ISS PLASMA INTERACTION: MEASUREMENTS AND MODELING

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Abstract

Ionospheric plasma interaction effects on the International Space Station are discussed in the following paper. The large structure and high voltage arrays of the ISS represent a complex system interacting with LEO plasma. Discharge current measurements made by the Plasma Contactor Units and potential measurements made by the Floating Potential Probe delineate charging and magnetic induction effects on the ISS. Based on theoretical and physical understanding of the interaction phenomena, a model of ISS plasma interaction has been developed. The model includes magnetic induction effects, interaction of the high voltage solar arrays with ionospheric plasma, and accounts for other conductive areas on the ISS. Based on these phenomena, the Plasma Interaction Model has been developed. Limited verification of the model has been performed by comparison of Floating Potential Probe measurement data to simulations. The ISS plasma interaction model will be further tested and verified as measurements from the Floating Potential Measurement Unit become available, and construction of the ISS continues.

Introduction

The International Space Station (ISS) becomes electrically charged due to electron collection by the exposed positively charged edges of solar cells in its photovoltaic (PV) arrays. This electron current collected depends on the temperature and density of the ionosphere plasma. A Floating Potential Probe (FPP) flown on ISS in 2001 showed that the highest charging voltages occurred at orbital eclipse exit. Modeling of the charging process shows that high voltages require a combination of low electron temperature and high plasma density. For hazard management and operational control, the ISS program needs methods for predicting charging voltages for the different ISS configurations through Assembly Complete.

Therefore, the charging of ISS surfaces with respect to the plasma in lower earth orbit occurs due to the main following mechanisms:

- Induction electric potentials (v×B·L) due to the motion of the spacecraft relative to the ambient plasma in the earth's magnetic field
- Electron collection on the edges of positively charged photovoltaic (PV) cells in the solar arrays
- Electron loss to the ambient plasma due to recombination with plasma ions on electrically conducting surfaces of the spacecraft
- Second order effects including electron loss due to photoemission and secondary emission

The variability of plasma parameters (electron-ion density, electron and ion temperatures, and spacecraft velocity relative to the plasma) results in substantial variations of charging with solar cycle, space weather, solar illumination, vehicle configuration, vehicle material and construction, and operational configuration and orientation.

The following paper addresses these mechanisms and applies them to give predictions of charging on the ISS. Each of these mechanisms is discussed below. Some discussion of on-orbit measurements is given followed by the introduction of the ISS plasma interaction model. Results of model predictions are followed by a brief section of the variability of plasma parameters.

On-Orbit Measurements

The FPP flown on ISS Flight 4A provided measurements of on-orbit structure potential from December 2000 to April 2001. The FPP device failed after April 2001 from unknown causes. This device also provided Langmuir probe plasma density and temperature measurements. At charging peaks, FPP Langmuir probe measurements of plasma density and temperature data suffered telemetry dropout when the FPP voltage went below –10V.[1,2]

When the PCUs are off, the FPP shows negative voltage spikes at ISS eclipse exit. The maximum voltage measured at the FPP in 2001 was –23V, including (v×B·L) induction potentials (Figure 1). This charging of ISS results from electron collection on the PV arrays. The transient nature of the charging was unanticipated, as was the low magnitudes of the peak voltages. Also, unanticipated were the small values of the PCU emission currents (< 0.1A compared to expected values of about 1A). Figure 2 shows that with the PCUs activated, the ISS structure voltages clamp at low values, consistent with (v×B·L) induction potentials. PCU #2 discharge current over an orbit is shown in Figure 3. The current does not exceed 100mA. The figure also delineates the International Reference Ionosphere (IRI 2001) electron temperature prediction. The electron temperature increase at eclipse exit is consistent with peak eclipse exit potential decrease as indicated in Figure 1.

Early program modeling of the PV array electron collection gave relatively large collection currents, predicting large PCU emission currents with PCUs on. With PCUs off, large electron collection currents result in large negative potentials unless electron loss mechanisms are available to offset electron collection. Electron collection occurs on the exposed, positively charged edges of solar cells in gaps between cells on ISS arrays.

Electron collection is enhanced by a condition known as “snapover” which increases the effective collecting area of the arrays. Snapover is a condition of increased electrical conductivity of the array surface, resulting from a high positive bias voltage on the solar cells. This condition was assumed for both gap and exterior surfaces of the arrays in the first analytical model of electron collection. Felder, et al. (1993) estimated the threshold for snapover of the ISS PV arrays at 160V.[3]

Early modeling of ISS plasma interactions neglected electron loss mechanisms to estimate upper limits for PCU emission currents for design purposes. The present model incorporates an “ion collection” area that summarizes the various electron loss mechanisms in a single term. Electron loss mechanisms are described in the next section.

Plasma Interaction Model

The Plasma Interaction Model (PIM) results from a collaboration between The Boeing Company and SAIC (under subcontract to The Boeing Company). Figure 4 gives a schematic of the PIM. Input parameters for the PIM consist of the environmental parameters (Te, Ne and B), the vehicle’s location in latitude, longitude and altitude, the configuration of the PV arrays (shunt configuration and array position angles) and the ion collecting area and current-voltage relation. Collection of electrons and ions on the arrays, masts[4] and structure are indicated as contributing to the total current to the vehicle. The induction voltage arising from the motion of the vehicle through the ionospheric plasma and the geomagnetic field contributes to the vehicle potential for both quasi-steady and time-dependent cases. This potential, due to Faraday‘s Law, is $(v \times B \cdot L)$.

A small negative potential (~–0.2V) arises in the model due to the difference between ion and electron fluxes at the surfaces of the solar cell cover glasses. This potential prevents electron collection everywhere except between cell gaps. Both analytic and numerical-simulation solutions support this model of electron collection on the PV arrays.[5,6] This methodology is discussed in Mikatarian, et al. (2002).[7]

There are a number of mechanisms available to reduce ISS’ net electron collection and therefore the magnitude of the negative structure potential. These include (** second order effect for ISS):

- Electron recombination with thermal or ram ions on conducting vehicle surfaces, including conducting wires in the PV array mast structures (also called “ion collection”)

- Electron loss or ion collection at gaps between solar cells with low positive potentials in PV arrays
- Ion collection by conducting, grounded materials on vehicle thermal blankets, connectors, etc.
- Photo-emission of electrons due to solar UV radiation **
- Secondary electron emission due to energetic electron or ion impacts **
- Field emission from charging to keV potentials by energetic electrons (auroral charging) **

Any electron loss or ion collection mechanism reduces the net electron current available to charge the vehicle structure. Evaluating these mechanisms, we find that electron loss through ion collection dominates.

Treating the totality of electron loss and ion collection mechanisms as a single "effective ion collection area", a value of about $35m^2$ minimizes the differences between FPP measurements and model–calculated values. Conducting areas are most likely found on ISS pressurized elements, near the centerline of the ISS configuration through Flight 12A. The electrical effect of this area is to ground the ISS to the ambient plasma near the centerline of the vehicle.

Analysis

Some of the pertinent input parameters to the PIM discussed above are shown in Figure 1. The parameters are plotted against FPP measurements. The parameters shown here include the PV array normal to the ISS velocity vector, the latitude and longitude variation and the number of strings shunted on each of the arrays for ISS configuration 5A. All of these parameters must be accounted for in simulations of ISS charging to predict similar variations observed as the FPP measurements. In addition, the plasma properties are generated using IRI.

The magnetic field obtained through IRI plays an important role and effects the potentials on the ISS based on (vxB.L). Figure 5 delineates a potential contour of the ISS due to magnetic induction. This potential does not include the collection effect of the PV arrays. The spacecraft location is south of Australia where the largest magnitude of magnetic field strength has been shown to occur. While the pressurized segments of the ISS structure are near –10V, the variation from the tip of one PV array to the other is in the range of 30V.

In order to identify the 'ion collection' area of the ISS, all FPP eclipse exit charging data during nominal operations were compared to PIM predictions. The comparisons are consistent with a value of $35m^2$ as the amount of ion collection area present on the ISS. As discussed earlier, the ion collection area is an effective term that may account for other ISS plasma interaction mechanisms. Therefore, one must be careful when using this as a physical area present on ISS surfaces.

Comparison between the FPP potential measurements and PIM predictions at the charging peaks (occurring at eclipse exit) are shown in Figure 6. The effect of variability of the plasma properties must be accounted for due to the uncertainty of eclipse exit temperatures at high latitudes.[8] The indication of 3σ variability uses values obtained from Figure 7.[9] The combination of –3σ on Te values and +3σ on ne values are the predictions for extreme cases with very low probability of occurrence.

Concluding Remarks

A model describing the plasma charging on the International Space Station has been presented. The model accounts for solar array charging, magnetic induction, ion collection, and the variability of the ionospheric plasma properties. The model can be used to assess the various ISS build configurations and the effect of seasonal and solar cycle effects upon the vehicle charging.

The computer model has been used to calculate ISS structure potentials for comparison between the calculations and FPP flight measurements. High latitude electron temperatures derived from the IRI 2001 model ionosphere are highly variable. This necessitates adoption of "worst-case" values for charging hazard assessments by the ISS program.

During ISS Flight ULF1.1, the Program will be integrating into ISS a Floating Potential Measurement Unit (FPMU) which will be used to measure structure potential and ionospheric plasma (electron temperature and number density) properties. During CYs 2005 and 2006 additional arrays will be deployed which should yield enhanced charging on the structure. Comparisons between the computer model calculations and the FPMU flight measurements will be made on a continuing basis as the flight data is obtained.

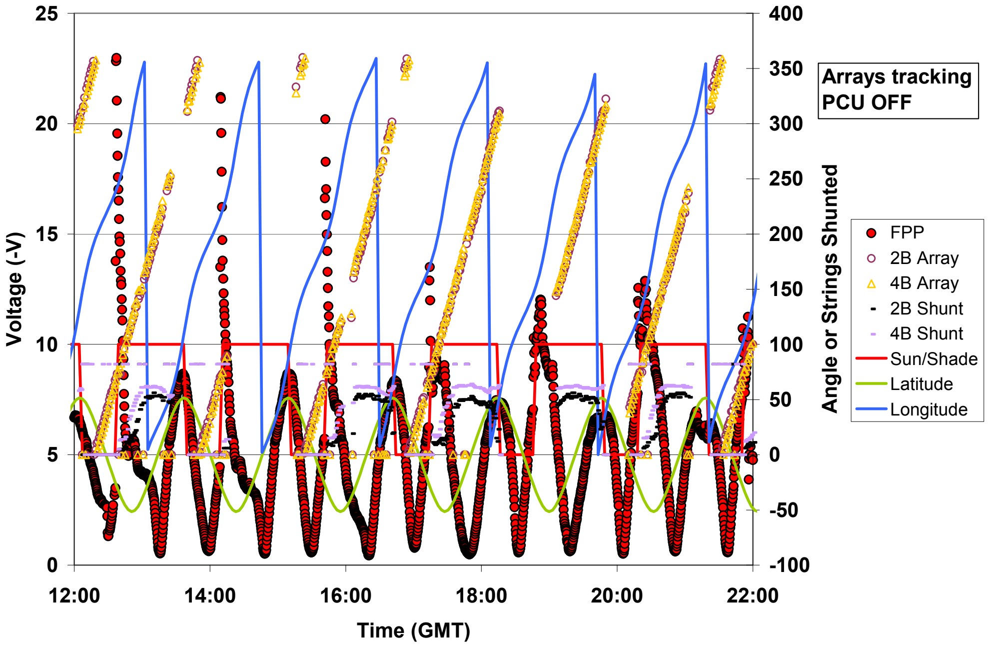


Figure 1. FPP Potential and pertinent parameters for an ISS orbit (PCUs in standby mode).

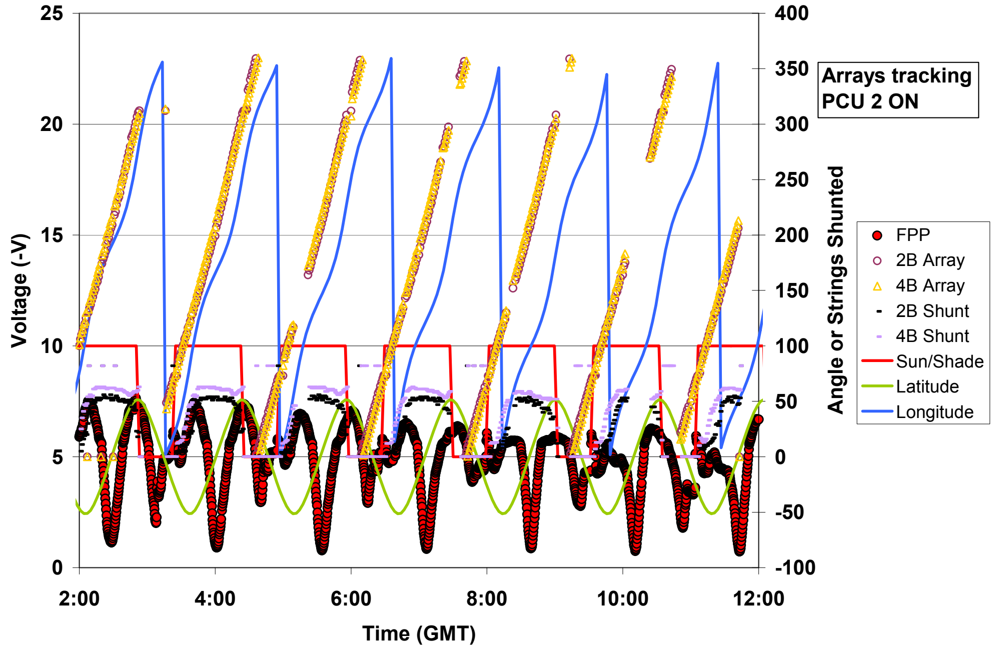


Figure 2. FPP Potential and pertinent parameters for an ISS orbit (PCU 2 in discharge mode).

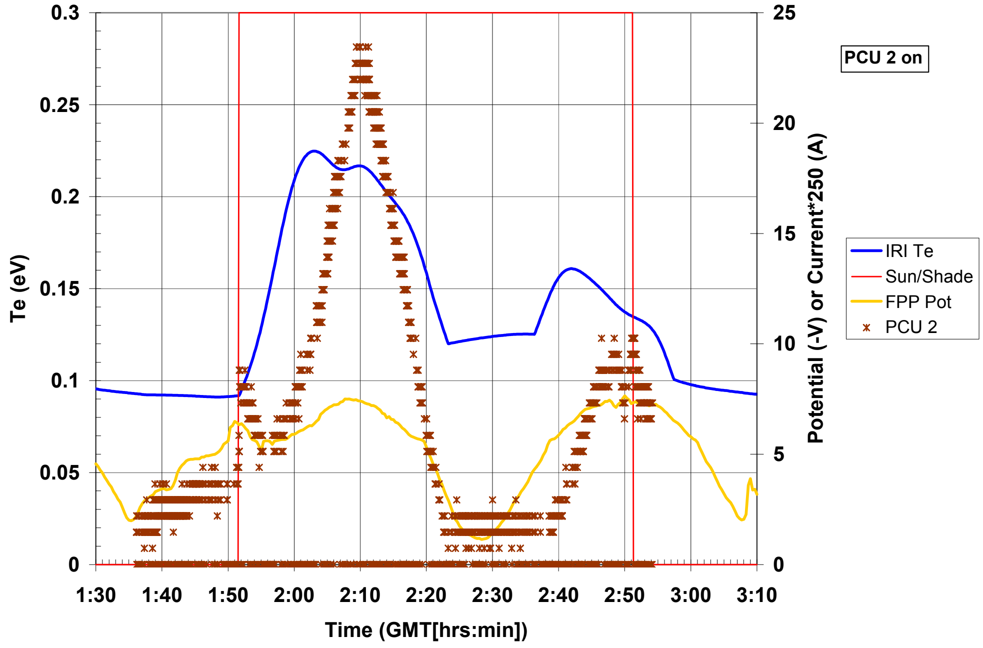


Figure 3. PCU #2 discharge current over full orbit.

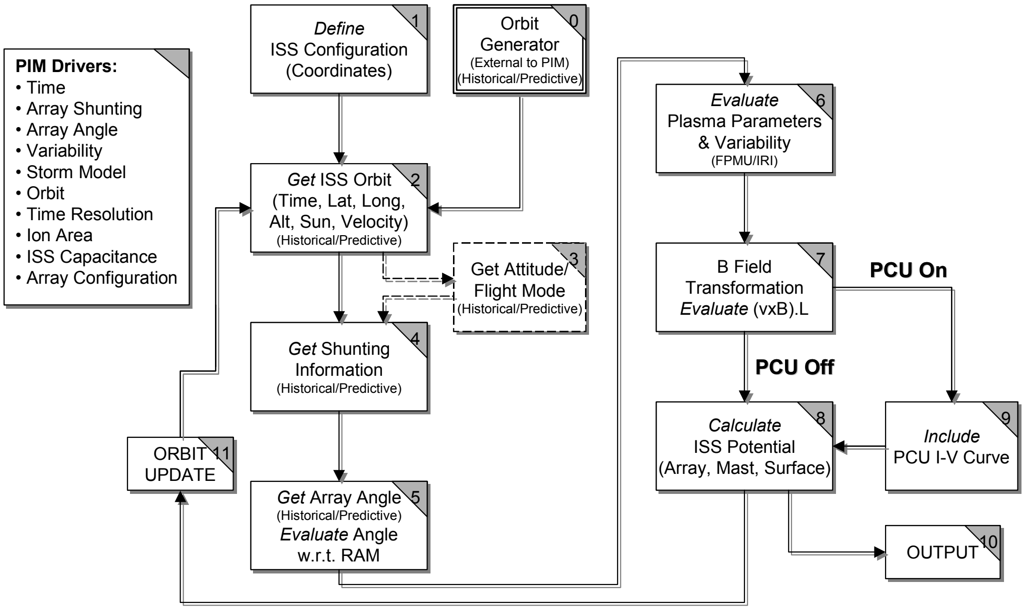


Figure 4. Overview of ISS Plasma Interaction Model.

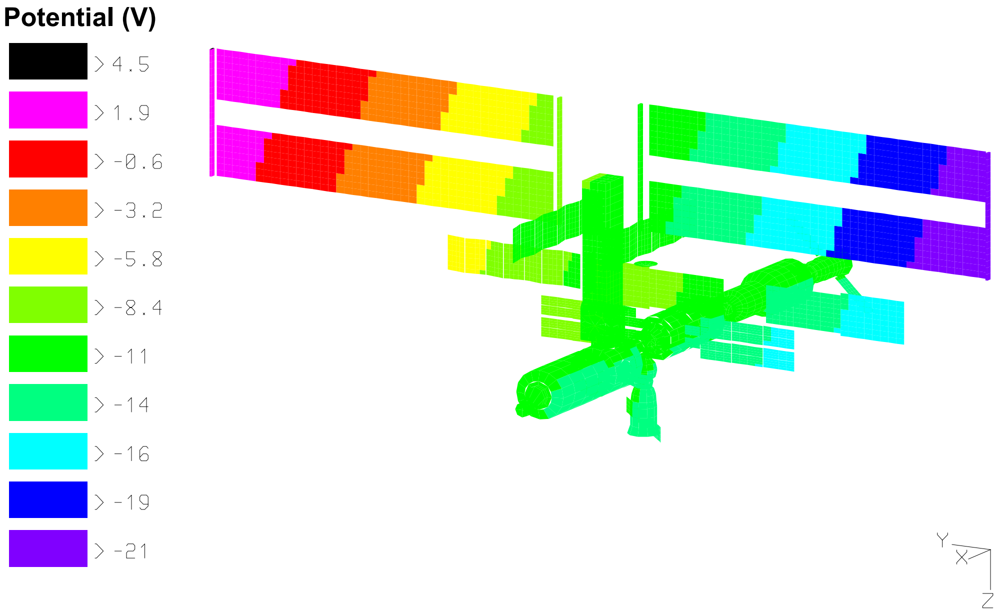


Figure 5. ISS potential variation due to magnetic induction.

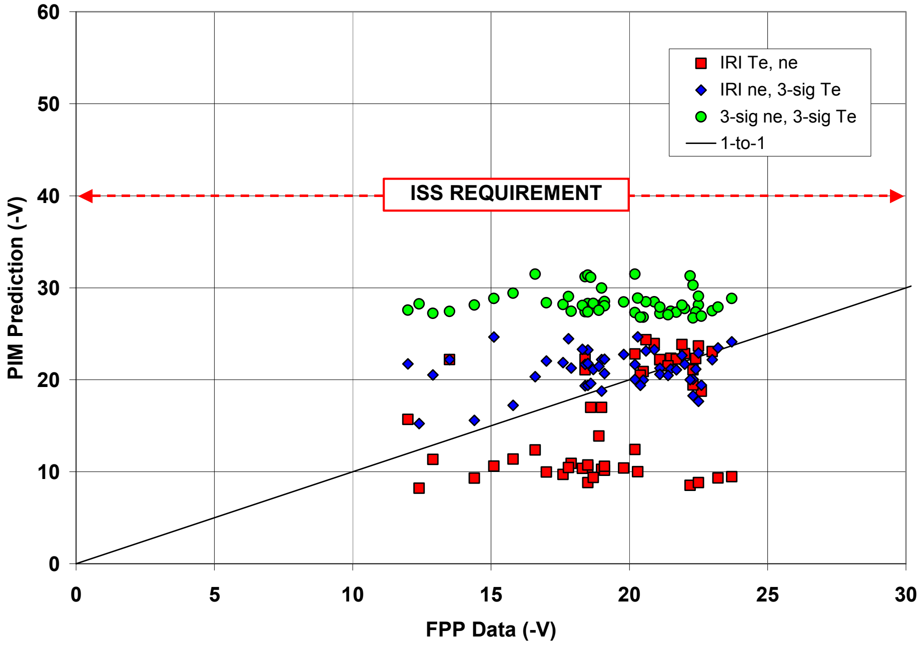
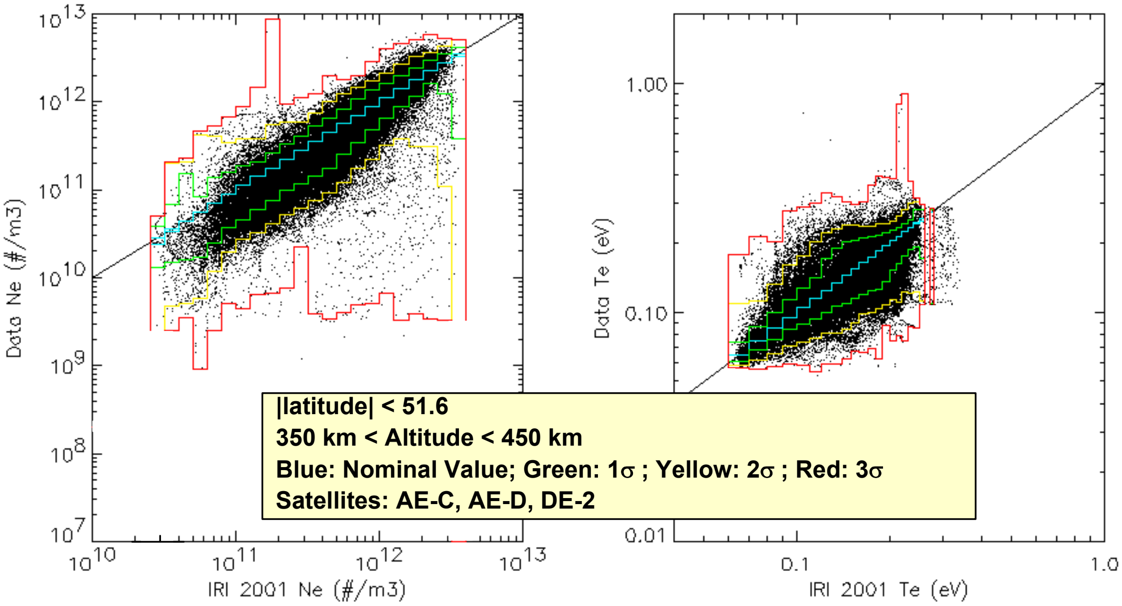


Figure 6. PIM predictions compared to FPP data (including variability).



|latitude| < 51.6
350 km < Altitude < 450 km
Blue: Nominal Value; Green: 1σ ; Yellow: 2σ ; Red: 3σ
Satellites: AE-C, AE-D, DE-2

Figure 7. Satellite data plotted as a function of IRI temperature and density values for ISS orbit.

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