Correlation of ISS Electric Potential Variations with Mission Operations

Emily M. Willis, Joseph I. Minow, Linda Neergaard Parker

Abstract— **Spacecraft charging on the International Space Station (ISS) is caused by a complex combination of the low Earth orbit plasma environment, space weather events, operations of the high voltage solar arrays, and changes in the ISS configuration and orbit parameters. Measurements of the ionospheric electron density and temperature along the ISS orbit and variations in the ISS electric potential are obtained from the Floating Potential Measurement Unit (FPMU) suite of four plasma instruments (two Langmuir probes, a Floating Potential Probe, and a Plasma Impedance Probe) on the ISS. These instruments provide a unique capability for monitoring the response of the ISS electric potential to variations in the space environment, changes in vehicle configuration, and operational solar array power manipulation. In particular, rapid variations in ISS potential during solar array operations on time scales of tens of milliseconds can be monitored due to the 128 Hz sample rate of the Floating Potential Probe providing an interesting insight into high voltage solar array interaction with the space plasma environment. Comparing the FPMU data with the ISS operations timeline and solar array data provides a means for correlating some of the more complex and interesting ISS electric potential variations with mission operations. In addition, recent extensions and improvements to the ISS data downlink capabilities have allowed more operating time for the FPMU than ever before. The FPMU was operated for over 200 days in 2013 resulting in the largest data set ever recorded in a single year for the ISS. In this paper we provide examples of a number of the more interesting ISS charging events observed during the 2013 operations including examples of rapid charging events due to solar array power operations, auroral charging events, and other charging behavior related to ISS mission operations.**

Keywords—ISS; FPMU; plasma; charging; potential; array
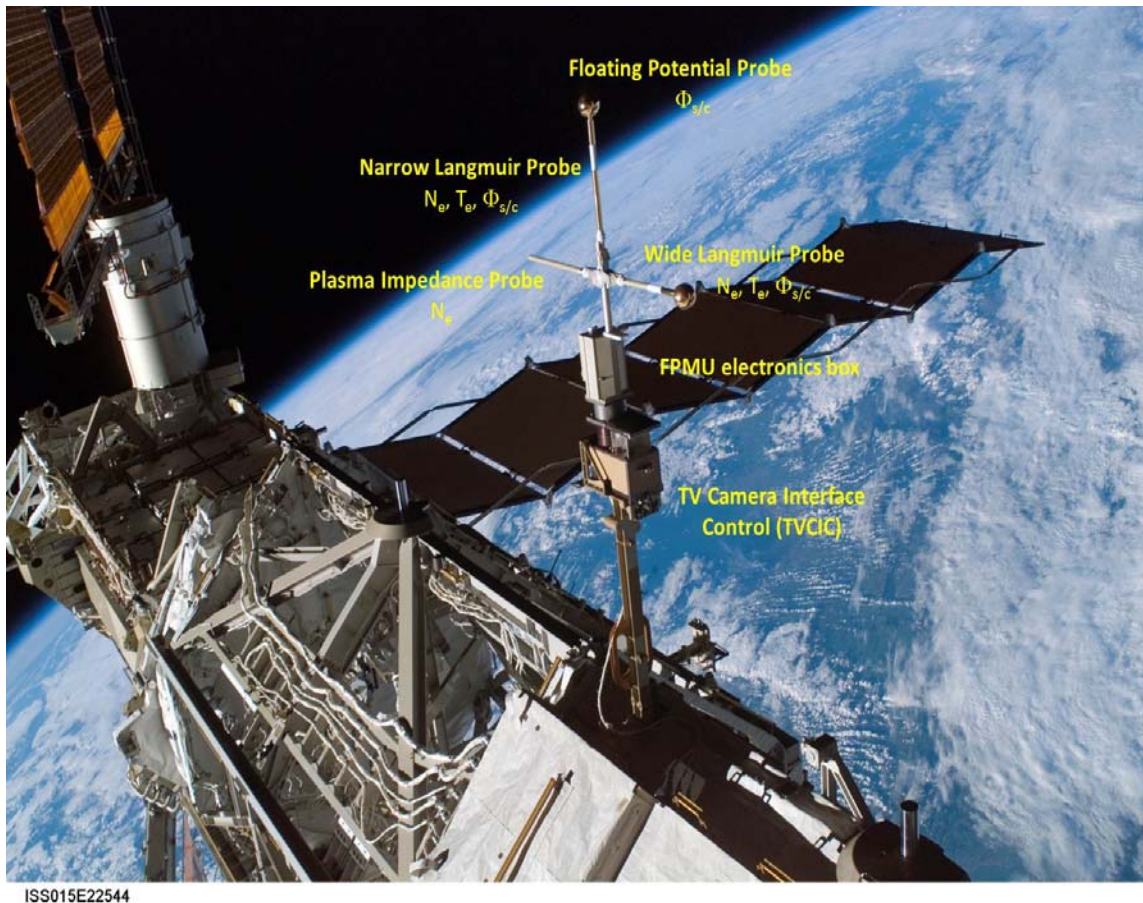
I.   INTRODUCTION

Orbiting approximately 400 km above the Earth, the International Space Station (ISS) is a unique research laboratory used to conduct ground-breaking science experiments in space. The ISS has eight Solar Array Wings (SAW), and each wing is 11.7 meters wide and 35.1 meters long. The SAWs are controlled individually to maximize power output, minimize stress to the ISS structure, and minimize interference with other ISS operations such as vehicle dockings and Extra-Vehicular Activities (EVA). The Solar Arrays are designed to operate at 160 Volts. These large, high power solar arrays are negatively grounded to the ISS and collect charged particles (predominately electrons) as they travel through the space plasma in the Earth's ionosphere. If not controlled, this collected charge causes floating potential

variations which can result in arcing, causing injury to the crew during an EVA or damage to hardware [1]. The environmental catalysts for ISS floating potential variations include plasma density and temperature fluctuations and magnetic induction from the Earth's magnetic field. These alone are not enough to cause concern for ISS, but when they are coupled with the large positive potential on the solar arrays, floating potentials up to negative 95 Volts have been observed. Our goal is to differentiate the operationally induced fluctuations in floating potentials from the environmental causes. Differentiating will help to determine what charging can be controlled, and we can then design the proper operations controls for charge collection mitigation. Additionally, the knowledge of how high power solar arrays interact with the environment and what regulations or design techniques can be employed to minimize charging impacts can be applied to future programs.

II.   FLOATING POTENTIAL MEASUREMENT UNIT

The Floating Potential Measurement Unit (FPMU), shown in Fig. 1, is a collection of four probes: the Plasma Impedance Probe (PIP), Wide-sweep Langmuir Probe (WLP), Narrow-sweep Langmuir Probe (NLP), and the Floating Potential Probe (FPP). Together, these instruments are able to determine the ISS floating potential (FP) as well as the ion and electron density (N_i, N_e) and electron temperature (T_e) of the local plasma environment [2,3]. The collected data is downlinked to the FPMU Workstation at MSFC where it is processed and archived. The Space Environments Team at MSFC analyzes the collected data with respect to the ISS position along the orbital path, the timing of ISS eclipse and sunlit phases, and the current space weather conditions to determine the environmental sources causing significant changes in floating potential.

We focus on FPP and WLP observations for this work. The FPP measures ISS frame potentials relative to the ambient plasma environment at a rate of 128 Hz allowing detailed monitoring of frame potential variations at high time resolution. Plasma density measurements are obtained from the WLP N_i parameter at a rate of 1 Hz. Electron density is assumed to be equal to the ion density due to quasi-neutrality. A description of the data analysis algorithms used to obtain the potentials and plasma density parameters from the FPMU instrument suite is described by Wright et al. 2008 [2].

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Fig. 1. The Floating Potential Measurement Unit (FPMU) deployed on the ISS measures the ISS floating potential and the density and temperature of the local plasma environment. It was developed by Space Dynamics Laboratory in collaboration with Utah State University under contract to the NASA/Johnson Space Center

III. ISS FLOATING POTENTIAL PROFILES

Fig. 2, "The Charging Mosaic", illustrates a number of floating potential profiles currently being investigated for ISS. These are plots of the ISS floating potential (Volts) versus time. Each plot is a 5 minute time interval. They range from simple, well understood potential fluctuations to complex potential variations with currently unknown causes.

i) Normal eclipse exit: Characterized by a rise time less than 10 seconds and decay time greater than 1 minute. This is typical of the ISS coming into sunlight. The arrays are pointed into ram and string voltages increase quickly.

ii) Rapid eclipse exit: Characterized by a rise time less than 10 seconds and decay time less than than 1 minute. These rapid potential peaks correlate with lower plasma densities.

iii) Eclipse entry: Floating potential increases as the ISS moves into darkness and arrays are unshunted.

iv) Auroral charging: With an inclination of 51.6 degrees, the ISS occasionally travels through an auroral event and floating potential increases occur from the precipitating auroral electrons. These events are independent of solar array operations.

v) Positive charging: Observed events have been less than one second in duration. The largest event observed was 55 Volts. The cause of these events is currently unknown.

vi) – ix) Additional uncharacterized peaks: These floating potential fluctuations are possibly a combination of the others caused by complex solar array operations. They occur during the early part of insolation (sunlit portion of the orbit).
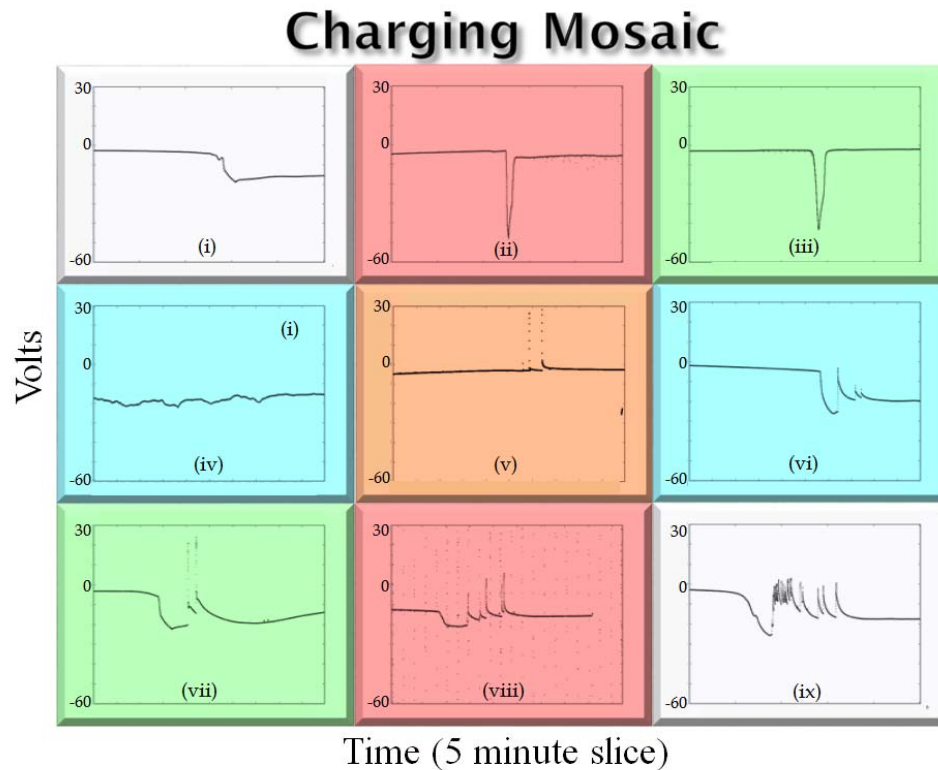
Charging Mosaic

Fig. 2, The Charging Mosaic, illustrates the range of ISS floating potential profile currently being investigated. The y-axis shows the floating potential in Volts and the x-axis for each plot is a 5 minute time interval

IV. SOLAR ARRAY OPERATIONS

In order to determine charging levels related to ISS operations, it is important to understand how the ISS solar arrays operate. Fig. 3, Solar Array Block Diagram, shows a basic block diagram of the operations being investigated for correlation with potential fluctuations.

There are eight Solar Array Wings (SAW) on ISS, each has 82 strings of solar cells that are controlled individually to meet the changing power needs of the ISS. The arrays rotate via Beta Gimbal Assemblies (BGA) and Solar Alpha Rotary Joints (SARJ) to maximize power production, minimize stress to the structure, and also move for other specific operations such as vehicle dockings.

During insolation, the Sequential Shunt Unit (SSU) provides the automatic regulation of the arrays by turning strings of cells on and off as needed to support loads. When a string is "shunted" all generated current is sent back to the array, and the voltage on that string is zero. During the eclipse portion of the orbit, the Battery Charge Discharge Units (BCDU) provide the regulation of the power. The current flows into the Direct Current Switching Unit (DCSU) and is sent to the ISS loads [4].
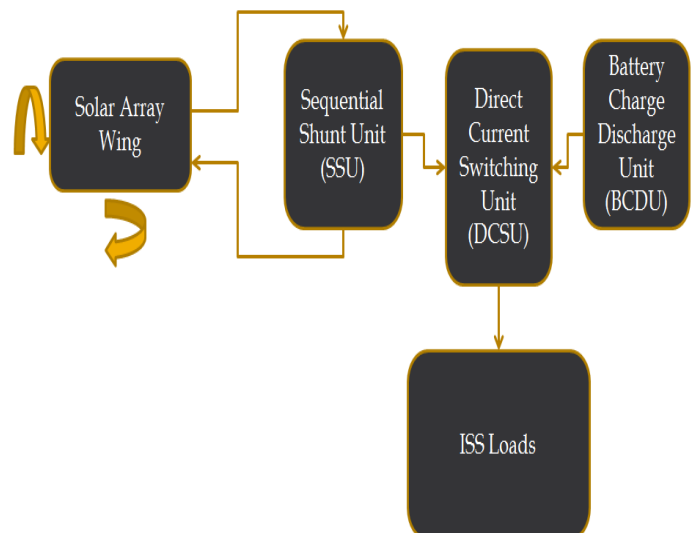

Fig. 3, Solar Array Block Diagram, shows the main components involved in causing floating potential variations. There are eight Solar Array Wings (SAW) on ISS. The arrays rotate via Beta Gimbal Assemblies (BGA) and Solar Alpha Rotary Joints (SARJ). During insolation, the Sequential Shunt Unit (SSU) provides the automatic regulation of the arrays. During the eclipse portion of the orbit, the Battery Charge Discharge Units (BCDU) provide the regulation of the power. The current flows into the Direct Current Switching Unit (DCSU) and is sent to the ISS loads.

V. FLOATING POTENTIAL CORRELATIONS

The following sections demonstrate how the ISS floating potential varies according to five parameters:

1) number of unshunted solar array strings (% of the total number of strings) as calculated from ISS data.

2) projection of the solar array area in the ram direction (C_A) calculated from ISS SARJ, BGA, and quaternion data. This value is plotted as a percentage of the active array area projected in the ram direction. At 100%, all eight arrays are pointed in ram. Negative 100% indicates all eight arrays are pointed in wake. Zero percent indicates all arrays are "edge-on", meaning the edge of the arrays are pointing in the ram direction.

3) plasma ion density (N_i) from the FPMU WLP

4) geographic latitude from Satellite Tool Kit (STK). The geographic latitude is an indication of the expected contribution to floating potential fluctuations from magnetic induction. Higher latitudes result in increased floating potential, with some correction required for the difference between magnetic and geographic latitude.

5) sunlight intensity from STK.

Each Figure has 4 panels. The first is a plot of the ISS floating potenial as measured by the FPMU FPP. The following three panels display the percentage of unshunted strings, C_A, plasma density (N_i) and geographic latitude. The background color of all panels is an indication of the sunlight intensity where gray represents eclipse (no sunlight on the arrays) and white represents insolation. The x-axis on all plots is Greenwich Mean Time.

As the arrays enter insolation, the potential on the unshunted arrays quickly rises to 160 Volts. As the potential across a string of solar cells increases, the exposed portions of the semiconductor and interconnects collect electrons, which increases the negative floating potential of the ISS. The coverglass on the solar arrays collects electrons and begins developing a potential barrier which slows the collection of electrons on the conductive surfaces of the arrays [5]. As the potential barrier increases, electron collection decreases. The floating potential continues to fluctuate through the orbit as the number of unshunted strings, position of the arrays, and magnetic induction vary.

A. ISS Floating Potential during Normal Operations

Fig. 4, Floating Potential during Normal Operations, illustrates the potential profile for normal ISS operations. During normal operations, the arrays are approaching ram at eclipse exit, all strings are unshunted in order to supply power to the loads and recharge the batteries. By orbital noon, the batteries are charged which results in a decreased load. Many strings are shunted due to this decrease in load. At the same time, the arrays are no longer pointed in the ram direction, so the charge collection, and therefore floating potential, is minimized. In this instance, the magnetic induction and ram collection contributions are in synchronization.
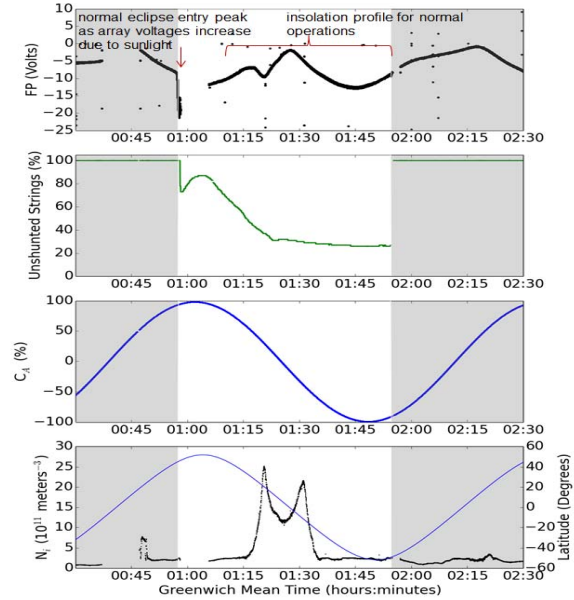

Fig. 4, Floating Potential during Normal Operations, illustrates a typical charging profile. There is an initial increase in floating potential when sunlight is incident on the arrays, then it decreases through the rest of the orbit as strings are shunted and arrays rotate.

B. ISS Floating Potential with Parked Arrays

During special operations, such as vehicle dockings, the arrays are "parked", meaning they do not track the sun but are fixed in a designated position. Fig. 5, Floating Potential Increase Correlated with Parked Solar Arrays, illustrates how this "parked" configuration affects the floating potential. Instead of the floating potential decreasing at orbital noon, it increases because the arrays are pointed in ram and still receiving enough sunlight to maintain a high positive voltage. When the arrays are unparked and begin moving out of the ram direction, the floating potential decreases accordingly.
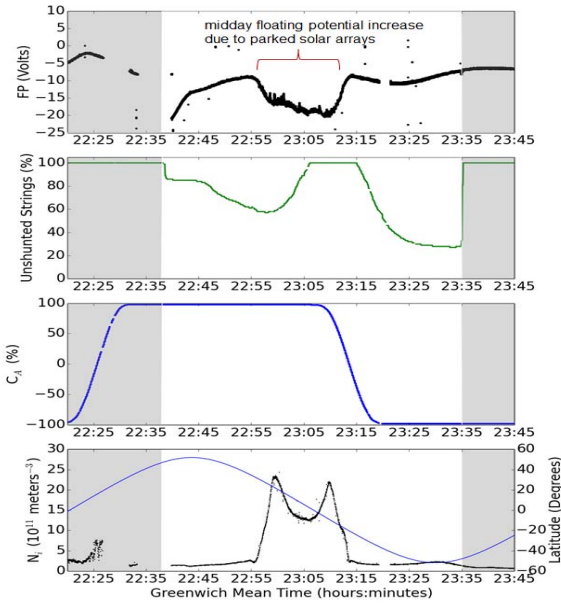
Fig. 5, Floating Potential Increase Correlated with Parked Solar Arrays, illustrates an increase in floating potential midday due to arrays being parked in the ram direction.
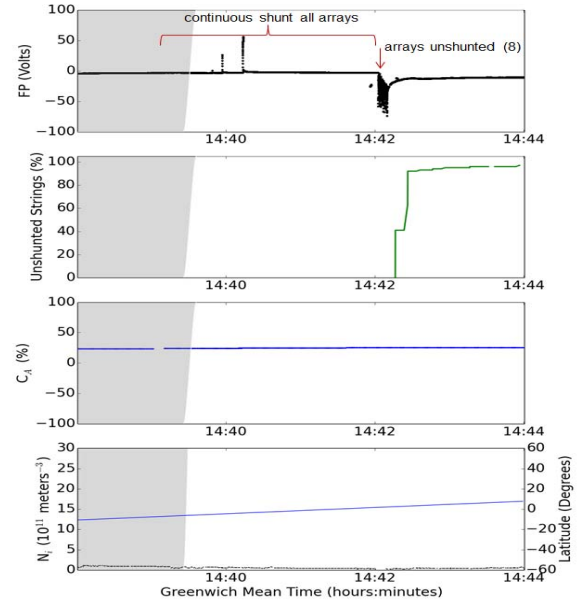

Fig. 6, Floating Potential with All Arrays Shunted During Insolation, illustrates the effects on floating potential of shunting and unshunting all eight arrays during insolation

C. ISS Floating Potential with Arrays Shunted and Unshunted during Insolation

Fig. 6, Floating Potential with All Arrays Shunted During Insolation, illustrates the results of shunting operations during insolation. In order to observe the effects of unshunting arrays in sunlight, all eight arrays were commanded to a shunt state until three minutes into insolation. While the arrays were shunted, large positive floating potential fluctuations were observed. As each array was unshunted, a large negative fluctuation occurred.

Fig. 7, Floating Potential with One Array Shunted during Insolation, illustrates a similar effect as Fig 6. In this instance, one entire array was shunted due to an anomaly on ISS. As the station entered insolation with the array shunted, the positively oriented fluctuations occurred. Unshunting the array resulted in a rapid charging peak with a large negative potential. The array was again shunted, which had little effect on the floating potential.

These floating potential profiles are not well understood, but occur regularly when an entire array is held in a shunted state as the ISS enters insolation and then unshunted in full sunlight. The low data rate (1/10 hertz) of ISS systems data creates a challenge for observing any correlations for these fast fluctuations.
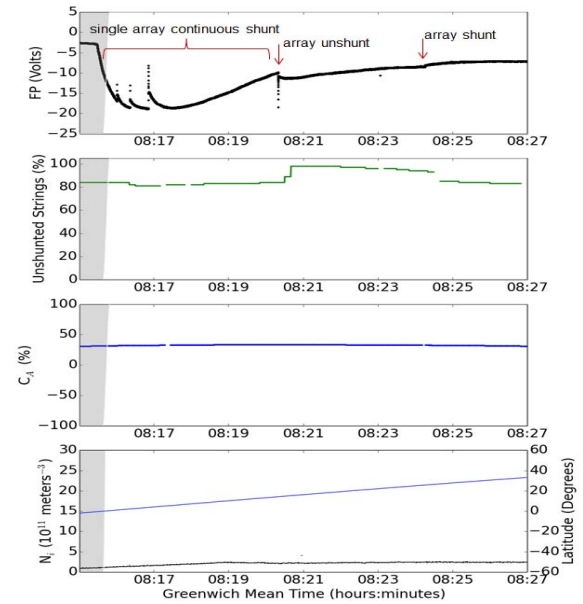

Fig. 7, Floating Potential with One Array Shunted during Insolation, illustrates the effects on floating potential of shunting and unshunting one entire array during insolation

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SUMMARY

While the environmental causes of ISS floating potential variations are relatively well characterized, there remain some unknowns regarding the impact of ISS operations. Characterizing the effects of ISS operations is a difficult task due to the complexity of the array design and operations and the limited array data available. This is especially true of the fast fluctuations measured by the FPMU FPP. It is important to attempt to characterize the effects of ISS operations so that we can design proper operations controls for charge collection mitigation and incorporate lessons learned into future vehicle designs.

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