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Observations and Validation of Plasma Density, Temperature, and \( O^+ \) Abundance From a Langmuir Probe Onboard the International Space Station

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Abstract The Floating Potential Measurement Unit (FPMU) has been operational on board the International Space Station (ISS) since 2006. One of the instruments in the FPMU suite is a spherical wide-sweeping Langmuir probe, referred to as the WLP, which is sampled at a temporal cadence of 1 s giving in-situ measurements of the plasma density and electron temperature. In this study we present our refinements to the Langmuir probe analysis algorithm that address the uncertainties associated with photoelectron emission current from the metal probe. We also derive the fraction of \( O^+ \) ions as a secondary data product, which shows decrease in \( O^+ \) abundance in the post-midnight sector during solar minimum. The derived plasma parameters are compared and validated with an independent in-situ measurement technique, overlapping ground-based incoherent scatter radar measurements, as well as International Reference Ionosphere model output. The reduced data set spans the entire solar cycle 24 and shows the F-region ionosphere variance at ISS altitudes.

1. Introduction

The Floating Potential Measurement Unit (FPMU) has been operating on board the International Space Station (ISS) since 2006 (Barjatya et al., 2009). The primary objective behind the deployment is to monitor the complex surface charging (i.e., floating potential) behavior of the ISS in order to ensure astronaut safety during extra vehicular activity (EVA) (Mikatarian et al., 2003; Wright et al., 2008), and to validate the Plasma Interaction Model developed to predict ISS charging (Koontz et al., 2003, 2020). However, in addition to its primary purpose, FPMU adds substantial scientific value to the heliophysics community since it has been in a unique position to monitor the F-region ionosphere at an altitude of \(~400\) km for over an entire solar cycle.

In-situ satellite missions have historically been a good source of observations for the ionospheric community. These include a number of Low Earth orbit (LEO) satellites such as the Defense Meteorological Satellite Program (DMSP) at \(~850\) km (Huang et al., 2001), the SWARM constellation at \(~400–500\) km (Frisis-Christensen et al., 2006), the Communications/Navigation Outage Forecasting System (C/NOFS) mission at \(~400–600\) km (de La Beaujardière et al., 2004), the ROCSAT-1 at \(~600\) km (Yeh et al., 1999), and more recently, the Ionospheric Connection Explorer (ICON) (Immel et al., 2018) and COSMIC-2 (Anthes & Schreiner, 2019), both at \(~550–600\) km altitudes. These topside ionospheric missions all host in-situ instruments which have aided the scientific community with important discoveries and a deeper understanding of the topside ionosphere. Much has been learned since about the physics of frequently observed structures such as equatorial plasma bubbles (EPBs), traveling ionospheric disturbances (TIDs), as well as the global dynamics of rare events such as geomagnetic storms and solar eclipses. The explanation of the ionospheric behavior under such condition requires a knowledge of plasma conditions such as electron and ion densities, ion and electron temperatures, ion composition and three-dimensional drifts. The FPMU instrument discussed in this study complements all these observations through Langmuir probe derived plasma parameters and is the only resource of in-situ Langmuir probe observations at an altitude of \(~400\) km that covers low and mid latitudes for over 14 years.

FPMU is a suite of four plasma diagnostic instruments that include: (a) a gold-surfaced spherical floating potential probe (FPP) that measures the ISS spacecraft-charging between \(\pm 180\) V at 128 Hz sample rate, (b)
a gold-surfaced cylindrical narrow-sweeping Langmuir probe (NLP) that sweeps between ±4.9 V about the potential as measured by the FPP, (c) a gold-surfaced spherical wide-sweeping Langmuir probe (WLP) that operates over a voltage ranging from −20 to +80 V with respect to the ISS chassis ground, and finally (d) a radio frequency (RF) based plasma impedance probe (PIP) that measures the antenna impedance in a broad frequency range. The WLP and NLP current-voltage (IV) curves give measurements of plasma potential, electron and ion density, and electron temperature. The PIP impedance-frequency curves give measurements of absolute electron density by giving the location of the upper hybrid frequency. Further technical details, the description of the electronics associated with the instruments, as well as the calibration of the FPMU have been discussed in detail by Swenson et al. (2003). The plasma density and temperature data products returned by FPMU have been used in past studies addressing ionospheric variability during geospace events (Coffey et al., 2017; Yang et al., 2020). They have also aided data assimilation for models (Hartman et al., 2019), as well as model-data comparisons (Broadwater, 2013; Willis & Pour, 2018).

While FPMU has been operational since 2006, data is not collected continuously but only on a campaign basis. Since FPMU’s primary purpose is to determine the ISS’s frame potential to support EVA plasma hazards or changes in a charging configuration, the plasma parameter measurements are simply an added bonus. Designed for an operational life of 3 years, FPMU has far outlived its expected lifetime while measuring the ISS's plasma environment along with ionospheric variability. Since 2019, however, FPMU has been operated sparingly due to an intermittent ISS-provided power supply, and discussions are underway to replace the operating unit with a spare unit sometime in the near future. Figure 1 shows the days when FPMU was operated from 2006 to 2019. These days are shown as grayed-out blocks against the day of the year (left Y-axis) corresponding to which data exists. Overlaid on top of the figure is a plot of the number of sunspots (right Y-axis) showing the progression of the solar cycle. As seen in Figure 1, while there are a number of data gaps since the commissioning of FPMU, the instrument was operated over a major part of Solar Cycle 24 (i.e., 2008–2019) with a total coverage that amounts to ~ 34% of the total calendar days. The significant bulk of these measurements totaling ~ 80% were in the years 2011–2019. While FPP, WLP, and PIP have continued to operate nominally, NLP performance has degraded over the years and is no longer utilized to reduce plasma parameters.

Table 1 shows the data products derived from FPMU, their sampling frequency, and the instrument utilized for this data product. Additionally, we classify these data products as primary or secondary, with the primary data products derived directly from the in-situ measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency (Hz)</th>
<th>Type</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron temperature</td>
<td>1</td>
<td>Primary</td>
<td>WLP</td>
</tr>
<tr>
<td>Electron density</td>
<td>1</td>
<td>Primary</td>
<td>WLP</td>
</tr>
<tr>
<td>Electron density</td>
<td>1</td>
<td>Secondary</td>
<td>PIP</td>
</tr>
<tr>
<td>Plasma potential</td>
<td>1</td>
<td>Primary</td>
<td>WLP</td>
</tr>
<tr>
<td>Floating potential</td>
<td>128</td>
<td>Primary</td>
<td>FPP</td>
</tr>
<tr>
<td>O⁺ percentage</td>
<td>1</td>
<td>Secondary</td>
<td>WLP</td>
</tr>
</tbody>
</table>
and the secondary data products derived from either further analysis of the primary products with some assumptions or incorporating external model outputs such as the International Geomagnetic Reference Field (IGRF).

Changes are required to the original data processing algorithm to address aging instrumentation, changing solar activity, as well as enhancements to the algorithm to give new data products. In particular, one source of error in the original FPMU analysis algorithm was the uncertainty associated with photoelectron emission current that may contribute to errors in estimated densities. Photoemission has been neglected in the FPMU data analysis based on the assumption the plasma currents dominate the charging process in the high density LEO environment where FPMU operates. As detailed by Barjatya et al. (2009), the electron and ion densities from the WLP analysis generally agree with each other, but the standard deviation in the derived electron density was higher than that of derived ion density. This was largely due to noisier measurements in the electron saturation region of the measured IV curve. Thus, ion density is used as a better proxy for quasineutral plasma density. However, ion collection current measurement is similar to emitted photoelectron current measurement, and since the original analysis algorithm did not handle the photoelectron emission current appropriately, the uncertainties in measured densities were higher in the dawn and dusk sectors. Incorporating photoemission to the data analysis algorithms can also improve the plasma density parameters during the daytime particularly in solar minimum for low plasma densities. We address that in the algorithm presented in this study.

Another possible source of error during times of low solar activity is the assumption that the F-region ionosphere around the ISS orbit consists primarily of O\(^+\) ions. While this assumption, to a large extent, is true for solar maximum, the dominance of O\(^+\) can decrease sufficiently enough during periods of low solar activity that the effects of H\(^+\) ions on the measured IV curve cannot be ignored. This variance in O\(^+\) percentage is demonstrated in Figure 2 which uses International Reference Ionosphere (IRI) data to plot the O\(^+\) fraction of the total ion population for 5 latitudes — 0\(^\circ\), 30\(^\circ\)N and S, and 60\(^\circ\)N and S, for 2006–2019 and averaged over all the longitudinal sectors. As is evident, O\(^+\) ions constitute a lesser fraction of the total ion population across all latitudes for the years of solar minima compared to solar maxima. The decrease is especially acute at higher latitudes. Furthermore, there is an even steeper decrease in O\(^+\) fraction in local winter at higher latitudes during periods of reduced solar activity. Increasing gradients in neutral temperature can also decrease the scale height and in turn change the O\(^+\)/H\(^+\) transition height which affects the ion composition at 400 km (Heelis et al., 2009; Titheridge, 1976). Thus, the effect of lighter ion species on the measured IV curve needs to be taken into account to attain better accuracy in derived ion density.

Figure 2. Shown above is the solar cycle dependency on the fraction of O\(^+\) at local midnight at 400 km, as per International Reference Ionosphere. Each profile represents a unique geodetic latitude and an average of different longitude sectors.
In the following sections, we will delve into the above mentioned sources of errors and discuss how we address them in the improved data analysis algorithm. This analysis technique should be broadly applicable to data analysis of any Langmuir probe in the ionosphere for plasma typically encountered at LEO altitudes. The remainder of the study is arranged in the following way. In Section 2 we highlight the details and intricacies of the Langmuir probe data processing so as to analyze the probe measurements consistently over an entire solar cycle. A synopsis of the results obtained from the FPMU data set are presented in Section 3 along with relevant discussions and comparisons with other instruments and techniques. We conclude with a summary of the key highlights in Section 4.

2. Langmuir Probe Analysis Algorithm

The general Orbital Motion Limited (OML) equations and the related theory of the response of electrical probes in plasma have been extensively discussed in previous literature (Chen, 1965; Barjatya et al., 2009; Hoegy & Wharton, 1973; Mott-Smith & Langmuir, 1926). For the purposes of this study we shall restrict our focus only to ion saturation region of the IV curve, and specifically to addressing two effects: the impact of lighter ion species on the OML theory-based data analysis method and the impact of photoelectron current emission in low density ionospheric plasma.

2.1. Impact of Increased H\textsuperscript{+} Ions

The spherical WLP collects ion current when it is biased negative with respect to the plasma potential. In this regime, for typical ionospheric plasma conditions at ISS altitudes, the “mesothermal” condition is satisfied wherein the thermal motion of the ions is much less than the orbital velocity (~7.4 km/s), which is again much less than the thermal velocity of the electrons (Brace, 1998). However, the situation is complicated when lighter H\textsuperscript{+} ions are present. The thermal velocity of ions varies as the inverse of the square root of the atomic mass number. Thus, an increase in H\textsuperscript{+} ion concentration results in larger ion collection current when compared to only the heavier O\textsuperscript{+} ions being present.

This argument is demonstrated through Figure 3, where we show the simulated IV characteristics in the ion-saturation region for a two-species plasma with 10% H\textsuperscript{+} ion and 90% O\textsuperscript{+} compared to one entirely composed of O\textsuperscript{+} ions. The curves are generated for a plasma density of 10\textsuperscript{10} m\textsuperscript{-3} and electron temperature of 1,500 K, an ion temperature of 900 K for a satellite ram velocity of 7.4 km/s. The plots are shown against the voltage applied to the probe with respect to the plasma potential. Even with the same density, the collected current is larger in the case of the mixed plasma because of a non-negligible thermal current contribution from the lighter hydrogen ions. Since the OML theory-guided current increases with increasing attractive potentials, the separation between the two cases also increases with larger negative voltages. Thus, if the effect of an increased H\textsuperscript{+} fraction in the ambient plasma density is not taken into account, the higher current measurement may erroneously be interpreted as higher plasma density. As shown in Figure 2, this can be

![Figure 3](image-url)

**Figure 3.** The simulated IV curves in the ion saturation region demonstrating an almost 20% increase in ion current collection owing to a 10% H\textsuperscript{+} population in a majority O\textsuperscript{+} plasma.
a significant problem in periods of low solar activity especially at higher latitudes, and hence needs to be incorporated in the curve-fitting algorithm that we discuss next.

Our curve-fitting algorithm solves for the necessary parameters in two stages. The first stage returns the plasma density and the electron temperature estimates along with the plasma potential and a crude fit for the ion mass. In the second stage, we refine the mass obtained into the relative composition of the O\(^+\) and H\(^+\) species. In both stages, the region of choice is the entire ion-saturation region from \(-20\) Volts to \(0.1\) Volts above the floating potential \((V_f)\).

In the first stage, we solve for the following equation which is sum of the individual current components for this section of the IV curve:

\[
I = -I_{\text{ram}} - I_{\text{OML}} + I_c. \tag{1}
\]

Here \(I_{\text{ram}}, I_{\text{OML}},\) and \(I_c\) are respectively the contributions from the ion ram component, the ion OML current, and the electron retardation current. Since the current from the probe to the plasma is considered positive, the ion and electron collection currents are negative and positive respectively. The individual current components are given by:

\[
\begin{align*}
I_{\text{ram}} &= n_i A_{\text{proj}} e V_{\text{ISS}}, \\
I_{\text{OML}} &= I_{\text{th}} \left( 1 - \frac{e(\phi - \phi_p)}{k_B T_e} \right), \\
I_c &= I_{\text{th}} \exp \left( \frac{e(\phi - \phi_p)}{k_B T_e} \right), \\
I_{\text{thj}} &= n_j q_j A \frac{k_B T_j}{2\pi m_j}.
\end{align*}
\]

The term \(j\) denotes the types of species with subscripts \(e\) denoting electrons and \(i\) denoting ions. Thus, \(T\), \(m\), and \(I_{\text{th}}\) with the appropriate subscripts denote the electron or ion temperature, atomic mass, and the thermal current respectively. The parameter \(\phi\) is the applied voltage to the probe, \(\phi_p\) is the plasma potential, and \(\beta\) is a parameter which describes the rate of increase of OML current for attractive potentials (Barjatya et al., 2013). The ISS orbital velocity \(V_{\text{ISS}}\) is approximately \(7.4\) km/s. For the ram current the projected area \(A_{\text{proj}}\) is used. For the currents originating from the thermal species, the collection area denoted by \(A\) is typically larger than \(A_{\text{proj}}\) due to ambipolar diffusion in the plasma wake and taken to be half of the total collection area of the sphere (Barjatya et al., 2009).

In the preliminary phase of our data analysis process we identify the floating potential \((V_{\phi})\) from the zero crossing point of the IV curve. We then obtain a primitive measure of the plasma potential \((\phi_p)\) and the ion density \((n_i)\). The rough estimate for the plasma potential \(\phi_p\) is the voltage corresponding to a maximum in the first derivative of the measured current within \(+1.5\) volts of \(V_f\). For the first rough estimate for \(n_i\), we extrapolate a linear fit of the ion saturation line to the estimated \(\phi_p\), at which point the majority of the ion contribution is expected to be the ram current. As discussed above the contribution of thermal ions may not be negligible for higher amount of H\(^+\) ions but we leave that refinement for the later stages of the fitting routine. With these initial estimates for \(n_i\) and \(\phi_p\), we move on to Stage I of the data analysis where we perform a Levenberg-Marquardt (LM) (Moré, 1978) non-linear fit (Newville et al., 2016) to Equation 1, assuming quasi-neutral plasma \((n_i = n_e)\). The chosen region of fit is the entire ion-saturation and the electron retardation region from \(-20\) V to \(0.1\) V above \(V_f\). It is particularly important to include the entire ion-saturation region in the fitting process in order to make use of the sensitivity to ion-mass for large attractive probe potentials for ions as shown in Figure 3. Stage I of the LM fitting routine returns estimates for the total ion density \(n_i\), the refined plasma potential \(\phi_p\), and the electron temperature \(T_e\). In addition, estimates are also obtained for the ion temperature \((T_i)\), the effective ion-mass \((m_i)\), as well as the \(\beta\) parameter from OML theory in the ion-saturation region. The estimates of \(n_i, T_e,\) and \(\phi_p\) thus obtained are considered final and constitute the primary data products of the fitting routine. However, the relative split of the percentage of O\(^+\) and H\(^+\) from the total ion contribution remains to be conducted since the effective mass represents the combined ion population assuming a single mass. This metric is thus an artificial ion-mass metric for the net OML current from individual ion constituents which is resolved in the next stage of the fitting process.
In the second stage, we assume the plasma to be composed of \( O^+ \) and \( H^+ \) only and try to estimate the individual split of these two constituents. We employ a method similar to Klenzing and Rowland (2012) and Hoegy and Brace (1999). Instead of using the OML currents in Equations 1 and 2, we use the following equations for the \( O^+ \) and \( H^+ \) ion currents for attractive potentials applied to a spherical probe in the ion saturation region:

\[
I_k = I_{b_k} \left[ \frac{1}{2} \exp(-r_k^2) + \frac{\eta^2 + 1}{2} \right] \frac{1}{2} \sqrt{\pi} \text{erf}(r_k),
\]

where,

\[
r_k = \frac{\mu_0}{\sqrt{2k_B T_k / \mu_k}},
\]

\[
\eta = \frac{e(\phi - \phi_p)}{k_B T_j}.
\]

The index \( k \) refers to \( O^+ \) or \( H^+ \) and \( \mu_0 \) is the drift velocity of ions in the satellite reference frame. Note that the typical values of \( r_k \) vary with the species and is minimum for \( H^+ \) ions.

The equations for the spherical probe currents are applicable to the mesothermal plasma at ISS altitude which is drifting at speeds of a few 100s of m/s which is much less than the ram velocity (~7.4 km/s). This results in a distribution of plasma that is a drifting Maxwellian with an anisotropy in the direction of the ram compared to cross-track directions. The drift speed in the satellite reference frame is close to the ram velocity, and thus at these altitudes the \( r \) parameters in Equation 4 have values greater than 1 whereas the convergence to the limiting OML regime (when the debye length is infinitely large compared to the probe dimension) is only obtained when \( r \) approaches 0 which is uncommon for supersonic flow at mid-latitudes. In essence, Equation 3 is an effective way to bypass the limiting OML case, in a manner which is similar to the fitting of the \( \beta \) parameter as discussed by Barjatya et al. (2013).

Klenzing and Rowland (2012) also establish that the impact of the ion temperature on the ion current is much less compared to the \( O^+ \) fraction. Since the ion current is sensitive to the latter parameter, we make use of a second stage of fitting and split the total \( n_i \) estimate from the first stage into \( O^+ \) and \( H^+ \) constituents. The ions are also assumed to be in thermal equilibrium and a single ion-temperature is used for both \( O^+ \) and \( H^+ \). The non-linear fitting routine for this stage is performed by fixing the total \( n_i, T_i \) and \( V_p \) parameters and fitting for the \( O^+ \) and \( H^+ \) fractions. The fitting is performed from the same region of the IV curve as in Stage I. The ion temperatures are allowed to vary between 600 and 1800 K, but the estimates of \( T_j \) are not reliable since the IV curve is less sensitive to \( T_j \) as discussed previously.

Figure 4 shows the 2-step fitting process for a randomly picked IV curve from the FPMU WLP data set. The left and right panels show the Stage I and Stage II curve-fitting process respectively. In both cases, the measured IV curve is shown in black which is smoothed using a low-pass third order filter to yield a smoother curve shown in red, which is then analyzed using the non-linear curve fit method described above. The resultant fit is then shown in blue. The noise in the measured IV curve is primarily from the low-gain channel of the WLP which measures larger currents away from the retardation region. The parameters obtained from the fits are mentioned in text within figures. As seen in the left panel of the figure, we obtain an effective mass between 1 and 16 amu at the end of stage I and estimates of \( n_i, T_i \), and \( V_p \). These are then used in Stage II to refine the effective mass of 15 amu to approximately 94.49\% \( O^+ \) and the rest assumed to be \( H^+ \).

The reduction in the \( \chi^2 \) value also shows how the fit residuals improve after fitting for two different species.

### 2.2. Choosing a Photoelectron Emission Current Profile

The ISS orbits the Earth in a mid-inclination circular orbit at ~400 km altitude. Consequently, the ISS completes one orbit in ~90 min, and a large portion of this period is spent in sunlight. Since the WLP has a gold surface, photons striking the surface emit photoelectrons, which is interpreted as an additional ion collection current. This additional photoelectron emission current exists as long as the probe potential is not positive enough to attract the emitted electrons back. Essentially this regime encompasses all of the ion
saturation current regime when the probe potential is less than the plasma potential. In some cases, there may be some contribution from secondary electrons but this current is present mostly in the electron saturation current regime and is much smaller compared to the large electron current. Hence we concentrate on only the removal of the primary photoelectron emission current from the recorded IV curve.

The photoelectron emission current depends on the spectrum of incoming radiation, the work function of the metal (gold), and on the surface area illuminated by sunlight (Merritt, 2018). Of these, the photoelectron emission current density for gold is known to be $29 \mu A m^{-2}$ (Hastings & Garrett, 1996) and indicative of the work function contribution for the appropriate light source that is, sunlight. Thus, the construction of the correct photoelectron emission current profile for WLP depends solely on the surface area of the spherical probe that is exposed to sunlight. After identifying the contribution from photoelectrons we remove this additional current from the recorded WLP IV curve before attempting to obtain any density and temperature estimates. In other words, the removal of the photoelectron current precedes the steps of the IV curve analysis listed from Equation 1 and we proceed with the analysis in Section 2.1 only after the photoelectron part of the collected current is removed. Hence, the veracity of the obtained estimates depends greatly on the choice of the photoelectron contribution.

In the simplest case, when the WLP is in eclipse, there is no photoelectron emission current, and when it is in sunlight, instantaneously the maximum area exposed is its projected area of $\pi r^2$. If we assume a transition of this form which is abrupt across the local dawn (at ISS altitudes), then the resulting profile will lead to a maximum photoelectron emission current of $2.35 \times 10^{-7}$ A ($I_{\text{max}}$) when the ISS is in daylight and 0 A elsewhere. We refer to this profile as a flat photoelectric profile where the fraction of the WLP projected area exposed moves from 0 to 1 across the terminator. The resulting values of $n_e$ are shown in Figure 5, where we show the WLP ($n_i$, red) and PIP ($n_i$, green) derived densities during a 3 hr segment of the orbit on September 6, 2017. PIP is a radio frequency probe that is immune to surface charging and gives absolute electron densities (Barjatya et al., 2009). The densities are shown along the left Y-axis, while the fraction of the WLP projected area exposed to sunlight is plotted in blue along the right Y-axis.

As can be seen, the two probes agree fairly well in high density instances where any photoelectron emission current effect is expected to have minor impact on the derived ion density results. However, when a low density section of the orbit coincides with an eclipse entry or eclipse exit instance, the ion densities derived

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**Figure 4.** The 2-stage fitting process is demonstrated above. The description of each panel is shown in the textbox above. The zero current line is shown in green dashed-dot format. The final parameters are $n_i, T_e, \phi_p$ from Stage I and O+ fraction from Stage II.
from WLP undershoot the electron densities derived from PIP. In Figure 5, the eclipse exits are noted in thick lined ellipses wherein the ISS comes out of local night to sunlight, and the eclipse entries are noted as small dotted ellipses wherein the ISS enters into darkness from sunlight. One possible explanation for this lower derived $n_i$ could be if too much of the ion saturation current is being attributed to photoelectron emission current. It is possible that there is some shadowing or some other unknown phenomenon that results in lesser than maximum photoelectron current emission during eclipse entry/exit. As we do not know the exact situation in orbit, we attempt to develop a mathematical way to model the illuminated area transition between eclipse and sunlight that can be applied consistently across all such instances in the data set that spans the entire solar cycle 24.

We argue that the area fraction responsible for the photoelectron current emission at any given time depends on the elevation angle to sun at that given instant, hereby referred to as the solar elevation angle. The solar elevation angle ($\theta$) is complementary to the solar zenith angle and assumes the value of $0^\circ$ when the ISS is at the horizon while the angle is $90^\circ$ at the zenith. Ideally the photoelectron contribution should be maximum at the zenith, minimum at the horizon, and eventually 0 as the elevation goes negative when the ISS is in eclipse. Since a small portion of solar EUV radiation can also reach the ISS beyond the horizon before dawn or after dusk through atmospheric refraction at concerned altitudes, we start accounting for photoelectron profile not from $0^\circ$ but from $-20^\circ$ from the horizon. The final mathematical formulation of the fraction ($f$) of the maximum illuminated area (the projected area) as a function of the solar elevation angle is shown below:

$$f \begin{cases} \text{min}(\sec(\theta + 20^\circ) - 1, 1), & \forall \theta \in [-20^\circ, 90^\circ] \\ 0, & \text{elsewhere.} \end{cases}$$

The condition where the fraction of exposed area is 0 applies to regions of the ISS orbit when the WLP is under eclipsed conditions and hence no photoelectron contribution needs to be accounted for. Figure 6 shows the solar elevation angle in panel (a), while the variation of the fraction of maximum sunlit area with the solar elevation angle is plotted in panel (b). As shown in the figure, the photoelectron contribution is thus a continuous function that starts at $20^\circ$ below the horizon. In such a way, we can also ensure a smooth transition from zero photoelectron current under eclipse which ramps up to a fraction of the maximum current at dawn and reaches the peak value as the ISS moves nearer to zenith.

The results of using the updated smooth transition of the photoelectron current emission profile are shown in Figure 7. The WLP and PIP derived densities agree much better for both eclipse exits and entries, while continuing to match in higher densities. Numerically, on average there is about 27% difference between the WLP and PIP densities (with respect to the WLP densities) for a flat photoelectron profile, decreasing

Figure 5. Figure shows comparisons between the wide-sweeping Langmuir probe (WLP) ion density (red) and the plasma impedance probe (PIP) electron density (green) when using a flat photoelectron profile. The two measurements differ significantly at eclipse entries and exits when the sunlit area used is rapidly transitioning from zero to maximum (eclipse exit) or from maximum to zero (eclipse entry).
to 13% for the case of the smoother transition profile of the illuminated area of WLP. We have verified this photoelectron current emission profile to work across numerous orbits throughout the FPMU data set by the cross comparison of WLP $n_i$ and PIP $n_e$.

3. Results and Discussions

The data products of the WLP analysis algorithm described above are next compared with IRI 2016 outputs (Bilitza et al., 2017) for the same physical quantities. Figure 8a shows 3 orbits on a randomly chosen day in 2018. The top column shows the WLP derived ion density in red, the PIP inferred electron density is shown in blue, and the IRI model output plasma density profile is plotted in black. The second panel shows the WLP derived electron temperature in red against the backdrop of the IRI prediction plotted in black. The WLP $T_e$ profile has been smoothed using a seven point moving mean filter. The third panel shows the O+ percentage as derived from WLP in red and the IRI prediction in black. The bottom-most panel shows the orbital parameters. The latitude and longitude are shown in green (left axis) and orange (right axis), respectively. In the same panel, the black profile shows the solar intensities in percentages (corresponding to the right axis) that demarcate the eclipse entries and exits corresponding to sunset and sunrise at local ionospheric altitudes.

Figure 6. The cartoon to the left shows the solar elevation angle ($\theta$) which determines the fraction of the maximum exposed area considered for photoelectron current. This variation is shown in panel (b) for all possible values of $\theta$ as specified by Equation 6.

Figure 7. The figure shows comparisons between the wide-sweeping Langmuir probe (WLP) ion density (red) and the plasma impedance probe (PIP) electron density (green) using the updated photoelectron profile. Measurements made by two independent techniques agree more at eclipse exits and eclipse entries using the new method of accounting for photo-electrons.
As can be seen in Figure 8a, the FPMU derived plasma parameters show small scale structures that deviate from the general average level as predicted by the IRI. The plasma density is consistent between PIP derived $n_e$ and WLP derived $n_e$. As these two instruments are completely independent measurements and distinct techniques, their remarkable agreement gives high confidence in the plasma density measurement.
For the day in question, the electron temperatures inferred are on average marginally higher than the IRI values while the opposite is true for the electron densities. We speculate that this deviation is a feature of collisional Maxwellian plasma in solar minimum. The lack of collisions when the densities are low lead to a plasma with higher electron temperature. Further studies need to be conducted to gauge if this holds true consistently for different levels of solar activity. This would be a subject of a subsequent study, potentially comparing FPMU outputs with other models as well.

The $O^+$ percentage levels which are secondary variables estimated from the WLP IV curve also show some expected and some interesting features. First, throughout the entire analyzed data set spanning solar cycle 24, the overall average $O^+$ fraction during sunlit hours is higher than the average $O^+$ fraction when the ISS is in eclipse. This is an expected feature in the ionosphere as the F-peak, and hence the $O^+/H^+$ transition height, is lowered when photo-production is not at the maximum levels as it is in day-time. However, interesting features are observed during local post-midnight hours, especially at higher latitudes during solar minimum, when the $O^+$ fraction drops dramatically. For the specific orbits presented in Figure 8a, the $O^+$ levels falls to less than 80%. Although the levels of these dropouts seem much larger than IRI predictions, past literature such as the studies by Aponte et al. (2013) and Kotov et al. (2015) have reported percentages of lighter ion species that significantly exceed model predictions during equinox. Again, future studies need to be focused on the extent of this effect and the climatology of these depletions, as well as cross comparison with closely located ion measurements from other satellites.

For the purpose of comparison with Figure 8a, we also present Figure 8b to demonstrate derived plasma parameters from multiple orbits of the ISS for a day in September from the solar maximum in 2013. We choose a quiet day (Kp ~ 2) similar to the day shown in Figure 8a. The features that are prominent in this data are the presence of pronounced crests in the dayside equatorial ionization anomaly (EIA), large plasma bubbles in the nighttime low-latitudes and the absence of the large depletions in $O^+$ fraction that were seen in Figure 8a. The average $O^+$ fraction is also higher compared to the orbits in solar minimum. As in the case of the solar minimum day, the average trend in FPMU data is similar to IRI but with expected finer scale features.

We also compare a case when simultaneous measurements were made by the FPMU in-situ and via remote sensing by the ISR at Millstone-Hill. The ISR scan can be used to derive ionospheric parameters which is a much-studied ground-based technique (Evans, 1969; Rishbeth & Lanchester, 1992). The results of the comparison are shown in Figure 9. The ISS overpass and the radar scans coincide around 21:10–21:17 UT. The overpass is shown in Panel (a) of the figure. Panels (b–d) to the right show the plasma density, electron temperature, and $H^+$ ion composition measurements made in-situ by the FPMU satellite (shown in red) as well the ones estimated from the ISR scan (shown in blue). The uncertainties in the ISR observations are shown as vertical bars (also in blue) along with the ISR scatter points. The ISR observations shown are only for the altitude range of 400–430 km. Since the radar scans along the azimuth and zenith cover a large range
of altitudes, it is necessary to include only observations that are close to the nominal altitude of the ISS orbit. At first glance the density estimates look worse but numerically they agree within 15% of the FPMU profile while the temperatures agree within 200 K (i.e., 10%). The temperature and H\textsuperscript{+} measurement at 21:17 UT is the farthest from the FPMU estimate but this is simply because the FPMU is at a larger distance (~100s of kms) from the co-locating radar scan point. The H\textsuperscript{+} composition which is only estimated from the ISR scan at altitudes above 400 km is also found to be accurate within 1.5%. Note that the FPMU data product is O\textsuperscript{+} fraction, but as we are assuming a two species plasma in our analysis, we can plot 1.0 − O\textsuperscript{+} as the H\textsuperscript{+} fraction. Thus, the four samples taken along the radar scan show that the measurements made by FPMU and ISR are in remarkable agreement. The accuracy of the derived plasma parameters across measurements implementing different measurement principles like that of the impedance probe (Figure 8) as well as that of a ground-based technique (Figure 9) establish the validity of the presented results.

At this point, some discussions are in order about the general sources of uncertainty in the data products especially during solar minimum. First, it should be mentioned that uncertainties in estimates during solar minimum are greater than the corresponding years of solar maximum. This is a direct consequence of the low current levels recorded by electrical probes when the background densities are reduced leading to low signal-to-noise ratios. Uncertainties due to photoelectric currents are also magnified for years in solar minimum. For a plasma density of \( \sim 10^{12} \text{m}^{-3} \), the ram current in Equation 2 is \( \sim 50 \) times the photoelectric current whereas for a density of \( \sim 10^{9} \text{m}^{-3} \), the same factor is about 0.5. Since lower plasma densities are a theme for years of solar minimum, the level of uncertainty scales with the lower levels of plasma densities. In addition, density depletions are also pretty common in the dawn sector and have been studied in previous satellite observations during solar minimum (de La Beaujardiere et al., 2009). Thus, the effect of an improper treatment of the photoelectron emission current profile can be potentially dramatic when the ISS comes out of eclipse. By properly choosing the photoelectron emission current profile as outlined in Section 2.2, we account for a large number of uncertainties in density estimation. Finally, there can be potential sources of uncertainty in the estimated O\textsuperscript{+} composition. As described in Section 2.1, the O\textsuperscript{+} fraction is a secondary variable which we make from an assumption that the ionospheric plasma at these altitudes are made up of only two species H\textsuperscript{+} and O\textsuperscript{+}. Additional low mass species like He\textsuperscript{+} may also contribute to the composition of the ionosphere which may slightly alter the number density of O\textsuperscript{+} ions. In addition, a very large ion drift can be a source uncertainty in the O\textsuperscript{+} fraction estimated. This is because, in such a case, the drift in the satellite reference frame used in Equation 4 may become very different from the ram velocity thereby reducing the validity of the assumption of the supersonic flow of the spacecraft relative to the plasma. Such a scenario is, however, not typical of the ionosphere encountered by the ISS. Thus the most significant source of O\textsuperscript{+} uncertainty is an uncertainty in the total density estimate itself since the percentage of O\textsuperscript{+} is derived secondarily from the estimate of density.

### 4. Summary

We present plasma parameter observations spanning 14 years from the WLP within FPMU aboard the ISS. The primary plasma parameter presented are the in-situ quasi-neutral plasma densities and electron temperatures at an altitude of about 400 km in the F-region terrestrial ionosphere. Standard OML theory guided data analysis has been used to infer these estimates from careful curve-fitting of the measured current-voltage (IV) relationships. Going beyond the standard Langmuir probe analysis, our algorithm has been augmented with an additional feature which involves resolving the ion composition between O\textsuperscript{+} and H\textsuperscript{+} constituents by leveraging the fine sampling of the ion saturation region by the wide sweeping probe. The introduction of O\textsuperscript{+} percentage as a data product is particularly useful since lower mass ions like H\textsuperscript{+} can be a relevant species in the F-region ionosphere at concerned altitudes during periods of reduced solar activity. By fitting for the split of O\textsuperscript{+} and H\textsuperscript{+} we also minimize potential errors in density estimates resulting from a combination of decreased signal level and increased lighter ions at solar minimum. The contribution of the photoelectrons emitted from the probe surface is also an important factor that can introduce uncertainties when current measurement levels are low. The presented data analysis method makes use of a photoelectron emission current profile that takes into account the orbit of the ISS and its relative position in the Sun-Earth system, so that the exposed area of the probe can be used to calculate the amount of photoelectron current emitted from the WLP. Presented results establish that the plasma
densities obtained from the WLP are in close agreement with those obtained from a PIP which is a different instrument in the FPMU suite and employs a different principle of estimating absolute electron density. We have also compared results with coincident measurements from a ground-based ISR scan. The accuracy of the estimates across measurements implementing different operating principles like that of the impedance probe (Figure 8) as well as that of an ISR (Figure 9) give confidence in the validity of the presented results.

The data set of observations utilizing the analysis algorithm as presented in this study will be publicly available for public use and will replace the presently existing data set hosted at the NASA Space Physics Data facility (SPDF) at https://cdaweb.gsfc.nasa.gov. The temporal and spatial diversity of the released data will likely aid the space physics community in research endeavors aimed at extending the scientific know-how of the related dynamics of an extremely important region in the terrestrial ionosphere.

Data Availability Statement

The open-source python software packages for running relevant models like pyglow for IRI (https://github.com/timduly4/pyglow) and pyIGRF 0.3.3 for IGRF (https://github.com/zyzytyz/pyIGRF). LMfit version 0.9.14 (https://lmfit.github.io/lmfit-py/) have been used for non-linear curve fitting. Processed data for the Millstone-Hill ISR have been obtained from the Madrigal database hosted at http://millstonehill.haystack.mit.edu/. The re-processed FPMU data set will replace the existing dataset hosted at the NASA Physics Data Facility hosted at https://cdaweb.gsfc.nasa.gov. In addition the data generated for this article will be made available for open access at https://doi.org/10.5281/zenodo.4667894.

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