both exhibit a strong correlation with F107. Including solar activity in the analysis of the database will provide an opportunity to reduce the variability in the deviation model (from Mikatarian et al., 2003).

Figure 10 provides a case for comparing results from the Ne and Te variability model with data values. The top and middle panels are time series of Ne and Te altitude profiles obtained by the incoherent scatter radar at Arecibo, Puerto Rico, for a series of days in March 1988. The daily electron temperatures rise at sunrise due to photoelectron heating of the neutral gas is apparent in the plots with a decrease in Te during the middle of the day where the electron density is a maximum (electron cooling is dependent on the electron density). Finally, as the electron density begins to decrease late in the day the electron cooling rate also decreases and the electron temperature rises again before sunset. After the sunlight no longer illuminates the ionosphere both the electron density and temperature decay to the nighttime values.

Electron densities and temperatures from the 404.5 km radar range gate, an altitude typical of the ISS orbital altitude, is plotted in the bottom panel of Figure 4. Results from the IRI-2001 model are overplotted to show the model representation of the Te values and statistical results are indicated for sunrise and daytime periods. Statistics for these results include all data in the database from 350 km to 450 km altitude, solar zenith angle < 120 degrees, and latitudes between +/- 51.6 degrees. Note that while the extreme low temperature values indicated by the -“3σ” level are not significantly less than the night time observations, the daytime extreme values can be much greater than the observations.

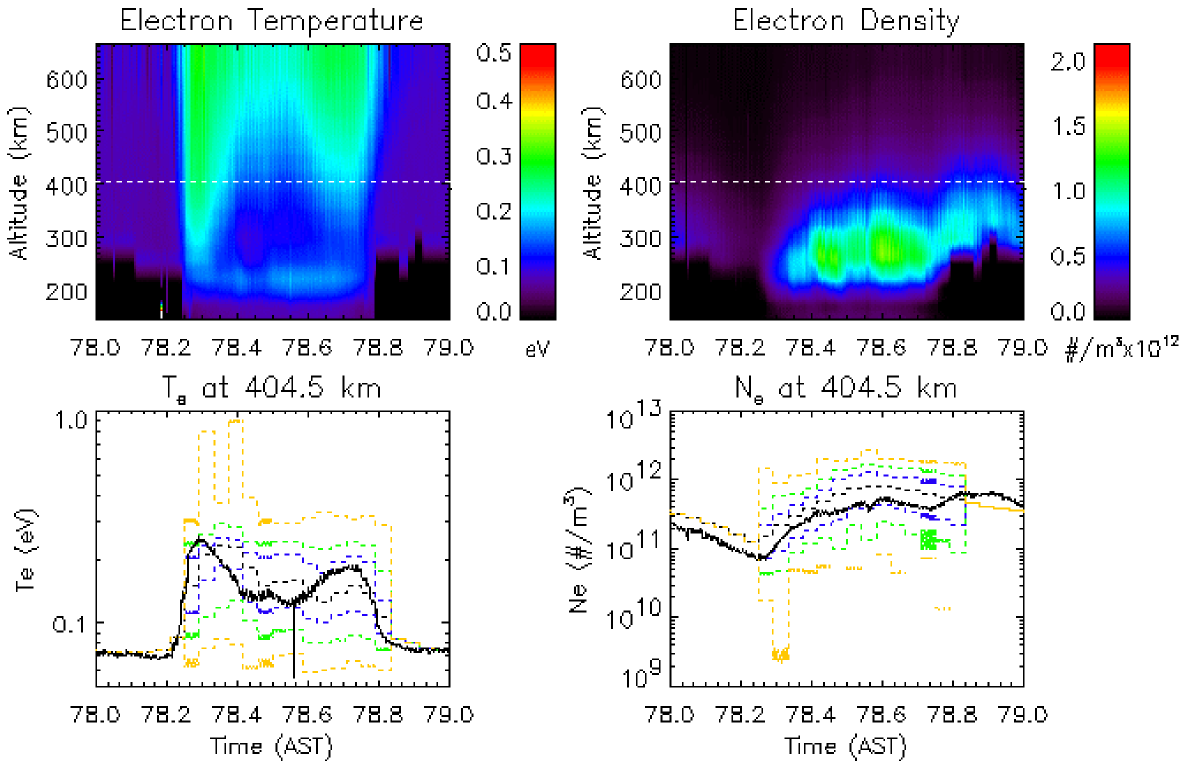


Figure 10. Incoherent scatter radar Ne and Te measurements on 18 March 1988 at Arecibo, Puerto Rico. Ne (top left) and Te (top right) are altitude profiles as a function of time (day 78 of year 1988 in Atlantic Standard Time) with the values of temperature and density given by the color scale. The Ne, Te values from ~405 km are plotted in the bottom panels (solid black line) with the corresponding IRI-2001 values (dotted black line). Estimates of the "1,2, and 3 σ" variability (blue, green, and yellow, respectively) are given for daytime periods when the variability database is applicable (from Minow, 2003).

Determination of the maximum charging levels anticipated for future ISS configurations will similarly require estimates of plausible worst case charging conditions as well as estimates of how frequently these conditions may be encountered. Implementation of the variability model provides a convenient method of incorporating Ne and Te statistics based on historical values into a simple computer model.

Summary

Preliminary results from a technique developed to provide statistical variations in electron density and temperature values in addition to the mean values available from standard empirical ionosphere models has been described. Historical in-situ observations of Ne and Te from the AE-C, D, and E and DE-2 satellites provide a database of observations from which deviations from the IRI-2001 empirical ionosphere model can be derived. Deviations of Ne and Te values in the database from the IRI model results provide the variability about the model results.

Current activities are focused on collecting additional data sets to enhance the historical database. The current set of satellite data contains over a million data values. Adopting a set of 10 degree latitude bins, 10 degree longitude (or local time) bins, and 100 kilometer altitude bins will require the data to be distributed among 5832 bins. Assuming the data is relatively uniformly distributed, there will be between 100 and 200 points per bin. The data however is not uniformly distributed in altitude or latitude due to the orbital dynamics of the spacecraft and some altitude regions or range of latitudes will contain many more data values than others. Work is underway to acquire additional satellite and incoherent scatter radar data sets that will fill out the database. Implementation of algorithms for computing density and temperatures over a range of altitudes based on observations at a single altitude are also a possible technique for enhancing the database.

Acknowledgements

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References

1. Mikatarian, R., H. Barsamian, J. Kern, S. Koontz, and J.F Roussel, Plasma charging of the International Space Station, presented at the 53rd International Astronautical Congress, The World Space Congress 2002, 10-19 October, Houston, TX, 2002.

2. Mikatarian, R., H. Barsamian, J. Alred, J. Kern, J. Minow, and S. Koontz, Electrical Charging of the International Space Station, AIAA-2003-1079, presented at the 41st AIAA Aerospace Sciences Meeting, Reno, NV, January 6-9, 2003.

3. Minow, J.I., Development and Implementation of an Empirical Ionosphere Variability Model, 34th COSPAR Scientific Assembly, Houston, TX, October 10-19, 2002.

4. Bilitza, D., Topside models: status and future improvements, Adv. Space Res., 14, 17-26, 1994.

5. Bilitza, D., International Reference Ionosphere - status 1995/96, *Adv. Space Res.*, 20, 1751-1754, 1997.

6. Bilitza, D., International Reference Ionosphere 2000, *Radio Science* 36, 261-275, 2001.

7. Brace, L.H., R.F. Theis, and A. Dalgarno, The cylindrical electrostatic probes for Atmosphere Explorer –C, -D, and –E, *Radio Science*, 8, 341 – 348, 1973.

8. Krehbiel, J., L.H. Brace, R.F. Theis, W.H. Pinkus, and R.B. Kaplan, The Dynamics Explorer Langmuir probe instrument, *Space Science Instrumentation*, 5, 493, 1981.

9. Brace, L.H., Langmuir probe measurements in the ionosphere, in *Measurement Techniques in Space Plasmas: Particles*, edited by R.F. Pfaff, J.E. Borovsky, D.T. Young, pp. 23 – 35, American Geophysical Union, Washington, D.C., 1998.

10. Ferguson, D.C., "Charging of the International Space Station due to its High Voltage Solar Arrays", presented at the 17th Space Photovoltaic Research and Technology Conference, Ohio Aerospace Institute, Cleveland, OH, September, 2001.

11. Ferguson, D.C., G.B. Hillard, T.L. Morton, R. Personen, ISS FPP Ionospheric Electron Density and Temperature Measurements - Results, Comparison with the IRI-90 Model, and Implications for ISS Charging', AIAA-2003-1083, 2003.

12. Ferguson, D. C., T. L. Morton, and G. B. Hillard, First results from the Floating Potential Probe (FPP) on the International Space Station, AIAA-2001-0402, 2001.