Validation of ISS Floating Potential Measurement Unit Electron Densities and Temperatures

Victoria N. Coffey[1], Joseph I. Minow[1], Linda N. Parker[2], Them Bui[3], Kenneth Wright, Jr.[4], Steven.L. Koontz[5], T. Schneider[1], J. Vaughn[1], and P. Craven[1]

[1]NASA, Marshall Space Flight Center, Huntsville, Alabama 35812, USA
[2]Jacobs Engineering, ESTS Group, Huntsville, Alabama 35812, USA
[3]Allied Aerospace, ESTS Group, Huntsville, Alabama 35812, USA
[4]University of Alabama-Huntsville, Huntsville, Alabama, 35899 USA
[5]Johnson Space Center, Houston, Texas, 77058 USA

Abstract: Validation of the Floating Potential Measurement Unit (FPMU) electron density and temperature measurements is an important step in the process of evaluating International Space Station spacecraft charging issues .including vehicle arcing and hazards to crew during extravehicular activities. The highest potentials observed on Space Station are due to the combined VxB effects on a large spacecraft and the collection of ionospheric electron and ion currents by the 160 V US solar array modules. Ionospheric electron environments are needed for input to the ISS spacecraft charging models used to predict the severity and frequency of occurrence of ISS charging hazards. Validation of these charging models requires comparing their predictions with measured FPMU values. Of course, the FPMU measurements themselves must also be validated independently for use in manned flight safety work. This presentation compares electron density and temperatures derived from the FPMU Langmuir probes and Plasma Impedance Probe against the independent density and temperature measurements from ultraviolet imagers, ground based incoherent scatter radar, and ionosonde sites.

1. Introduction

The Floating Potential Measurement Unit (FPMU) is a multi-probe instrument package installed on the ISS in August 2006. It is designed to measure the floating potential of the International Space Station (ISS) and the density and temperature of the local ionospheric plasma environment for use in evaluating spacecraft charging issues for the ISS vehicle [*Ferguson et al.*, 1990; *Carruth et al.*, 2001; *Mikatarian et al.*, 2003a,b]. This instrument suite provides direct measurements of ISS spacecraft charging as continuing construction leads to changes in ISS size and configuration. The FPMU consists of four probes: a floating potential probe, two Langmuir probes, and a plasma impedance probe. The four probes are: a Floating Potential Probe (FPP), a Plasma Impedance Probe (PIP), a Wide-sweep Langmuir Probe (WLP), and a Narrow-sweep Langmuir Probe (NLP). The FPMU has been described elsewhere [*Swenson et al.*, 2003; *Swenson et al.* 2004; *Swenson et al.*, 2005] and is shown in Figure 1.

The calibration equations are first applied to the raw telemetry, the Level-0 data, of each sub-component to generate the Level-1 data correcting instrument response to temperature sensitive components. Level-2 data is then obtained by deriving the plasma properties from the curve-fitted data to the expected theoretical response. Presently we are going through the process of the validation of the instrument data by comparing the derived temperatures and densities to each other and to independent measurements of orbital satellites and ground based incoherent scatter radar and ionosondes. This validation effort consists of comparing FPMU plasma data to other published, independent sources of plasma data to demonstrate that the FPMU data lies within the statistical variability of other plasma data sources. To achieve this goal, we will make use of (1) conjunctions of ISS with other orbiting satellites for approximately the same time and volume of space; (2) ISS overflights of ground-based Incoherent Scatter Radar (ISR) sites where measurements of ionospheric plasma density and temperatures are available; (3) ISS overflgihts of Digisonde stations providing electron density values; and (3) conjunctions of ISS with historical satellite missions for approximately the same volume of space and space weather "environment conditions" (i.e., time of year, location in the solar cycle, AE index, etc.). In this paper will only discuss (1) and (2) by making Ne and Te comparisons using the TIMED Global Ultraviolet Imager (GUVI), the European Digital Upper Atmosphere Server (DIAS) Digisondes, and the Millstone Hill Incoherent Scatter Radar.

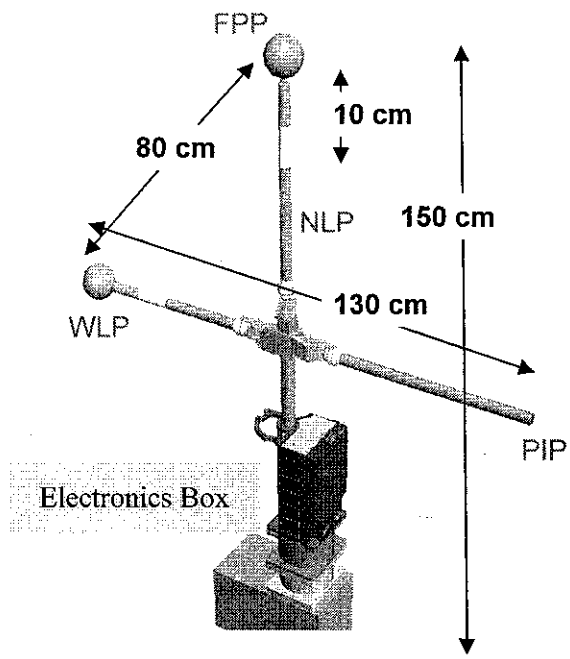

Figure 1. Diagram of FPMU in its deployed state with indicated dimensions.

2. Electron Density Comparisons

2.1 Intra-FPMU comparison

There are several sources of plasma density within the FPMU: NLP ion density (Ni), NLP electron density (Ne), WLP electron density (Ne), and PIP-Ne. In this section we will compare the derived densities between the WLP and PIP.

2.1.1. Wide Sweep Langmuir Probe (WLP), FPMU suite

The Wide-Sweep Langmuir Probe (WLP) is a gold plated sphere of radius 5.08 cm. A voltage sweep from -20 V to 80 V relative to chassis ground is applied to the probe, and the resulting currents to the probe are measured. Sweeps are accomplished each second, with the potential sweeping up one second and back down the next. The sweep is comprised of three parts: steps of ~250 mV from -20 V to 0 V, steps of ~25 mV from 0 V to 50 V, and steps of ~250 mV from 50 V to 80 V. The small step size from 0 V to 50 V region allows the determination of Te (which requires several samples in the electron retarding portion of the sweep). The derivation of the electron densities from the WLP and PIP are described in detail in *Wright et al.* 2007 (these proceedings).

2.1.2 Plasma Impedance Probe (PIP), FPMU Suite

The Plasma Impedance Probe (PIP) consists of an electrically short dipole antenna electrically isolated from the ISS. The dipole is oriented perpendicular to the ram flow direction, is external to the ISS sheath, and is 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, and magnetic field strength can potentially be deduced from these impedance measurements. 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 can be determined at a 512 Hz rate.

As described in more detain in *Wright et al.* 2007 (these proceedings), due to time constraints before flight hardware delivery, the PFP hardware analysis was not completed and so the PFP only rarely is able to lock-in on the proper frequency and yield meaningful data. However, the results are better for the impedance sweep data. From the 0-deg phase location on the electrical impedance (phase and magnitude) we obtain an approximation for the upper hybrid frequency. The inability to consistently track affects the phase versus frequency measurement such that the phase is shifted and no second-zero phase crossing occurs for most of the time. The magnitude versus frequency variation always has a peak and the frequency location of this peak can be used as a 1st-order approximation for the upper hybrid frequency.

From cold plasma wave theory, the upper hybrid frequency (f_{uh}) is a combination of the plasma frequency and the cyclotron frequency and is given by

$$f_{uh}^2 = f_p^2 + f_c^2 \text{, where} \tag{1}$$

f_p = plasma frequency = $(1/2\pi)(4\pi n q^2/m_e)^{1/2}$,
f_c = electron cyclotron frequency = $qB/2\pi m_e = 2.8 \times 10^6$ B(gauss) Hz,
n = plasma density, q = electron charge, m_e = electron mass, and B = magnetic field.
Solving for this equation gives:

$$n(m^{-3}) = 1.24 \times 10^{-2} [f_{uh}^2 - f_{ce}^2] . \tag{2}$$

The electron cyclotron frequency is calculated from the International Geomagnetic Reference Field model (http://modelweb.gsfc.nasa.gov/models/igrf.html/) using the ISS orbit track information.

Not much of the available PIP data has been processed but a comparison of the PIP-derived density with the WLP-derived ion density on August 5, 2006, Day 217 is shown in Figure 2. Agreement between the probes appears to be very good between the WLP, the PIP phase and PIP magnitude data. The data shown below is from all telemetry frames regardless of checksum but most of this scatter can be removed by analyzing data for checksums ≤ 4.

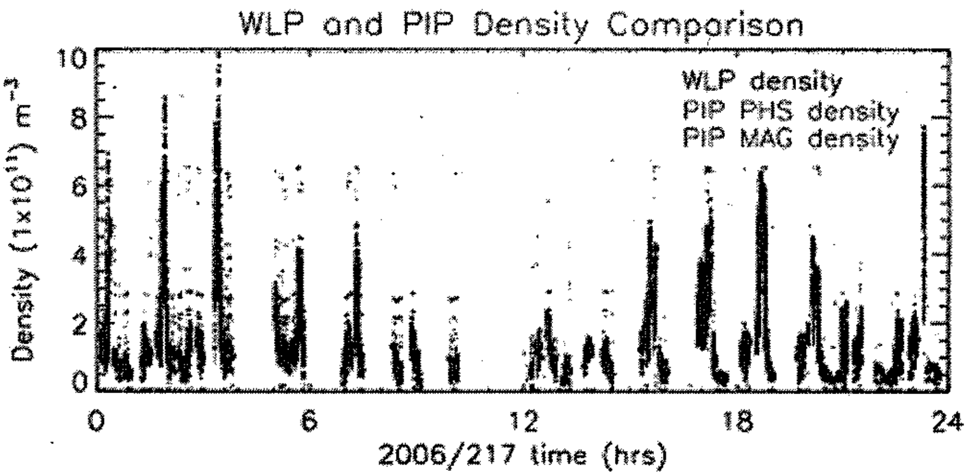

Figure 2. Derived density comparisons of the FPMU WLP and PIP

2.2 Ultraviolet Imager – Global Ultaviolet Imager (GUVI)

Independent comparisons were made with the electron density profiles obtained by the Global Ultraviolet Imager [*Paxton et al.*, 2004] onboard the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) spacecraft. GUVI is a far ultraviolet (115 to 180 nm) scanning spectrograph imager that provides horizon-to-horizon images in 5 selectable wavelength intervals. These wavelengths (HI 121.6 nm, OI 130.4 nm, OI 135.6 nm, and N2 Lyman-Birge-Hopfield bands 140-150nm and 165 to 180 nm are chosen in order to produce the GUVI key parameters. These are chosen to support the TIMED mission science objectives.

GUVI uses a scan mirror to sweep its 11.78 degree field-of-view from horizon-to-horizon up to 140 degrees in the plane perpendicular to the orbital plane and up onto the limb that is away from the Sun. The geometry of the scanning technique is shown in figure 3. For a nominal 625 km orbital altitude, GUVI will scan up to a 520 km tangent altitude providing a nearly complete coverage of the globe on successive orbits. A typical orbit includes day, night, and auroral observations with a swath width of about 3000 km. Successive orbits provide overlapping coverage at the poles and nearly contiguous coverage at the equator. GUVI electron density limb profiles are only available however during the night sector of each orbit because the technique of reconstructing electron density profiles is based on monitoring airglow emissions at 135.6 nm which are nearly exclusively the result of the dissociative recombination reaction

$$O_2^+ + e^- \rightarrow O + O$$

in the F-region ionosphere [*DeMajistre et al.*, 2004].

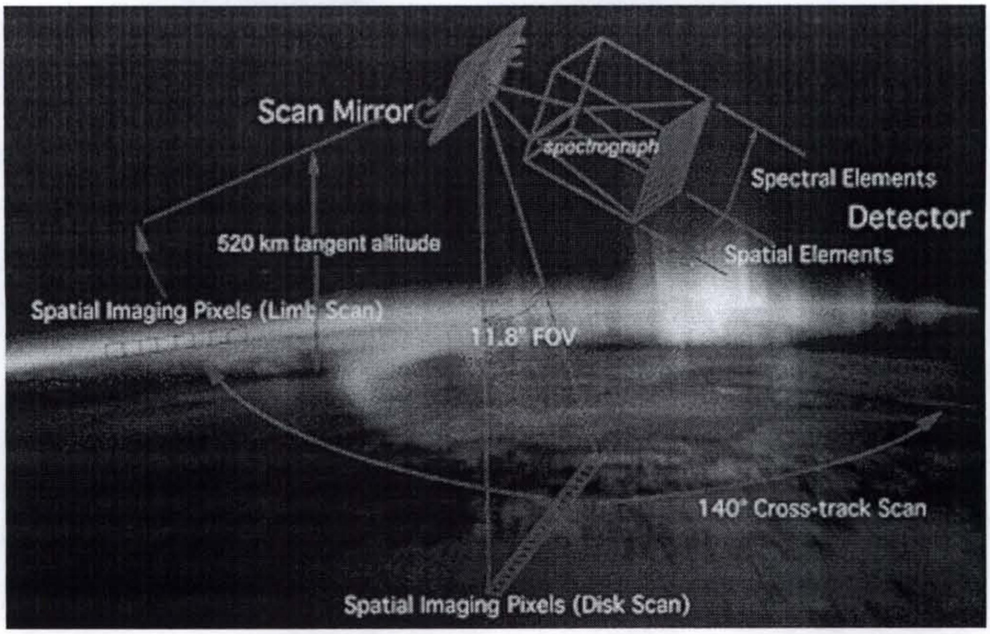

Figure 3. The scanning description of the Global Ultraviolet Imager (GUVI)

The derived electron densities of the WLP were compared to the GUVI electron density profiles. If the parallel GUVI measurement was made within the time and spatial volume of the ISS orbit path the data was obtained. The top panel of Figure 4 shows the corresponding GUVI density values which occur within a time, latitude, longitude, and altitude range of 5 min, 12 degrees, 24 degrees, and 10 km respectively of an ISS WLP density measurement. The bottom panel shows the same GUVI data referenced to the WLP data for the whole day regardless of time and location. The GUVI densities are at values lower and higher than the WLP by more than a factor of 2 but the values are within the broad range of the WLP densities for this day.

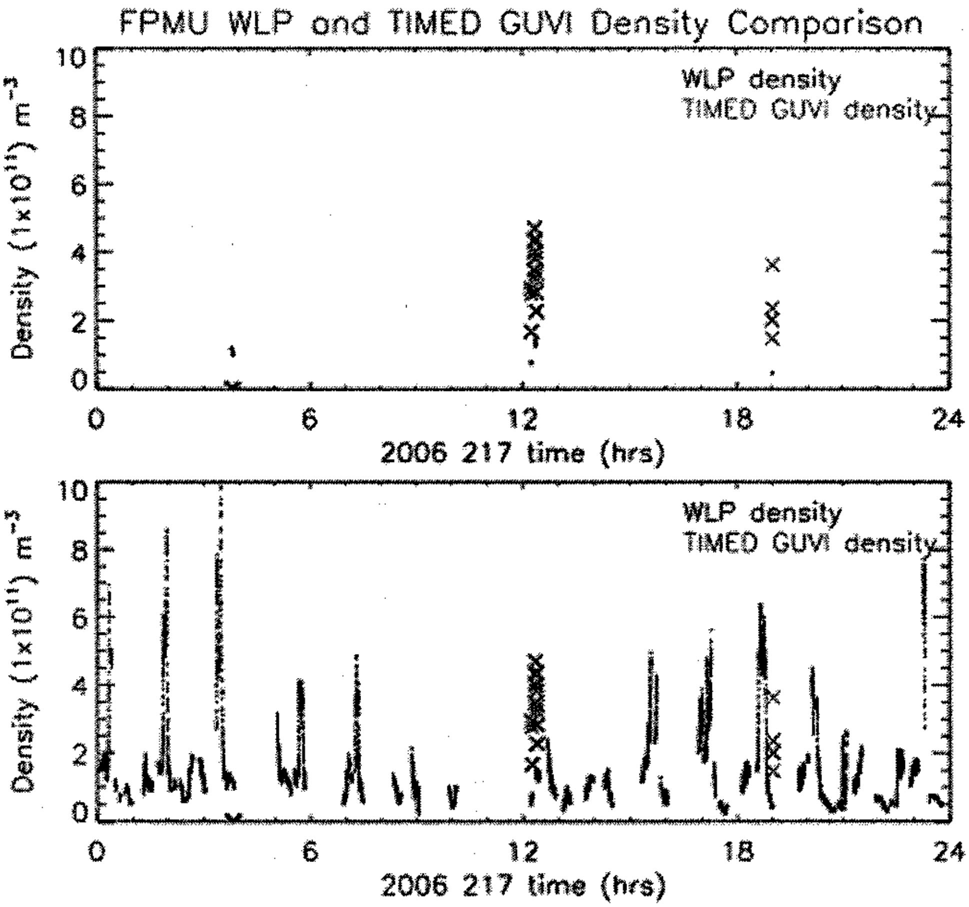

Figure 4. Derived density comparisons between the FPMU WLP and GUVI

2.3. Ionosondes - European Digital Upper Atmosphere Server (DIAS)

We also compared the electron densities derived from the WLP to that of the European Digital Upper Atmosphere Server (DIAS) [*Belehaki et al.*, 2005, 2006]. This network server of eight digisonde stations located throughout Europe became operational in August, 2006. It integrates and homogenizes all the raw ionospheric data gathered by the eight ionospheric stations. The products delivered are real-time and historical ionograms, f-plots, and maps of the ionosphere based on the foF2 and M(3000)F2 parameters.

Ionosondes provide direct measurements of the maximum critical frequency reflected from the F2 ionosphere electron density peak (foF2) and virtual heights (h'F2) derived from the round trip travel time of the wave from the transmitter to the F2 layer peak and back to the receiver. Electron density profiles are derived from ionospheric soundings by modeling the radio wave propagation through a model ionosphere including the effect of density dependent wave velocities. Electron density profiles are obtained by adjusting the plasma density as a function of altitude in the models to fit the observed travel times of the transmitted and received waves.

Given the observed values of foF2 and the M(3000)F2 propagation factors from participating stations, DIAS uses a teal-time technique for updating the Simplified Ionospheric Region Model (SIRMUP) model to generate maps of the ionospheric conditions over Europe. For example, in the case of the F region, the maximum electron density, NmF2, is related to the critical frequency foF2 by the formula

$$N_mF2/m^{-3} = 1.24 * 10^{10} (f_oF2/MHz)^2 . \qquad (3)$$

These DIAS maps are produced every 15 minutes as a function of altitude. Since the ISS altitudes range from 343 – 360 km, the derived electron densities of the WLP were compared to those derived by the DIAS network at the altitude of 350 km. The sites providing the data for August 5, 2006, Day 217 was provided by the Rome, Athens, Ebre, Juliusruh, Pruhonice DIAS sites. The top panel of Figure 5 shows the WLP and DIAS derived densities within the volume of time, latitude, longitude and altitude range of 15 min, 12 degrees, 24 degrees, and 10 km respectively. The bottom panel shows the same DIAS data referenced to the WLP data for the whole day. Again, the comparison in the bottom panl is regardless of time and location. The top panel shows that the WLP and DIAS derived densities are within a factor of 2 for this day.

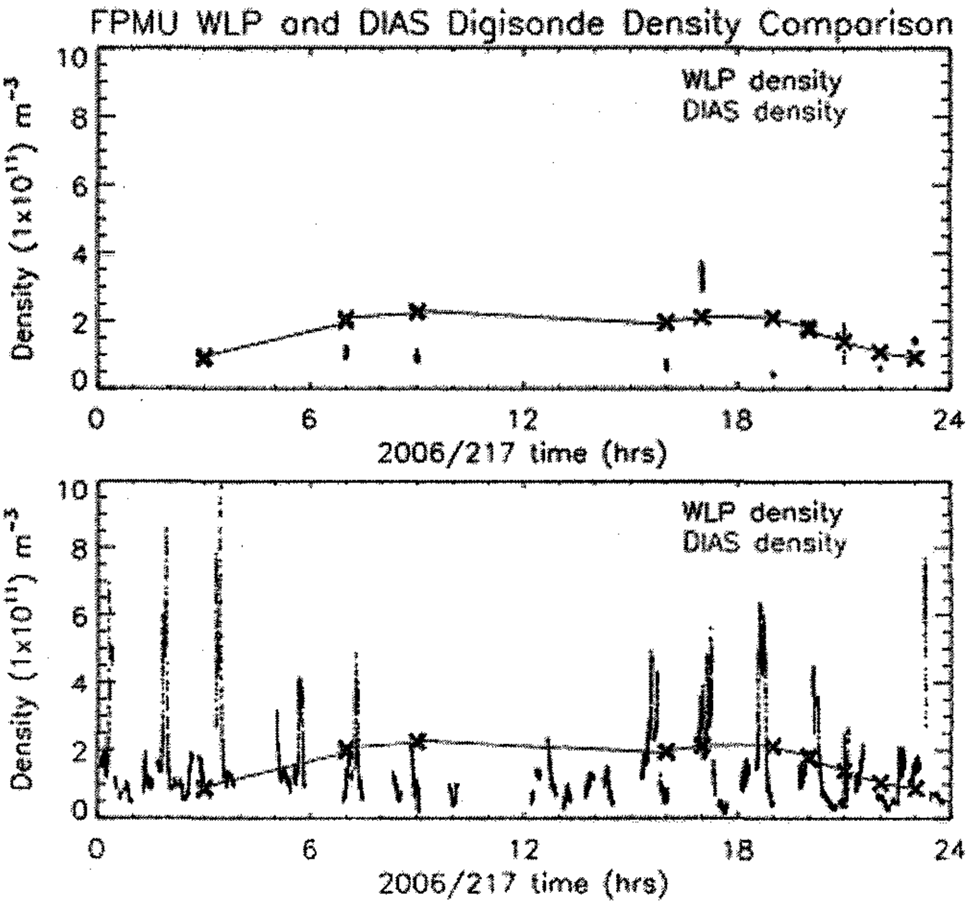

Figure 5. Comparison of derived densities between the FPMU WLP and

2.4 Incoherent Scatter Radar (ISR) - Millstone Hill

Derived density comparisons were made between the FPMU WLP and the Millstone Hill Incoherent Scatter Radar [*Evans et al.*, 1970; *Oliver et al.*, 1979] for March 3, 2007, Day 062. This ISR site derives densities for the ISS altitudes and orbit in latitude but there was no overlap in longitude. As with the previous density comparisons, if the specified volume of time and space in latitude, and altitude of the Millstone Hill data was within a given range of the ISS, the Millstone Hill ISR data was obtained. The top panel of Figure 6 shows the WLP and Millstone ISR derived densities within the volume of time, latitude, and altitude range of 60 min, 16 deg, and 100 km respectively. The bottom panel shows the same Millstone ISR data referenced to the WLP data for the whole day. The top panel shows approximately a 33% difference between the averaged densities of the WLP and Millstone Hill at that time. This includes the Millstone Hill stated density errors.

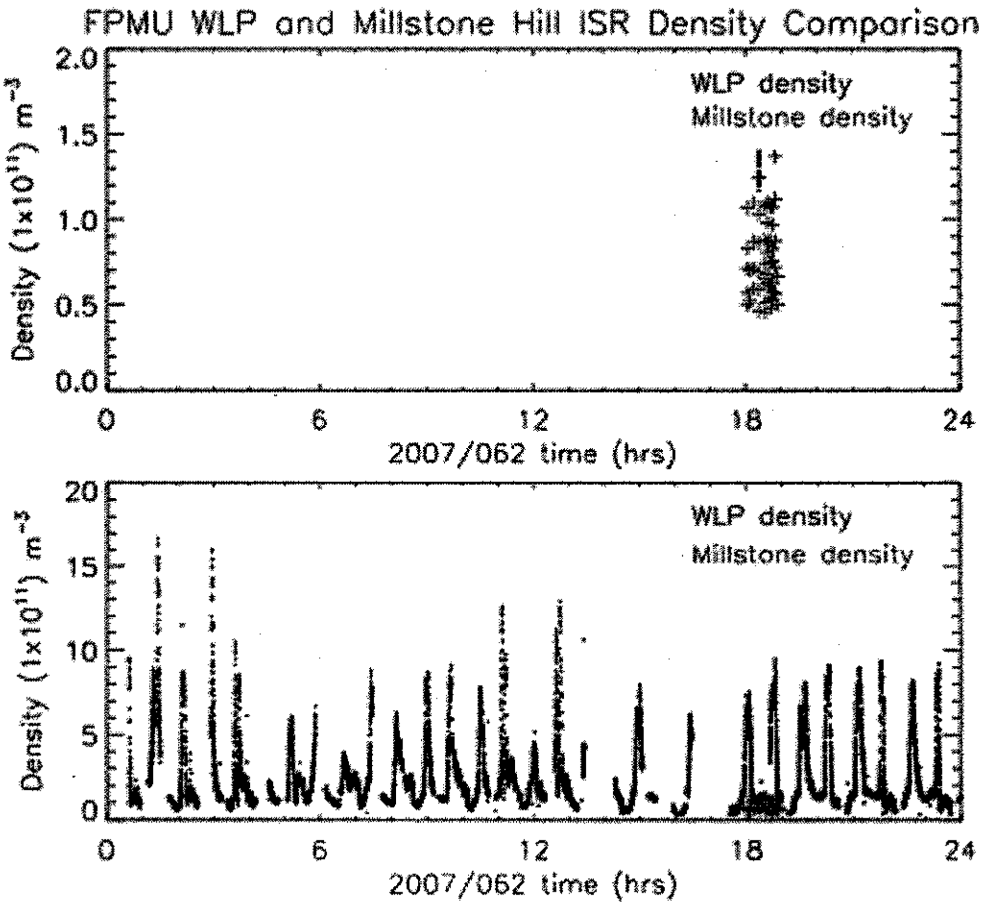

Figure 6. Comparison of derived densities between the FPMU WLP and Millstone Hill Incoherent Scatter Radar

3. Electron Temperature Comparison

Two sources of electron temperature (Te) are available from the FPMU: NLP-Te and WLP-Te. We will make comparisons to the WLP-Te in this section. The derivation of the electron temperatures from the WLP and PIP are described in detail in Wright, et. al (2007 these proceedings).

3.1 Incoherent Scatter Radar (ISR) - Millstone Hill

Derived temperature comparisons were made between the FPMU WLP and the Millstone Hill Incoherent Scatter Radar. This ISR site was within the ISS latitudes and had parallel measurements with the WLP on March 3, 2007, Day 062. If the volume of data in time and space (latitude and altitude) from Millstone Hill was within a given range of the ISS parameters, the Millstone Hill ISR data was used for this comparison. The ISR makes a very narrow sweep in longitude and did not overlap with the ISS orbit. Figure 7 shows the WLP and Millstone Hill derived temperatures for this day. The top panel is of the WLP and Millstone ISR data within the volume of time, latitude, and altitude range of 60 min, 16 deg, and 100 km respectively. The bottom panel shows the same Millstone ISR data referenced to the WLP data for the whole day. The WLP temperature values overlap well with the Millstone Hill temperatures.

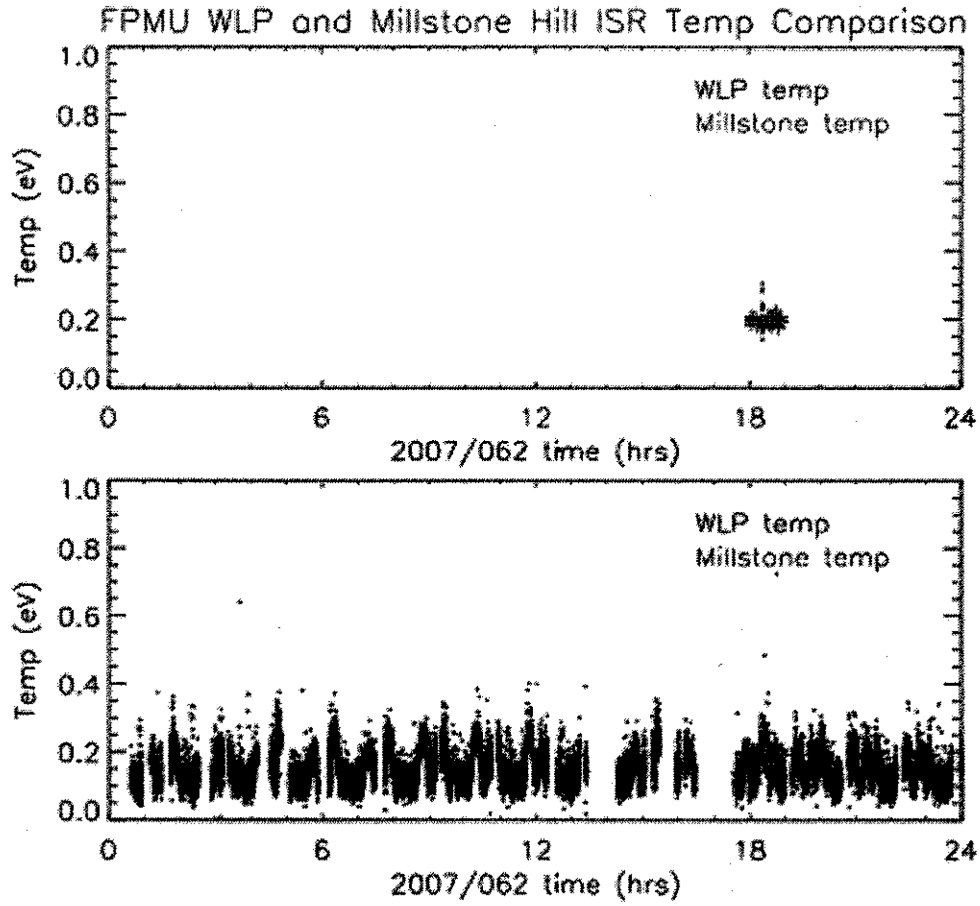

Figure 7. Comparison of derived temperatures between the FPMU WLP and Millstone Hill Incoherent Scatter Radar

4. Summary

Since August 2006, the FPMU has operated for several data sessions and is meeting its secondary requirement of providing measurements of the local ionospheric plasma. In this paper we continue the process of validating the ionospheric data obtained and compare the derived electron density between two of the FPMU instruments; the WLP and PIP (see Wright et al. 2007). We also made electron density comparisons between the WLP and the DIAS Digisonde server, the TIMED GUVI ultraviolet imager, and the Millstone Hill Incoherent Scatter Radar. Derived electron temperature comparisons were made between the WLP and the Incoherent Scatter Radar at Millstone Hill. The density obtained between the FPMU instruments are in very close agreement with each other and within a factor of 2 of the independent datasets. The derived electron temperatures were within the same temperature range.

5. Acknowledgements

We want to thank Them Bui for processing the FPMU data and preparing it for analysis.

We also want to thank Aroh Barjatya for answering all of our PIP related questions. We want to thank Robert Demajistre from John Hopkins Applied Research Lab for processing the GUVI data for the WLP density comparison. We appreciate the access and all the processing of the databases that were used for this study including the TIMED GUVI data, the DIAS Digisonde network, and the Millstone Hill Incoherent Scatter Radar.

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MSFC-203 PRESENTATION

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[1]NASA MSFC, [2]Jacobs Engineering, [3]Allied Aerospace, [4]University of Alabama, Huntsville, [5]NASA JSC

Abstract

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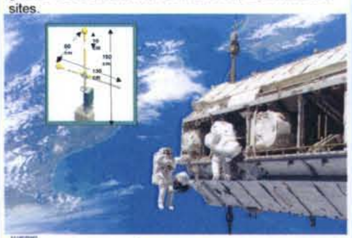


Figure 1. FPMU diagram and instrument location on ISS starboard Truss.

Electron Density

Intra-FPMU Comparison

There are several sources of plasma density within the FPMU: NLP ion density (Ni), NLP electron density (Ne), WLP electron density (Ne), and PIP-Ne. In this section we will compare the derived densities between the WLP and PIP (phase and magnitude). The derivation of the electron densities from the WLP and PIP are described in detail in Wright, et. al 2007 (these proceedings).

FPMU WLP and PIP

The PIP measures the electrical impedance (magnitude and phase) of the antenna over a 100 KHz to 20 MHz range. From the 0-deg phase location on the electrical impedance, an approximation for the upper hybrid frequency is obtained and electron densities derived. A comparison of the WLP and PIP (phase and mag) derived density on August 5, 2006, Day 217 is shown in Figure 2. Agreement between the probes appears to be very good .

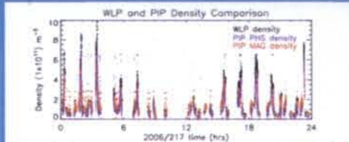


Figure 2. Derived density comparisons between the FPMU WLP and PIP

Ultraviolet Imaging - TIMED Global Ultraviolet Imager (GUVI)

Independent comparisons were made with the electron density profiles obtained by GUVI [Paxton et al., 2004] onboard the TIMED spacecraft. The geometry of the scanning technique is shown in figure 3. A typical orbit includes day, night, and auroral observations with a swath width of about 3000 km. Electron density limb profiles are typically only available on the night-side though due to the technique of reconstructing electron density profiles is based on monitoring airglow emissions at 135.6 nm which are nearly exclusively the result of the dissociative recombination reaction

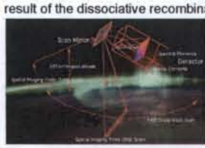


Figure 3. The scanning description of the TIMED Global Ultraviolet Imager (GUVI)

The derived electron densities of the WLP were compared to the GUVI electron density profile. Figure 4 shows the corresponding GUVI density values occurring within the time, latitude, longitude, and altitude range of 5 min, 12 degrees, 24 degrees, and 10 km respectively of the ISS WLP measurement. The GUVI densities are within the WLP densities within a factor of 2.

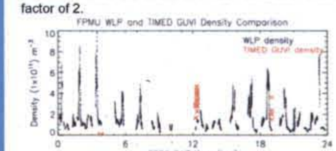
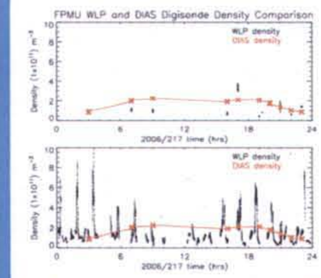


Figure 4. Comparison of derived densities between the FPMU WLP and TIMED Global Ultraviolet Imager (GUVI)

European Digital Upper Atmosphere Server (DIAS)

Electron densities derived from the WLP were compared to that of the European Digital Upper Atmosphere Server (DIAS) [Belehaki et al., 2005, 2006]. This network server of eight digisonde stations is located throughout Europe and produces ionospheric maps every 15 minutes as a function of altitude. Since the ISS altitudes range from 343 – 360 km, the derived electron densities of the WLP were compared to those derived by the DIAS network at the altitude of 350 km. The sites providing the data for August 5, 2006, Day 217 was provided by the Rome, Athens, Ebre, Juliusruh, Pruhonice DIAS sites.

The top panel of Figure 5 shows the WLP and DIAS derived densities within the volume of time, latitude, longitude and altitude range of 15 min, 12 degrees, 24 degrees, and 10 km respectively. The bottom panel shows the same DIAS data referenced to the WLP data for the whole day. The top panel shows that the WLP and DIAS derived densities are within a factor of 2 for this day.



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Incoherent Scatter Radar (ISR) - Millstone Hill

Derived density comparisons were made between the FPMU WLP and the Millstone Hill Incoherent Scatter Radar [*Evans et al.*, 1970; *Oliver et al.*, 1979] for March 3, 2007, Day 062. The top panel of Figure 6 shows the WLP and Millstone ISR derived densities within the ISS volume of time, latitude, and altitude range of 60 min, 16 deg, and 100 km respectively. The bottom panel shows the same Millstone ISR data referenced to the WLP data for the whole day. The top panel shows approximately a 33% difference between the averaged densities of the WLP and Millstone Hill at that time. This error includes the Millstone Hill stated density errors.

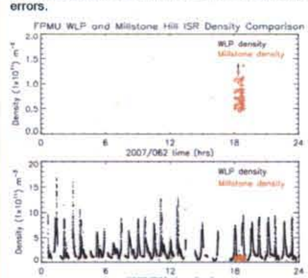

Figure 6. Comparison of derived densities between the FPMU WLP and Millstone Hill Incoherent Scatter Radar

Electron Temperature

Two sources of electron temperature (Te) are available in the FPMU: NLP-Te and WLP-Te. We make comparisons to the WLP-Te in this section. The derivation of the electron temperatures from the WLP and PIP are described in detail in Wright, et. al 2007 (these proceedings).

Incoherent Scatter Radar (ISR) - Millstone Hill

Derived temperature comparisons were made between the FPMU WLP and the Millstone Hill Incoherent Scatter Radar. This ISR site was within the ISS latitudes and had parallel measurements with the WLP on March 3, 2007, Day 062. The ISR makes a very narrow sweep in longitude and did not overlap with the ISS orbit. The top panel of Figure 7 shows the WLP and Millstone ISR data within the volume of time, latitude, and altitude range of 60 min, 16 deg, and 100 km respectively. The bottom panel shows the same Millstone ISR data referenced to the WLP data for the whole day. The WLP temperature closely correlates with the Millstone Hill electron temperature.

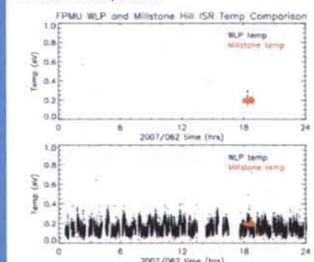

Figure 7. Comparison of derived temperatures between the FPMU WLP and Millstone Hill Incoherent Scatter Radar

Summary

Since August 2006, the FPMU has operated for several data sessions and is meeting its secondary requirement of providing measurements of the local ionospheric plasma. In this paper we continue the process of validating the ionospheric data obtained and compare the derived electron density between two of the FPMU instruments; the WLP and PIP (see Wright et al. 2007). We also made electron density comparisons between the WLP and the DIAS Digisonde server, the TIMED GUVI ultraviolet imager, and the Millstone Hill Incoherent Scatter Radar. The density obtained between the FPMU instruments are in very close agreement with each other and within a factor of 2 of the independent datasets. Derived electron temperature comparisons were made between the WLP and the Incoherent Scatter Radar at Millstone Hill. The derived electron temperatures are in good agreement.