CALIBRATING THE FLOATING POTENTIAL MEASUREMENT UNIT

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Abstract

The Floating Potential Measurement Unit (FPMU) is an instrument being developed to study the spacecraft surface charging of the International Space Station (ISS). Charging on the ISS is unique because of the station's size and the high voltage solar arrays with exposed interconnects. The FPMU consists of four instruments: a floating potential probe, two Langmuir probes, and a plasma impedance probe. These probes will measure the floating potential of the ISS, electron density, and electron temperature with redundancy. The instruments were calibrated using test loads over a range of temperatures. The FPMU is being integrated into the ISS at one of the existing external camera locations that places it in clear ram flow of the space plasma. Operational constraints of the ISS will result in the FPMU being used to obtain snapshots of data and not as a continuous monitor of the ISS charging and environment. The FPMU is awaiting launch to the ISS on the first flight of the Space Shuttle when it returns to service. This paper presents an overview of the FPMU instruments and calibration results.

Introduction and Background

The Floating Potential Measurement Unit (FPMU), shown in Figure 1, has been created to aid in the understanding of the complex surface charging physics of the International Space Station (ISS). The instrument was originally to be deployed on the ULF-1 mission in March of 2003 but was delayed by the Space Shuttle Columbia accident that occurred in February of 2003. A single FPMU is currently scheduled to be deployed when the Space Shuttle returns to flight and construction missions for the ISS resume. This will be no earlier than March of 2004. When deployed the FPMU will be used to characterize the charging physics and validate charging models after each stage of ISS assembly. Changes to ISS charging physics are expected as additional solar arrays are added to the structure due to their enhanced ability to collect electrons from the surrounding ionospheric plasma (1, 2). An overview of the FPMU and its mission has been previously presented by Swenson et al (3).

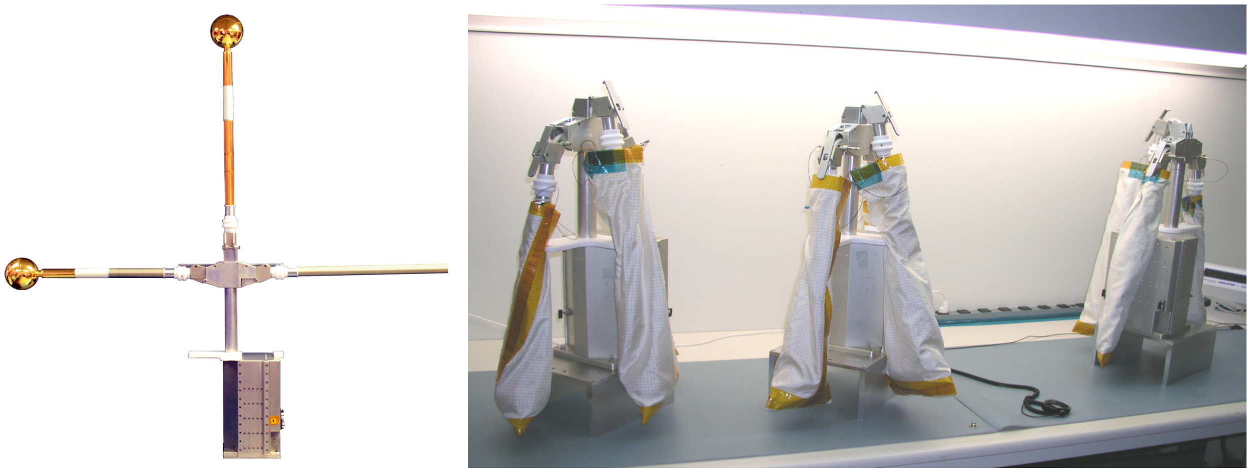

Figure 1. Photographs of the Floating Potential Measurement Unit (FPMU). (Left) Flight unit with sensors deployed. (Right) One flight unit and two flight-spares in protective covers with sensor booms stowed, October 2003.

Excessive charging of the ISS has been identified as a potential shock hazard to astronauts on Extra Vehicular Activity (EVA) due to the nature of the US space suit design. Industrial safety standards for workers around high voltage would indicate that this hazard exists when the floating potential of the ISS exceeds 40 Volts (4). There is also a concern for the long term stability of the anodized aluminum surfaces on the exterior of ISS modules. Charging greater than 80 Volts relative to the space environment causes electrical breakdown of the capacitive layer on the anodized aluminum due to its relatively weak dielectric nature (5). The dielectric breakdown results in arcs, sputtering, pitting and contamination of the surface properties. Over long periods of time this can change the surface temperature of ISS modules, creating a touch temperature concern for astronauts on EVA. These concerns prompted the construction of the FPMU and it predecessor, the Floating Potential Probe (6, 7, 8).

The FPMU development team was challenged at both systems and instrument levels primarily due to the short ten-month development requirement compounded by NASA's safety, testing, and documentation requirements. The FPMU is to be operational for a period of at least three years to cover the construction phase of the ISS and to provide measurements of vehicle floating potential, local plasma density, and electron temperature. To achieve these requirements commercial parts were used in radiation tolerant designs and multiple FPMUs were fabricated as replacement units. It was critical that there be evidence to indicate when, or if, FPMU data was erroneous. This was achieved by including significant internal system monitoring and by using multiple instrument and measurement techniques (floating probes, Langmuir probes, radio frequency probes). At the current stage of assembly, shown in Figure 2, there are no sites for external mounting of generic instruments on the ISS structure. The FPMU, therefore, masquerades as an external TV camera in order to receive power and transmit data encoded in TV images though the ISS video systems.

Instrumentation

The FPMU is comprised of four instruments to measure floating potential, plasma density and temperature. The instruments use different techniques or geometries to provide redundancy and cross-validation of the final data products. The instruments are the Floating Potential Probe (FPP), the Wide-sweeping Langmuir Probe (WLP), the Narrow-sweeping Langmuir Probe (NLP), and a Plasma Impedance Probe (PIP) as illustrated in Figure 2 (right). The FPMU is planned to be initially installed at camera port 2 on the end of the S1 truss of the ISS. This location will be out of the plasma wake for nominal ISS flight orientation. Interference or cross-talk between the individual instruments of the FPMU was a concern. The probe surfaces have been set at least two Debye lengths apart for a worst-case rarified and cold ionospheric plasma. The tip-to-tip distance from WLP to the PIP is 130 cm, and the whole instrument stands 150 cm tall. We briefly present an overview of each instrument.

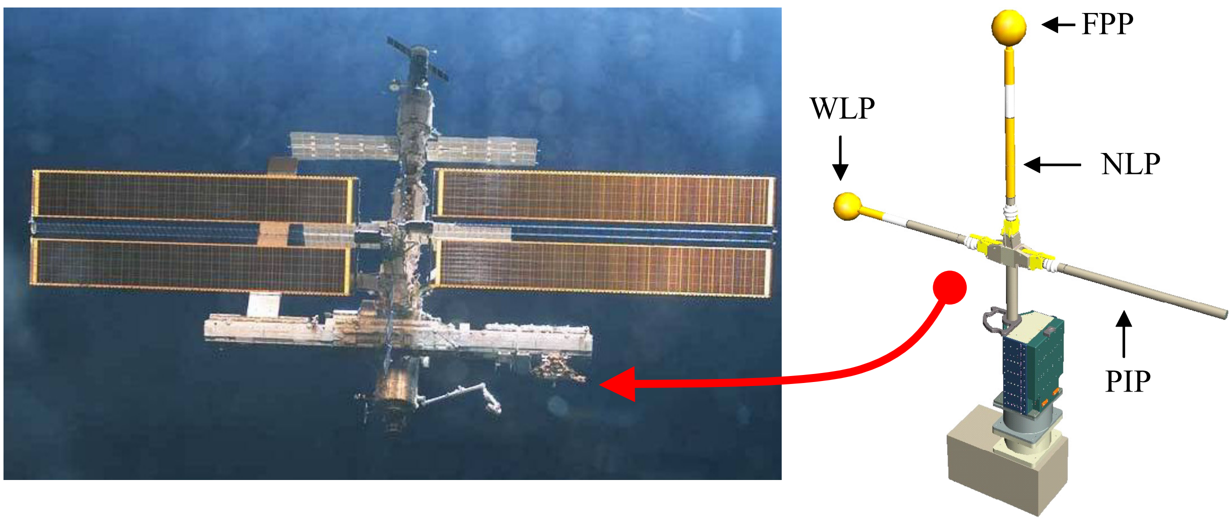

Figure 2. (Left) Photograph of the ISS December 2002. (Right) The FPMU showing the locations of the four instruments; Floating Potential Probe (FPP), Wide-Sweep Langmuir Probe (WLP), Narrow-Sweep Langmuir Probe (NLP), and the Plasma Impedance Probe (PIP).

The Floating Potential Probe (FPP) is a gold plated sphere of radius 5.08cm. The sphere is isolated from chassis ground by a high impedance circuit, approximately $10^{11}\Omega$. The sphere "floats" at a floating potential determined by local plasma conditions, which is within a few $k_B T_e$ of the plasma potential, and provides a good reference for measuring the potential of the ISS. Data is sampled as a 12-bit word with 100mV resolution.

The Wide-Sweep Langmuir Probe (WLP) is a gold plated sphere of radius 5.08cm. A voltage sweep from –20V to 80V relative to chassis ground, the ISS structure, is applied to the probe, and the resulting currents to the probe are measured. Sweeps are accomplished each second, with the potential sweeping from low to high voltage one second and back down from high to low the next. The sweep is comprised of three parts: steps of ~250mV from –20V to 0V, steps of ~25mV from 0V to 50V, and steps of ~250mV from 50V to 80V. This pattern was chosen as a balance between available telemetry space and the amount of data necessary to derive the required parameters. The small step size from 0V to 50V provides sufficient resolution for a determination of Temperature, T_e (which requires several samples in the electron retarding portion of the sweep). The floating potential can be obtained over the full –20V to 80V range, within the uncertainty requirement of ±2V. The current resulting from the applied voltage sweep is measured on two different 12-bit channels. The low-gain channel has a resolution of 700 nA/count and the high gain channel has a resolution of 3.5 nA/count. The high-gain channel has sufficient sensitivity to observe both photo emission and ion collection currents, whereas the low-gain channel is suited for observing ambient electron currents.

Measurement of ionospheric electron temperature by Langmuir probes is subject to significant error if the probe surface material does not have a uniform work function, or if the probe is not clean (10). Gold was chosen as the surface coating for the Langmuir probes owing to its nearly uniform work function when properly applied and cleaned (12) and its stability in the atomic oxygen environment of low earth orbit. The WLP can be cleaned on orbit by heating the probe surface to approximately 350 C. This is accomplished via a small halogen lamp inside the hollow sensor sphere that can be powered on and off. Cleaning Langmuir probes in this fashion has been shown to be effective by W.E. Amatucci et al (9).

The Narrow-Sweep Langmuir Probe (NLP) is a gold plated cylinder of radius 1.43cm and length 5.08cm. The NLP is placed mid-way on the boom supporting the FPP. The probe surface of the NLP is surrounded on each side by a gold-plated guard cylinder of radius 1.43cm and length 10.2cm, which are swept in synchrony with the NLP. A sweep from –4.9V to +4.9V, in steps of ~12mV, is applied to the NLP during one second, followed by a sweep down from 4.9V to –4.9V the next second. This sweep voltage is referenced to the floating potential measured by the FPP. Hence, even though the sweep range of the NLP is small compared to the possible range of ISS potentials, the electron and ion retarding regions of the plasma current-voltage profile will be seen, as the region sampled will move through the –180V to +180V range of the FPP to match the current conditions. This configuration will allow N_e (the local plasma density) and T_e to be determined at 1Hz. In addition, the ISS potential measured by the FPP will be verified, since if it is incorrect, the NLP will not be referenced to the proper potential and the transition from electron collection to ion collection will not be seen in the ±4.9V sweep.

The current resulting from the applied voltage sweep is measured on two different 12-bit channels. The low-gain channel has a resolution of 87.5 nA/count and the high gain channel has a resolution of 0.44 nA/count. Like the WLP the high gain channel has sufficient sensitivity to observe both photo emission and ion collection currents, whereas the low-gain channel is suited for observing electron currents. The surfaces of the NLP and WLP are both gold for the same reason: the desire for a uniform work function and stability in atomic oxygen. However, there is no heating lamp within the NLP, so there is no active cleaning mode for this probe.

The Plasma Impedance Probe (PIP) consists of an electrically short dipole antenna electrically isolated from the ISS. The dipole is normally oriented perpendicular to the ram flow direction and away from the ISS wake. The PIP measures the electrical impedance (magnitude and phase) of the antenna at 256 frequencies over a 100 KHz to 20 MHz range. Electron density, electron-neutral collision frequency, temperature and magnetic field strength can potentially be deduced from these impedance measurements (11). The PIP will also track the frequency at which an electrical resonance associated with the upper-hybrid frequency occurs using a technique known as the Plasma Frequency Probe (PFP). From this resonance the absolute plasma density will be determined at a 512 Hz rate with great accuracy. The PIP is considered an experimental instrument and has no formal NASA requirements for operation.

The performance of the FPMU instruments to measure the ISS floating potential, V_{ISS}, the local plasma density, Ne, and Temperature, Te are summarized in Table 1.

Table 1. The measured parameters, rates, and effective ranges for the FPMU instrumentation.

Instrument	Parameter	Rate	Effective Range
FPP	V_{ISS}	128Hz	-180V – +180V
WLP	Ne	1Hz	$10^9 m^{-3}$ – $5x10^{12} m^{-3}$
	Te	1Hz	500K – 3000K
	V_{ISS}	1Hz	-50V – 20V
NLP	Ne	1Hz	$10^9 m^{-3}$ – $5x10^{12} m^{-3}$
	Te	1Hz	500K – 3000K
	V_{ISS}	1Hz	-180V – +180V
PIP	Ne	512Hz	$10^8 m^{-3}$ – $10^{13} m^{-3}$

Calibration

The FPMU was calibrated by examining the response of the instruments to known loads or test conditions. These measurements were performed both under bench-top conditions and while the FPMU was undergoing thermal vacuum testing. Efforts were made to minimize noise during this process although this was not completely possible. When the FPMU was undergoing thermal vacuum testing long leads were run from the probe surfaces, through vacuum feed through connecters, and then to test equipment and loads external to the chamber. These long leads were a source of white noise that was detectable on the high gain channels of the WLP and the NLP but was largely below the detectable threshold of the low gain channels.

The calibration data has been reduced to a set of polynomial coefficients that are applied to the telemetered values (12-bit integers). The actual calibrations are stored in a file for use by the FPMU ground station software. The file contains blocks composed of one or more comments, followed by a line of polynomial coefficients of the form:

$$y = A_0 + A_1 x + A_2 x^2 + \ldots$$

where y is the calibrated quantity (volts, amperes, centigrade, etc) and x is the telemetered integer quantity. Each of the FPMU flight units has its own calibration file, with its own unique set of coefficients. The WLP and NLP are found to have calibrations that vary with the temperature of the electronics. Hence, the calibration coefficients, A_0 and A_1 are functions of temperature. The calibration file contains 4 coefficients for each of Langmuir probe channels. These four coefficients, called m_0, b_0, m_1, and b_1, respectively, are the coefficients that can be used to calculate A_0 and A_1 according to:

$$A_0 = b_0 + m_0 T_{12}$$
$$A_1 = b_1 + m_1 T_{12}$$

where T_{12} is the uncalibrated value (counts) of the FPMU Sensor Board Top Temperature Sensor (housekeeping measurement T_{12}). The corrected values for A_0 and A_1 are used to produce engineering values for the Langmuir probe channels. We now present a brief overview of the major calibration and test results for each of the FPMU instruments.

The FPP testing and calibration results are summarized in Figure 3. For FPMU serial number 4, A_0 and A_1 were found to be A_0 = -194.6 and A_1 = 0.095. The input resistance of the FPP must be sufficiently high such that the measurement current will be a small fraction of either the ambient ion or electron collection currents. This required that the input resistance of the FPP be greater than 10^9 Ohms and preferably as high as possible. This was tested by applying a capacitor in parallel with the probe, charging it to 3 Volts, and observing the resulting discharge curve, Figure 3 (right). This data was consistent with a leakage current dominated by discharge through the relatively dry air around the probe and the change of stray capacitance due to the motion of technicians near the probe conducting the test. The FPP testing and calibration results for each of the flight units showed similar results.

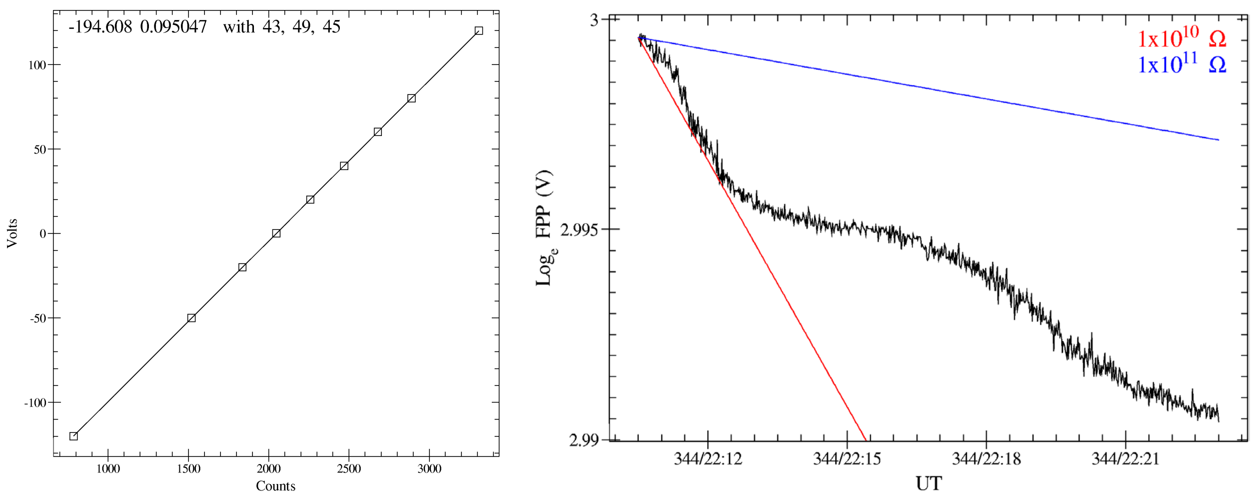

Figure 3. (Left) Calibration results of the FPP showing a linear response of instrument with applied voltage. (Right) Input resistance test of the FPP by capacitive discharge.

The WLP and NLP temperature dependent calibrations for the high gain channel are shown in Figure 4. The probes were calibrated over the range of 17 to 59 C while the expected operating range is 25 to 40 C and is thermostatically controlled. Several thousand IV curves were analyzed and the resulting calibrations for A_0 and A_1 are displayed as points. The trend lines are the resulting temperature dependent calibrations b_1 and m_1. The gain coefficient, A_1, is relatively insensitive to temperature for both probes and very near the desired values of 3.5 nA/count and 0.44 nA/count with a fraction of a count of drift with temperature. The noise or distribution of gain observed in Figure 4 is not expected for on orbit operation.

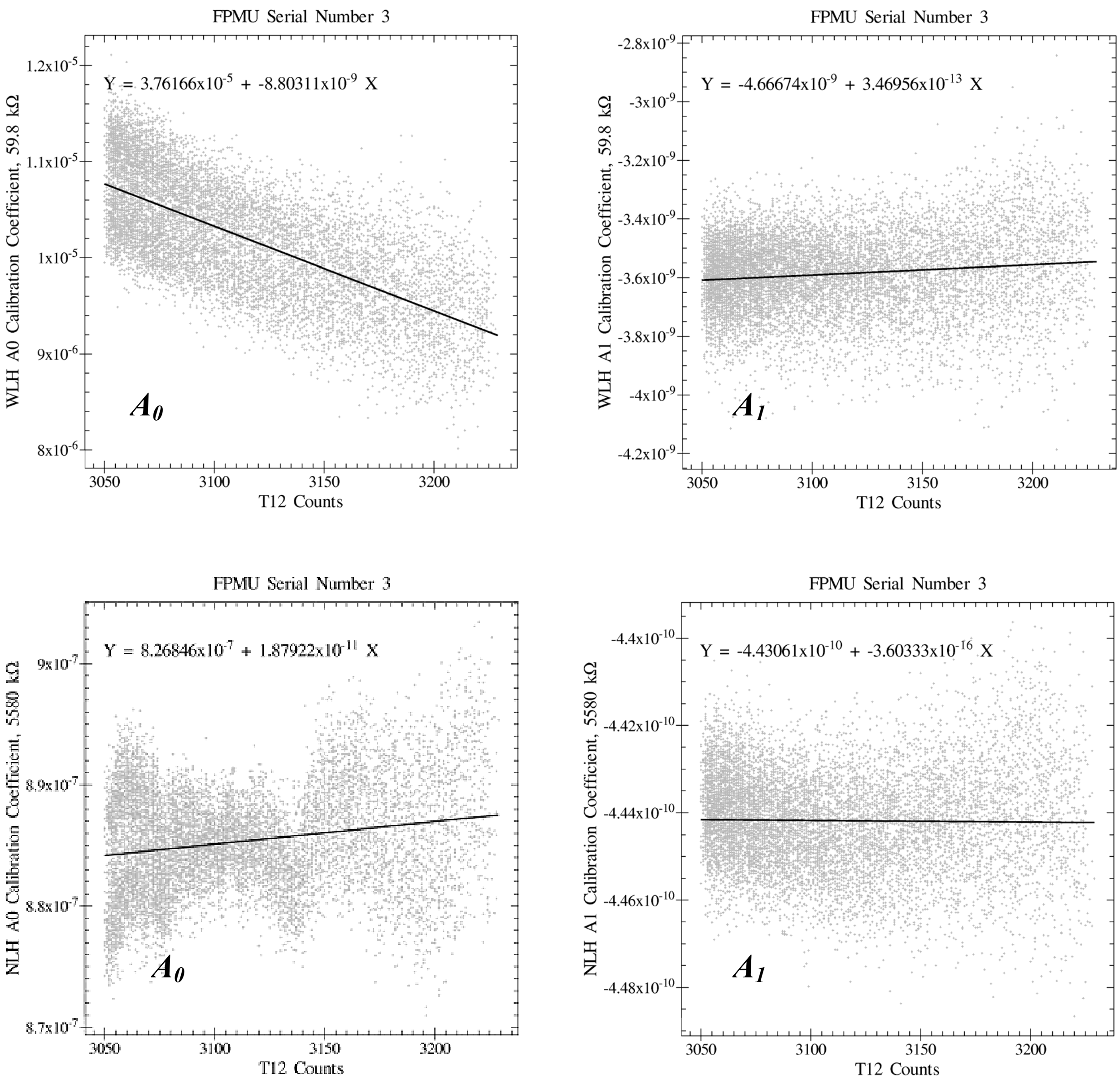

Figure 4. Temperature dependent calibration for the high gain channels of the Langmuir probes on FPMU serial number 3. The graphs are for the A_0 coefficient for the WLP (top left), A_1 coefficient for the WLP (top right), A_0 coefficient for the NLP (top left), A_1 coefficient for the NLP (top right). T_{12} counts are converted to centigrade by A_0=689.9 and A_1=-0.2068 giving a temperature range of 60 to 17 C for these plots.

The offset coefficient, A_0, that can be thought of as the zero reference level, shows considerable drift over the temperature range that corresponds to 350 counts for the WLP and 25 counts for the NLP. Neither of these drifts significantly change the range of currents that can be observed for normal ionospheric operations. The corrections for these drifts are critical to observing Ion currents as they are on the order of the expected photo emission currents.

Figure 5 presents the temperature dependent calibrations for the low-gain channels. They reflect that design goals have been achieved and show expected measurement quantization noise effects reflecting the technical simplicity of these channels relative to the high gain channels. The two lines for the WLP calibration result from the difference of one count of the measurement of the calibration load. The NLP similarly shows a faint bi-modal distribution resulting from one count of difference over the measurement range.

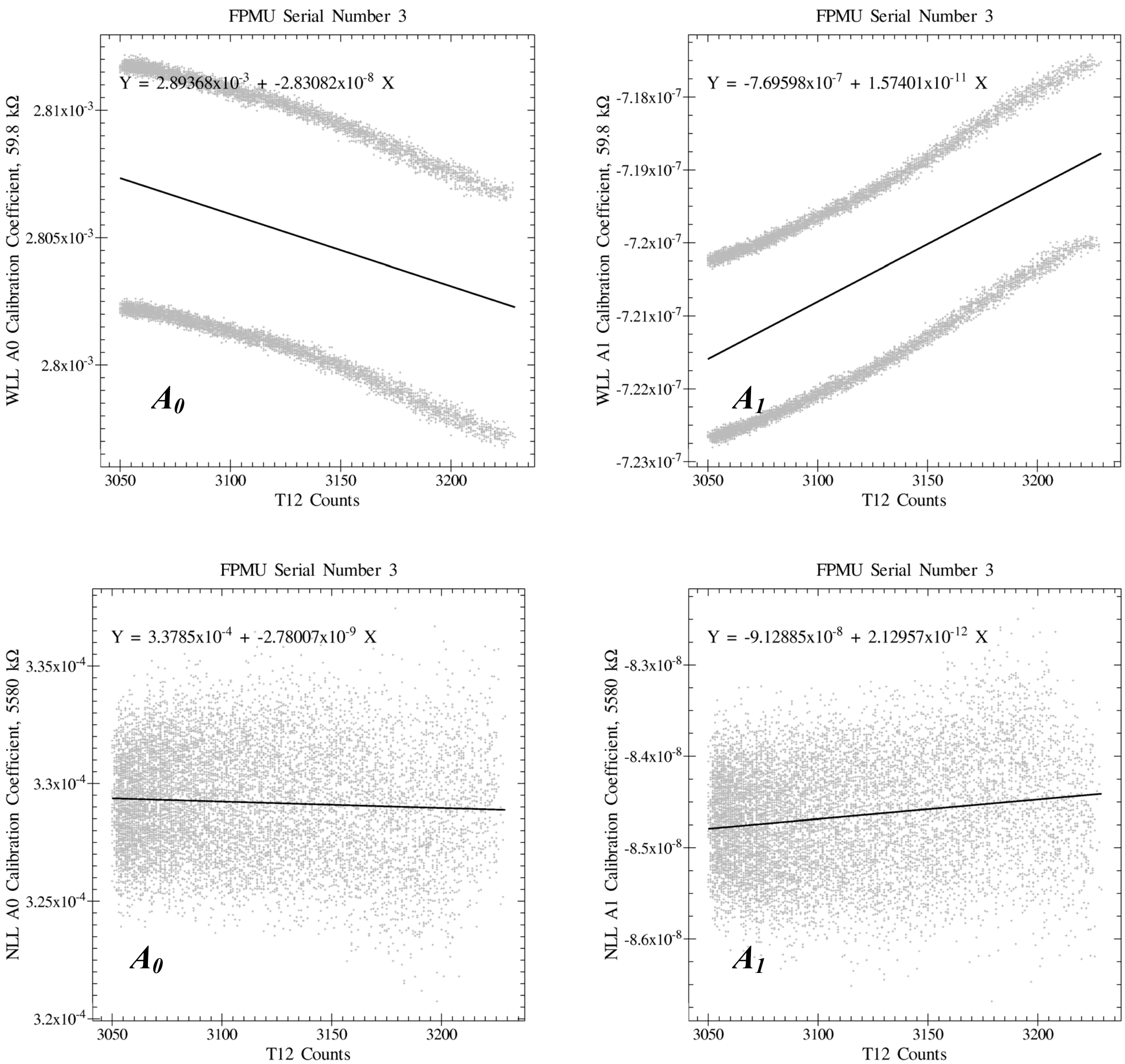

Figure 5. Temperature dependent calibration for the Low gain channels of the Langmuir probes on FPMU serial number 3. The graphs are for the A_0 coefficient for the WLP (top left), A_1 coefficient for the WLP (top right), A_0 coefficient for the NLP (top left), A_1 coefficient for the NLP (top right). T_{12} counts are converted to centigrade by A_0=689.9 and A_1=-0.2068 giving a temperature range of 60 to 17 C for these plots.

The PIP is a more complex instrument than the other FPMU instruments, and testing and calibration is problematic due to its RF operating range. The probe is calibrated before final assembly of the FPMU when the antenna components are not attached. A set of test loads consisting of resistors, capacitors, and inductors are placed at the antenna feed. The output of the magnitude and phase channels are then compared to the impedance of the loads as measured on a network analyzer (Figure 6, left). The resonance tracking PFP is tested with a R-L-C network that simulates the resonance observed at the upper-hybrid frequency. The results of this testing are shown in Figure 6 (right) where a 7.21 MHz resonance frequency calibrator is tracked with an accuracy of better than 0.1%.

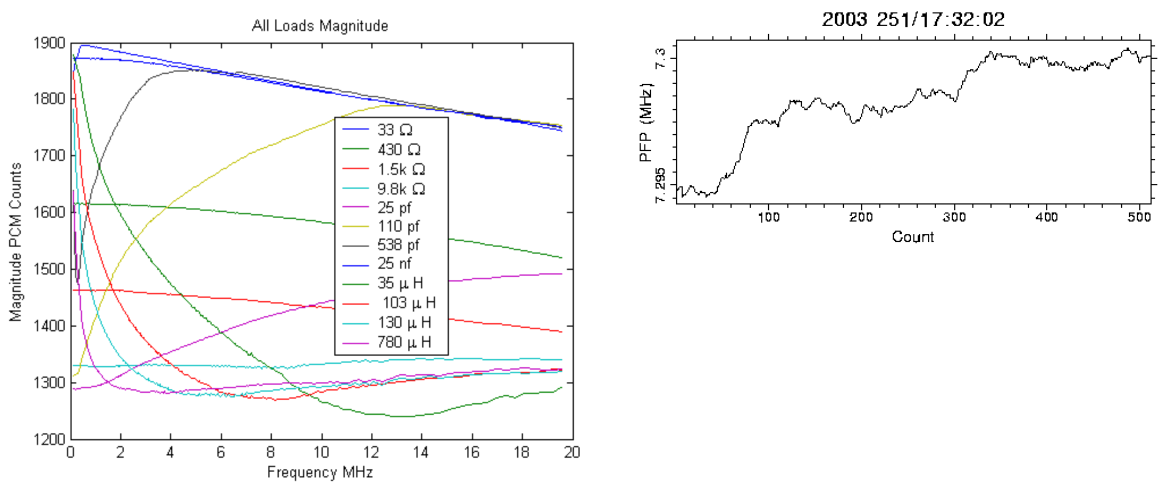

Figure 6. (Left) The magnitude channel of the PIP sweeps data for different calibration loads. (Right) The frequency tracked, or measured, by the PFP of a 7.21 MHz resonant network versus time or sample count.

The calibration of the PIP sweeps channels, magnitude and phase, are not completed at this time. The response of the instrument to a given load antenna load, Z_a, is given by:

$$\text{Magnitude} = K_1 + K_2 \,\text{Log}_{10}(\,|\,\alpha + Z_f/Z_a\,|\,)$$

$$\text{Phase} = K_3 + K_4 \,\text{Arg}(\,\alpha + Z_f/Z_a\,)$$

where K_1, K_2, K_3, K_4 are gain or offset coefficients for each of the channels and Z_f is the known feedback impedance of the preamplifier of the instrument. The constant α has a value from 0 to 1 and results from the subtracting of the RF drive signal from the measurement signal. Ideally α would be 0, resulting in the magnitude channel being a simple admittance measurement of the antenna, but α has a value of $1/11^{th}$ resulting in a coupling between the admittance magnitude and phase of the load for each of the measurement channels. The calibration of the PIP sweeps amounts to determine the value of the constants K_1, K_2, K_3, and K_4 at each of the 256 measurement frequencies. The calibration of the PIP sweep data to date has shown an absolute accuracy of only about 20% for the instrument, which is considerably off the 1% goal for the instrument. We are unsure whether this is a result of discrepancy of the applied loads due to the difference of measurement fixtures between the FPMU and the network analyzer used to determine the calibrators, or whether there is an additional oversight in our determinations of the calibration constants. Investigation and calibration are continuing and we are optimistic that a 1% to 5% absolute impedance measurement can be demonstrated.

Summary and Conclusions

The FPMU was produced under an extremely tight 10-month development schedule but was then placed under a one-year delay for deployment due to the Columbia accident. The calibration of FPP, WLP, and NLP show that these instruments have sufficient sensitivity to achieve NASA's mission of understanding the charging physics of the ISS. The sweep (magnitude and phase) of the PIP data stream has not been successfully calibrated at this time due to instrumentation issues. The instrument could not be corrected during development due to schedule constraints when the problem was identified. A correction is expected to be possible through the calibration and data analysis software.

The video interface for data transmission is both a boon and a bane for science uses of FPMU data. The large bandwidth available allows an unprecedented amount of raw instrument data to be transmitted to the ground. The direct comparison of so many different probe types simultaneously measuring the same space plasma is a first and is sure to lend insight into both Langmuir and RF probe theory. The WLP is a unique instrument in that it is the first Langmuir probe to be flown with such a large bias sweep (100 Volts) where all of the data is being transmitted to the ground. The ability to clean the surface of WLP may make it useful for studying the contamination environment of the ISS. The video system is a bane in that the FPMU will be operated largely as a snapshot instrument. There is no way to store FPMU data onboard the ISS and then later send it down at a higher data rate. This severely limits the usefulness of the FPMU as an ionospheric diagnostic instrument. A large dataset covering years of operation will not be produced as this would require a continuous, real-time ISS video link dedicated to the FPMU.

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