Observations of Transient ISS Floating Potential Variations during High Voltage Solar Array Operations

Emily M. Willis[1]

University of Alabama in Huntsville, Huntsville, AL, 35899, USA.

Marshall Space Flight Center, Huntsville, AL, 35812, USA.

Joseph I. Minow[2]

Langley Research Center, Hampton, VA, 23681, USA.

Linda N. Parker[3]

USRA Science and Technology Institute, Huntsville, AL, 35805, USA.

Maria Z. A. Pour[4]

University of Alabama in Huntsville, Huntsville, AL, 35899, USA.

Charles Swenson[5]

Utah State University, Logan, UT, 84322, USA

Ken-ichi Nishikawa[6]

University of Alabama in Huntsville, Huntsville, AL, 35899, USA.

Linda Habash Krause[7]

Marshall Space Flight Center, Huntsville, AL, 35812, USA.

   The International Space Station (ISS) continues to be a world-class space research laboratory after over 15 years of operations, and it has proven to be a fantastic resource for observing spacecraft floating potential variations related to high voltage solar array operations in Low Earth Orbit (LEO). Measurements of the ionospheric electron density and temperature along the ISS orbit and variations in the ISS floating potential are obtained from the Floating Potential Measurement Unit (FPMU). In particular, rapid variations in ISS floating potential during solar array operations on time scales of tens of milliseconds can be recorded due to the 128 Hz sample rate of the Floating Potential Probe (FPP) providing 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 transient floating potential variations with mission operations. These complex variations are not reproduced by current models and require further study to understand the underlying physical processes. In this paper we present some of the floating potential transients observed over the past few years along with the relevant space environment parameters and solar array operations data.

---

[1]Ph.D Student, Electrical and Computer Engineering, University of Alabama in Huntsville, Huntsville, AL and Natural Environments Branch, Marshall Space Flight Center, Huntsville, AL, AIAA Member.
[2]NASA Technical Fellow for Space Environments, Langley Research Center, Hampton, VA, AIAA Senior Member
[3]Associate Director, USRC Science and Technology Institute, Huntsville, AL
[4]Assistant Professor, Electrical and Computer Engineering, University of Alabama in Huntsville, Huntsville, AL, 35899.
[5]Professor, Electrical and Computer Engineering,Logan, UT, 84322
[6]Principle Research Scientist, Physics, University of Alabama in Huntsville, Huntsville, AL, 35899.
[7]Researcher, Marshall Space Flight Center, Huntsville, AL, 35812, AIAA Senior Member

American Institute of Aeronautics and Astronautics

I.   Introduction

The interactions of high power solar arrays with the space environment have been studied for decades. These studies have shown that solar array interactions with the local plasma environment can result in power loss, electric discharges, and surface degradation.[1] For the ISS, the safety of astronauts performing extravehicular activity (EVA) is also an important consideration.[2] Positively biased solar arrays were shown to interact with the surrounding space environment by collecting electrons from the plasma causing variations in the floating potential of the spacecraft, otherwise known as spacecraft charging.[3]

The ISS is a unique platform for observing the solar array/plasma interactions because of its large high voltage and high power solar arrays. The ISS has eight Solar Array Wings (SAW), and each wing is 11.7 meters wide and 35.1 meters long.[4] These solar arrays are designed to operate at 160V and are controlled both manually and automatically as required to maximize power output, minimize stress to the ISS structure, and minimize interference with other ISS operations such as vehicle dockings and EVAs. The negative terminals of the arrays are grounded to the ISS frame, which results in fluctuations of the ISS frame potential as the arrays interact with the surrounding plasma.

The Floating Potential Measurement Unit (FPMU), shown in figure 1, has been operational on board the ISS for 10 years. The primary purpose of the FPMU is to monitor the surrounding space environment and floating potential variations in support of astronaut safety during EVA, but it has also proven to be a valuable tool for studying the effects of high voltage array operations on spacecraft floating potential. The FPMU 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 as well as the density and temperature of the local plasma environment.[5,6] The FPP, with a 128 Hz sampling rate, is able to measure transient fluctuations in the frame potential.

Figure 1. The Floating Potential Measurement Unit (FPMU) is a collection of 4 probes deployed on the ISS. This instrument is used to measure the ISS floating potential as well as 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.

II.   Solar Array Operations

It is the complexity of the ISS power system design and operations that cause the remarkable environment interactions observed by the FPMU. 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. During nominal operations, the arrays are set to automatically rotate in order to maximize power production and minimize stress to the structure. There are also many ISS operations that have constraints requiring the arrays be put in a non-solar tracking configuration, and in some cases they are manually controlled or parked in a stationary position.[7] During normal operations, the power system provides automatic regulation of the arrays by turning strings of cells on (unshunting) and off (shunting) 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, power is provided by batteries.[4]

Each solar cell is approximately 8 cm x 8 cm and is covered with coverglass that is slightly larger. The cells are placed approximately 0.8 mm apart. The solar cells have wrap-through interconnections, so they are protected from direct contact with the plasma environment. The sides of the solar cells, however, are exposed. When the strings of cells are unshunted, and therefore positively biased, electrons are collected from the plasma directly to the solar cells through the gaps between the cells. An illustration of this process is shown in figure 2. The coverglass also collects electrons. Once the coverglass achieves a sufficiently negative charge, it has been shown to produce a "choking" effect, which reduces the electron collection.[8,9] As electrons collect to the exposed solar cell edges, the ISS frame potential is forced negative until an equilibrium is reached where the net current collected over the spacecraft is zero.
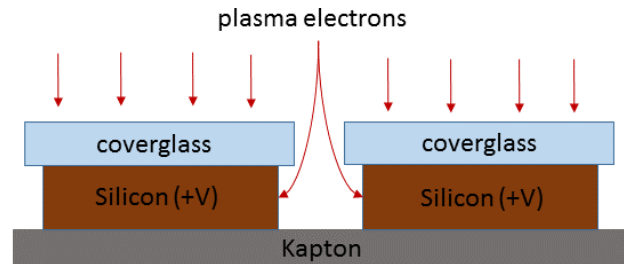

Figure 2. **Illustration of charge collection to ISS solar cells. When the strings of cells are unshunted, and therefore positively biased, electrons can be collected from the plasma directly to the solar cells through the gaps between the cells. As these electrons collect, the ISS frame potential is forced negative until an equilibrium is reached.**

III.   Standard ISS Floating Potential Observations

The FPMU provides a wealth of data throughout the ISS orbit. It allows observation of how the ISS floating potential varies with solar array operations. The standard floating potential variations are well documented[10] and are only summarized in this paper. The types of events can be divided two general categories: 1) natural (driven by the space environment) and 2) induced (driven by active ISS operations). The natural charging events can be further subdivided as follows:

a. Magnetic field effects

This is the motional electromotive force, i.e. the electric field is induced by the motion of the truss through the Earth's magnetic field.[11] The truss structure is approximately 100 meters long. The maximum induced electric field for low earth orbit occurs at high latitudes where the magnetic field has the largest vertical component. For the location of the FMPU on the ISS truss, this results in an approximately sinusoidal variation in floating potential over the course of an orbit.

b. Plasma variation

Local changes in plasma density and temperature can affect the ISS floating potential because they affect the electron flux and the ability of the arrays to capture the electrons. Specifically, an increase in plasma density accompanied by a decrease in plasma temperature can cause small variations. This type of effect is relatively common in the equatorial region due to the Appleton Anomaly.

c. Auroral

These charging events occur when the ISS is orbiting through the auroral region at night. During this time, the lower ambient plasma densities are accompanied by high energy precipitating electrons causing the station to float more negative.

Induced charging events can be caused by many ISS operations, such as maneuvers and dockings, however the focus of this paper is on events caused by solar array operations as described in section II. Up until

American Institute of Aeronautics and Astronautics

now, two types of solar array induced charging events have been documented and both are known to occur at eclipse exit. The two types of events are the normal charging event and the rapid charging event, and they are described as follows:

a. Normal charging event (NCE)

These events are induced by the increase in voltage on the solar arrays as the station enters sunlight. The increased voltage causes greater collection of electrons from the plasma, resulting in a more negative floating potential. The entry into sunlight is slow enough, that the charging of the coverglass is able to maintain a state of equilibrium current collection.[9] These events are modeled very well by programs such as the Plasma Interactions Model[12] and the Environments Workbench.[13]

b. Rapid charging event (RCE)

One of the great discoveries using the FPMU instrument was the RCE.[10] These events are also induced by the increase in voltage on the solar arrays as the station enters sunlight, but they are larger in magnitude and faster in duration than the normal eclipse exit charging. The events correlate with lower plasma densities and are characterized by rise times on the order of seconds and fall times of 10s of seconds. An empirical model was developed in which the maximum potential was calculated using a current balance equation with the assumption that only the outer edges of the array had exposed edges that were not choked off by an adjacent cell. Once this maximum potential was determined, the time constants for the rise and fall of the charging peak were determined using fits to collected data.[14] This model was further studied by incorporation into a computer simulation.[15, 16] These models provided a good representation of the RCEs and confirmed the importance of the solar array turn on time and material and plasma properties on the ISS charging profiles. Another study[17] was performed by creating a lumped element model (LEM) for the ISS. This LEM divided the ISS surfaces into four groups: anodized (dielectric) structures, conductive structures, solar array coverglass, and exposed solar cell material. A linear circuit was designed using these groups with sheath interfaces being approximated as a resistor in parallel with a capacitor, and the dielectric surfaces being modeled as capacitors. The conclusion of this study was that the RCEs were highly dependent on the value of the sheath resistance and capacitance and further work was needed to fully incorporate the non-linear characteristics of the sheath.

A typical floating potential profile for the ISS is illustrated in figure 3. The figure has five panels. The first panel is a plot of the ISS floating potential as measured by the FPMU FPP. The following four panels display the percentage of unshunted strings, the projection of the solar array area in the ram direction (A_{ram}), plasma density, 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 (sunlight on the arrays). The x-axis on all plots is Greenwich Mean Time (GMT). As the arrays enter sunlight, the potential across the unshunted strings of solar cells rises to 160 Volts. As the potential across a string of solar cells increases, the exposed portions of the semiconductor collect electrons, which increases the negative floating potential of the ISS. The coverglass also collects electrons forming a potential barrier and a screening effect, which slows the collection of electrons on the exposed solar cell edges under the coverglass.[9] The collection of ions remains relatively constant and is primarily a function of the spacecraft velocity. The floating potential continues to fluctuate through the orbit as the number of unshunted strings, position of the arrays, and magnetic induction vary. As the arrays rotate from ram-facing to wake-facing, the charging diminishes to the background level created by the magnetic induction.[18] The causes for these floating potential variations are well understood, and these types of variations are observed on a regular basis.

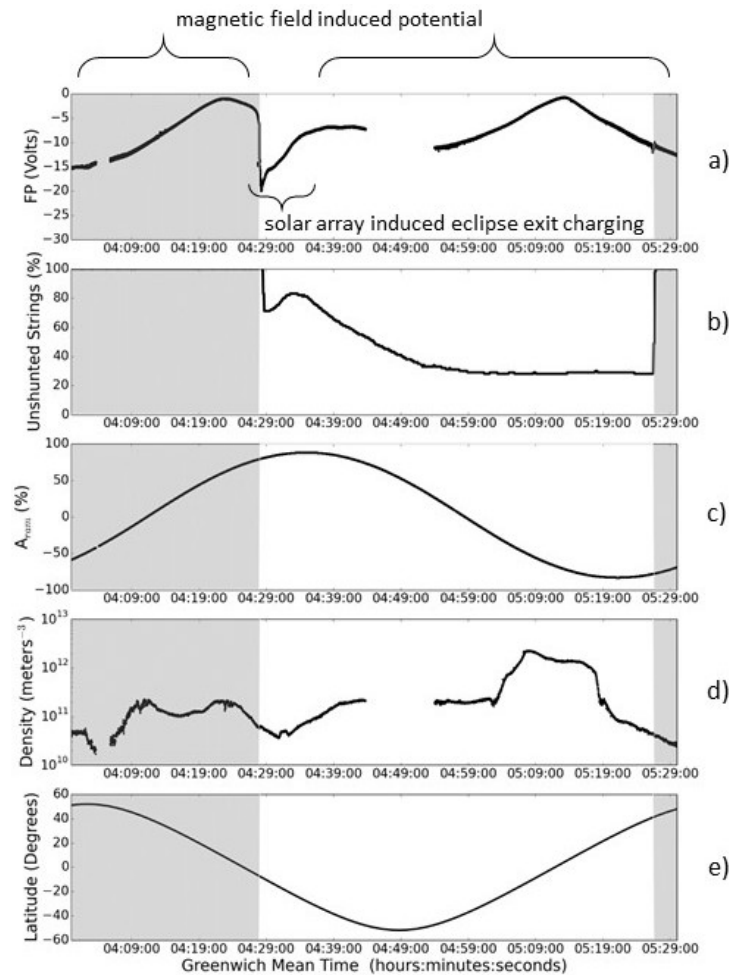American Institute of Aeronautics and Astronautics

Figure 3. Floating potential during normal operations on February 9th, 2013, illustrates a typical charging profile: a) shows the floating potential as measured by the FPMU FPP. The profile is a combination of magnetic field induced potential and eclipse exit charging. The gap in the profile indicates a time when no data was received, b) shows the percentage of ISS solar cell strings that are unshunted. The strings are all unshunted though the eclipse timeframe. As the arrays enter sunlight, the automatic regulation begins to shunt strings in order to control power output. When a string is unshunted in sunlight in sun-tracking mode there is approximately 160 V between its positive and negative terminals, c) as the arrays rotate, the projection of the surface area of the arrays in the ram-facing direction changes. This panel shows the projected area in the ram direction as a percentage of total array area. At 100 percent, all eight arrays are pointed in ram. Negative numbers indicate all eight arrays are pointed in the wake-facing direction. Zero percent indicates all arrays are edge-on, meaning the edge of the arrays are pointing in the ram direction, d) plasma density as measured by the FPMU WLP, and e) geographic latitude from Satellite Tool Kit (STK). This correlates well with the magnetically induced potential. Higher latitudes correlate with increases in magnetic field induced potential. In all panels, the gray shading indicates eclipse, and white indicates sunlight. This data is also taken from STK.

IV.   Transient ISS Floating Potential Observations

Recently, a new kind of solar array induced charging event has been observed. These are transient events characterized by a rise in spacecraft floating potential on a timescale of milliseconds followed by a fall in spacecraft floating potential on a timescale of tens of milliseconds. They are well correlated with solar array operations, but due to low data rate of solar array data (.1 Hz), exact comparisons are difficult. The transients appear when solar arrays are unshunted in full sunlight. This is not a standard mode of operation for the solar arrays and is a rare occurrence, but it has happened during off-nominal operations and solar array anomalies. A series of operations were performed in 2010 to specifically study the effect shunting and unshunting operations on the ISS floating potential, providing a good dataset to study the phenomena. One

example of the data taken during these operations is shown in figure 4. The arrays were held in a shunted state until in full sunlight and then commanded to unshunt. The result was a series of large transients, one for each array. The transients are large, approaching -100V in some cases, and quickly fall to the the background charging level.
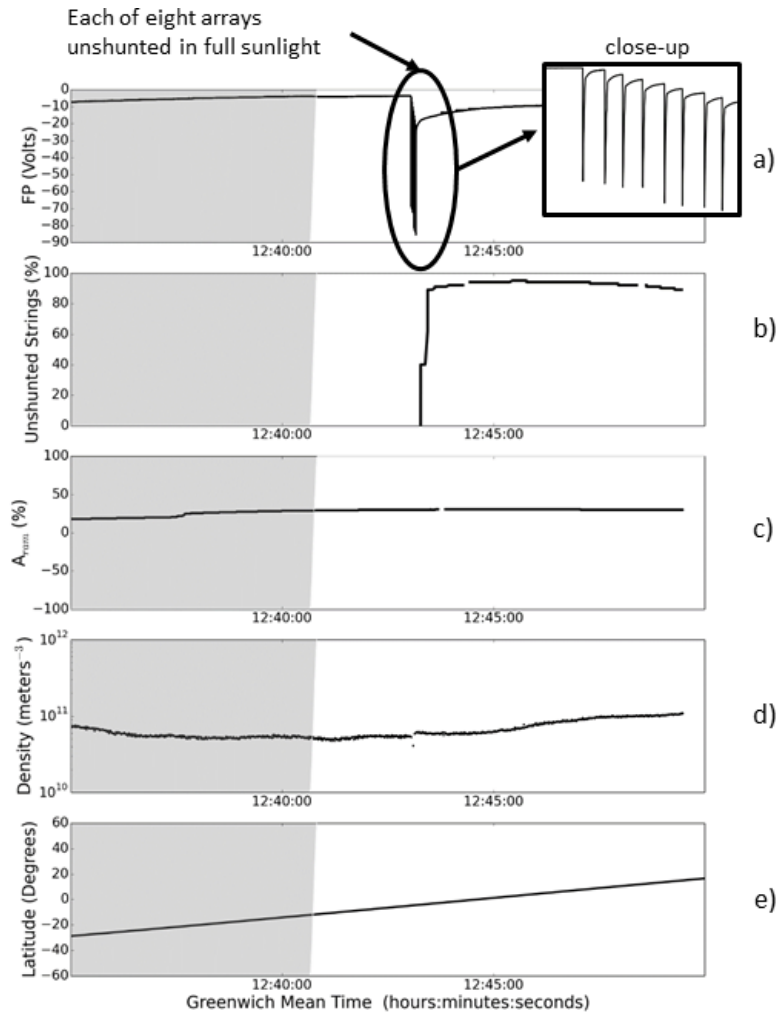

Figure 4. Floating potential (FP) transients on July 26, 2007. All arrays were unshunted in full sunlight: a) shows the floating potential as measured by the FPMU FPP with a close-up view of the transients. There is one transient for each array as it is commanded to unshunt, b) shows the percentage of ISS solar cell strings that are unshunted. In this case the strings are all held shunted until well into sunlight, and then they are all unshunted. When a string is unshunted in sunlight in sun-tracking mode there is approximately 160 V between its positive and negative terminals, c) as the arrays rotate, the projection of the surface area of the arrays in the ram-facing direction changes. This panel shows the projected area in the ram direction as a percentage of total array area. At 100 percent, all eight arrays are pointed in ram. Negative numbers indicate all eight arrays are pointed in the wake-facing direction. Zero percent indicates all arrays are edge-on, meaning the edge of the arrays are pointing in the ram direction, d) plasma density as measured by the FPMU WLP, and e) geographic latitude from Satellite Tool Kit (STK). In all panels, the gray shading indicates eclipse, and white indicates sunlight. This data is also taken from STK.

Transients were also observed during an off-nominal operation, in which one entire array was shunted as the ISS entered sunlight as shown in figure 5. Initially, positively oriented transients were observed. Approximately five minutes into sunlight, the array was unshunted, which resulted in a large negative transient. The array was again shunted, which had little effect on the floating potential.

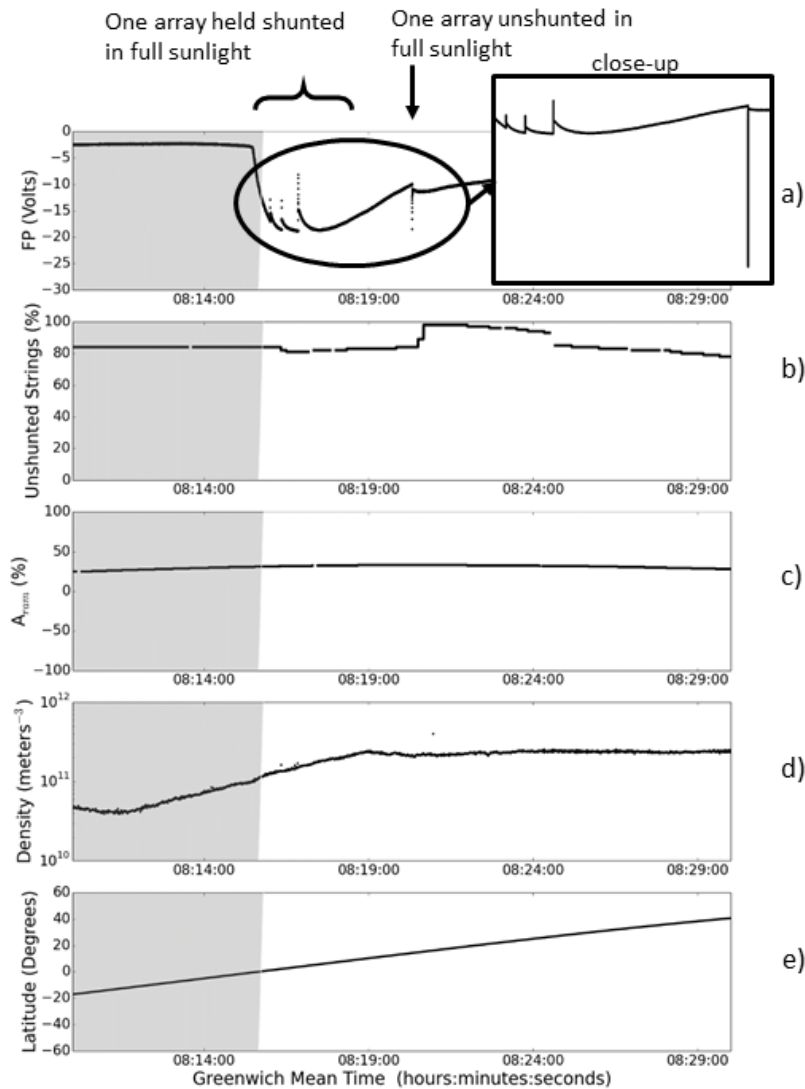American Institute of Aeronautics and Astronautics

Figure 5. Floating Potential (FP) Transients on May 10th, 2013. One array was held shunted for a period of time as the ISS moved into sunlight: a) shows the floating potential as measured by the FPMU FPP with a close-up view of the transients. Positive transients were observed during the time that the array was held in a shunted state. The array was then unshunted resulting in a large negative transient, b) shows the percentage of ISS solar cell strings that are unshunted. The strings on all arrays except for one were unshunted though the eclipse timeframe. One array was unshunted and then shunted again in sunlight. When a string is unshunted in sunlight in sun-tracking mode there is approximately 160 V between its positive and negative terminals, c) as the arrays rotate, the projection of the surface area of the arrays in the ram-facing direction changes. This panel shows the projected area in the ram direction as a percentage of total array area. At 100 percent, all eight arrays are pointed in ram. Negative numbers indicate all eight arrays are pointed in the wake-facing direction. Zero percent indicates all arrays are edge-on, meaning the edge of the arrays are pointing in the ram direction, d) plasma density as measured by the FPMU WLP, and e) geographic latitude from Satellite Tool Kit (STK). In all panels, the gray shading indicates eclipse, and white indicates sunlight. This data is also taken from STK.

More recently, one of the arrays was experiencing an anomaly which resulted in a series of automatic shunting and unshunting of the array. An example of the results of this anomaly is shown in figure 6. The time scales of these unshunt transient events do appear to vary with density, but the correlation is again difficult due to the low solar array data rate.
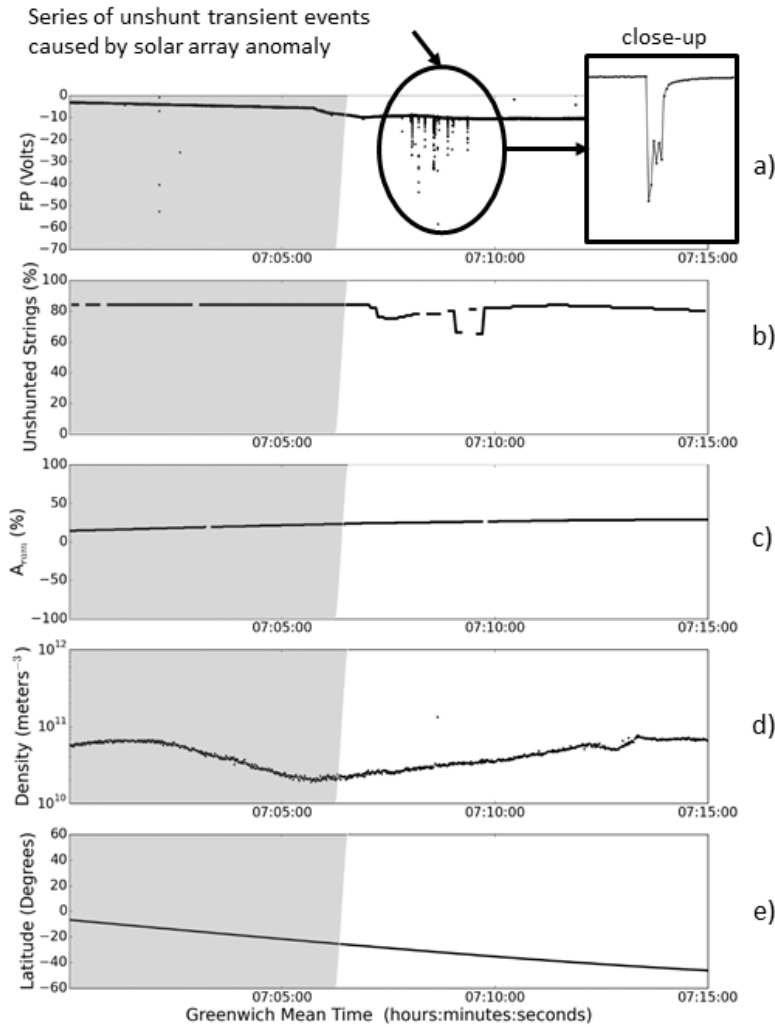
Figure 6. A series of floating potential (FP) transients occurring due to anomalous array unshunting during sunlight: a) a series of negative transients were observed consistent with array unshunt events. A close-up view of a portion of the transients is shown. Solar array anomalies known to cause unshunting events were observed in system data, but due to the limited data rate exact correlation is not possible, b) shows the percentage of ISS solar cell strings that are unshunted. Due to the limited data rate, the unshunting of the arrays is not recorded, c) as the arrays rotate, the projection of the surface area of the arrays in the ram-facing direction changes. This panel shows the projected area in the ram direction as a percentage of total array area. At 100 percent, all eight arrays are pointed in ram. Negative numbers indicate all eight arrays are pointed in wake-facing direction. Zero percent indicates all arrays are edge-on, meaning the edge of the arrays are pointing in the ram direction, d) plasma density as measured by the FPMU WLP, and e) geographic latitude from Satellite Tool Kit (STK). In all panels, the gray shading indicates eclipse, and white indicates sunlight. This data is also taken from STK.

These transients are unexpected phenomena and are not reproduced by current models, however it is possible that they are controlled by the same physical processes described by previous studies. The larger transients probably occur because more electrons are collected before the potential barrier on the coverglass is developed, and current models could simply be expanded to account for this time-dependent collection.

V. Conclusion

While the environmental causes of ISS floating potential variations are relatively well understood, there remain some unknowns regarding the charging induced by ISS solar array operations. In particular, the causes of the transient floating potential fluctuations recently observed and presented in this paper require

American Institute of Aeronautics and Astronautics

further investigation. These fluctuations are likely controlled by the same physical processes described by previous studies. It is important to investigate the cause of these events and continue to study the impacts of these transients on ISS or other high voltage solar power missions. Understanding the causes and effects of these transients and how they relate to ISS operations can enable development of more accurate models, operational controls, and design guidelines for future missions.

Acknowledgments

References

[1]Stevens, N. J., "Space Environmental Interactions with Biased Spacecraft Surfaces," *Space Systems and Their Interactions with Earth's Space Environmnet, AIAA, New York*, 1980, pp. 455–476.

[2]Koontz, S., Edeen, M., Spetch, W., Keeping, T., and Dalton, P., "Assessment and Control of Spacecraft Charging Risks on the International Space Station," *Proceedings of the 8th Spacecraft Charging Technology Conference*, 2003.

[3]Garrett, H. B., "The charging of spacecraft surfaces," *Reviews of Geophysics*, Vol. 19, No. 4, 1981, pp. 577–616.

[4]News, W. S., *Inside the International Space Station: Electrical Power System Astronaut Training Manual*, Progressive Management, 2011.

[5]Barjatya, A., Swenson, C. M., Thompson, D. C., and Wright Jr, K. H., "Invited article: Data Analysis of the Floating Potential Measurement Unit Aboard the International Space Station," *Review of Scientific Instruments*, Vol. 80, No. 4, 2009, pp. 041301.

[6]Wright Jr, K. H., Swenson, C. M., Thompson, D. C., Barjatya, A., Koontz, S. L., Schneider, T. A., Vaughn, J. A., Minow, J. I., Craven, P. D., Coffey, V. N., et al., "Charging of the International Space Station as Observed by the Floating Potential Measurement Unit: Initial Results," *Plasma Science, IEEE Transactions on*, Vol. 36, No. 5, 2008, pp. 2280–2293.

[7]Reddy, S. Y., Iatauro, M. J., Kürklü, E., Boyce, M. E., Frank, J. D., and Jónsson, A. K., "Planning and Monitoring Solar Array Operations on the ISS," *Proc. Scheduling and Planning App. Workshop (SPARK), ICAPS*, Citeseer, 2008.

[8]Chlouber, D. and Cowan, T., *Space Station Freedom Program (SSFP) Electrical Grounding Team Preliminary Integrated Assessment Report*, NASA Contract NAS 9-18200/B, 1991.

[9]Mandell, M. and Davis, V., "Electron Collection by International Space Station Solar Arrays," *8 th Spacecraft Charging Technology Conference*, 2003.

[10]Craven, P., Wright Jr, K., Minow, J., Coffey, V., Schneider, T., Vaughn, J., Ferguson, D., and Parker, L., "Survey of International Space Station Charging Events," *AIAA Paper*, Vol. 119, 2009, pp. 1–6.

[11]Ferguson, D. C., "vxB Effects on Space Station," *2nd International Energy Conversion Engineering Conference*, 2004, pp. 1–7.

[12]Barsamian, H., Mikatarian, R., Alred, J., Minow, J., and Koontz, S., "ISS Plasma Interaction: Measurements and Modeling," 2004.

[13]Chock, R. and Ferguson, D. C., "Environments WorkBench-an Official NASA Space Environments Tool," *Energy Conversion Engineering Conference, 1997. IECEC-97., Proceedings of the 32nd Intersociety*, Vol. 1, IEEE, 1997, pp. 753–757.

[14]Ferguson, D. C., Craven, P. D., Minow, J., and Wright, K., "A Theory for Rapid Charging Events on the International Space Station," *AIAA Atmospheric and Space Environments Conference*, 2009.

[15]Huang, J., Yi, Z., Zhao, H., Meng, L., and Liu, Y., "Model for Rapid-Charging Events for the International Space Station," *Journal of Spacecraft and Rockets*, Vol. 51, No. 1, 2014, pp. 11–15.

[16]Huang, J., Yi, Z., Zhao, H., Meng, L., and Liu, Y., "Mechanism for Rapid Charging Events on International Space Station," *Journal of Spacecraft and Rockets*, Vol. 51, No. 3, 2014, pp. 917–921.

[17]Hui, D., *A Model for Rapid Charging Events on the International Space Station*, Master's thesis, Utah State University, 2011.

[18]Alred, J., Mikatarian, R., and Koontz, S., "Impact of Solar Array Position on ISS Vehicle Charging," *44th Aerospace Sciences Meeting and Exhibit, Reno, NV*, 2006.