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Contamination effects on fixed-bias Langmuir probes

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Langmuir probes are standard instruments for plasma density measurements on many sounding rockets. These probes can be operated in swept-bias as well as in fixed-bias modes. In swept-bias Langmuir probes, contamination effects are frequently visible as a hysteresis between consecutive up and down voltage ramps. This hysteresis, if not corrected, leads to poorly determined plasma densities and temperatures. With a properly chosen sweep function, the contamination parameters can be determined from the measurements and correct plasma parameters can then be determined. In this paper, we study the contamination effects on fixed-bias Langmuir probes, where no hysteresis type effect is seen in the data. Even though the contamination is not evident from the measurements, it does affect the plasma density fluctuation spectrum as measured by the fixed-bias Langmuir probe. We model the contamination as a simple resistor-capacitor circuit between the probe surface and the plasma. We find that measurements of small scale plasma fluctuations (meter to sub-meter scale) along a rocket trajectory are not affected, but the measured amplitude of large scale plasma density variation (tens of meters or larger) is attenuated. From the model calculations, we determine amplitude and cross-over frequency of the contamination effect on fixed-bias probes for different contamination parameters. The model results also show that a fixed bias probe operating in the ion-saturation region is affected less by contamination as compared to a fixed bias probe operating in the electron saturation region.
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I. INTRODUCTION

Langmuir probes[1] are the standard instruments for electron density measurements in laboratory plasmas[2] as well as on satellites and sounding rockets in the ionosphere.[3,4] Swept-bias Langmuir probes provide measurements of absolute plasma density, temperature, and vehicle floating potential, but the probe I-V characteristics are known to be distorted by surface contamination effects, which may lead to erroneous measurements,[5,6] unless the probe is cleaned, for example, by heating or by using a fast sweep mode.[7] However, recent analysis has shown that with a properly chosen sweep function, the contamination parameters can be determined from the measurements,[8] and consequently, an accurate representation of the plasma characteristics can then be recovered.[9,10] Unlike swept-bias probes, fixed-bias Langmuir probes are mostly used to provide high temporal resolution relative density measurements. Most rocket payloads include a fixed-bias Langmuir probe because high time resolution measurement is an important instrument design criterion for studies of plasma turbulence and plasma gradients along the rocket trajectory. While contamination effects may also be present in the fixed-bias Langmuir probe data, they are not directly measurable and, hence, typically ignored.

Fixed-bias Langmuir probes that are used for relative density and density fluctuation measurements are calibrated with absolute density measurements gathered by independent techniques such as impedance probes or Faraday rotation measurements. The resistance of the contamination layer on any Langmuir probe reduces the probe voltage seen by the ambient plasma, which in turn reduces the absolute current that is measured by the probe, leading to measurements indicative of lower electron densities. Although the contributions from the contamination layer cannot be uniquely determined from the fixed-bias probe measurements, background plasma densities derived by periodically cross-calibrating fixed-bias Langmuir probes with other probes can still be very accurate. The density fluctuations, however, are influenced by the resistance-capacitance combination of the contamination layer in a manner, which varies with frequency of the density variations and could lead to a measured spectrum that is different than that of the actual fluctuations.

In this paper, we first detail our Langmuir probe contamination model and compare its results with data from a contaminated Langmuir probe aboard a sounding rocket. We will then use the same model to simulate density fluctuations on Langmuir probes with varying levels of contamination. We then conclude the paper with discussions of the results and implications for probe design.

II. SPICE MODEL SETUP

Our circuit model simulates contamination as a parallel combination of resistor-capacitor (RC) circuit elements.[8,11] The implementation of this circuit in SPICE is similar to that as developed by Barjatya and Swenson,[12] and is shown in Figure 1. In essence, the payload surface, the probe, and plasma create a closed circuit, as shown in Figure 1. The inputs to the SPICE model are: area of the payload surface, area of the probe surface, plasma density, and temperature, voltage applied to probe, and contamination parameters (R and C). The SPICE software then finds

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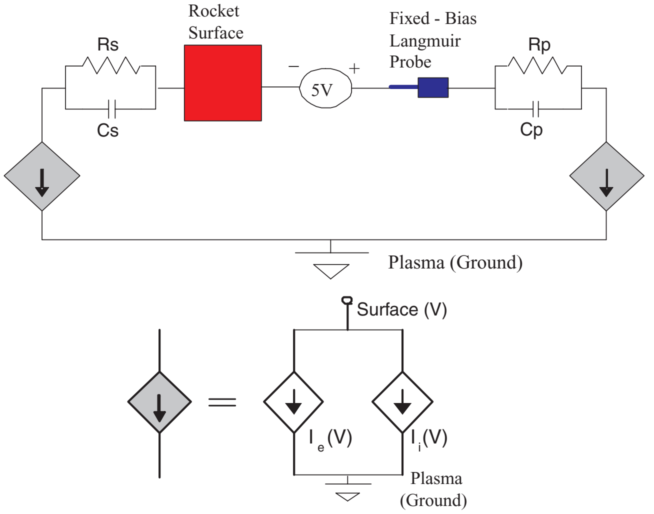

FIG. 1. SPICE model of a rocket payload with a Langmuir probe. Each SPICE sub-circuit (gray filled parallelogram) contains two voltage controlled current sources (white unfilled parallelograms) representing ion and electron thermal currents.

the equilibrium bias point where the electron and ion current through the circuit (i.e., payload-probe-plasma) is equal and consistent with Kirchhoffs laws. The electron and ion thermal currents are modelled as voltage dependent current sources represented by current collection equations from a simplified version of the orbital motion limited (OML) theory.[13,14] While the Langmuir probe can be modelled as any geometry (planar, cylindrical, or spherical) by choosing appropriate OML expressions, the rocket payload is always modeled with cylindrical electric probe OML expressions as our paper concentrates on sounding rocket missions specifically. The contamination on the probe is modelled as the parallel combination of R_p and C_p, and the contamination on the payload surface as the parallel combination of R_s and C_s. While R_p and C_p can typically be derived from measured *in situ* swept Langmuir probe data,[9] the contamination parameters on the rocket payload skin are expected to be very patchy in nature and cannot be directly determined. However, contamination on the large payload surface can be approximated as a parallel combination of several resistors and capacitors. As the value of the equivalent resistance goes down when several resistors are in parallel, whereas the value of the equivalent capacitance adds up, we model $R_s = 1\ \Omega$ and $C_s = 100\ \mu$F. Assuming that the sheath is one to two Debye lengths in size, the sheath capacitance is expected to be in several tenths of a pF in the mesosphere and several pF in the thermosphere. As the contamination capacitance is expected to be in μFs, we ignore sheath capacitance in our model. Finally, to keep the model simple and tractable, we have also ignored ion ram current as well as magnetic field effects on Langmuir probe I-V characteristics.

Our choice of using simplified OML theory expressions in the model warrants further explanation. OML or orbit motion limited theory was introduced by Mott-Smith and Langmuir[1] in their seminal paper on the subject. The expressions we use are an approximate version of the theory in the limit that the sheath is much larger than the probe radius. The following equation represents the current collected in either the electron, or ion saturation regions for a non-drifting, unmagnetized, and collisionless plasma, when the probe dimensions are much smaller than the Debye length:

$$I_j(\phi) = I_{th_j}\left(1 + \frac{q_j(\phi - \phi_p)}{k_B T_j}\right)^{\beta}, \tag{1}$$

where I_{th_j} is the random thermal current of charge species to the probe. Under these approximate OML expressions, the current in the electron and ion saturation regions depends on sensor geometry. Planar sensors measure a current that is independent of the probe voltage ($\beta = 0$), spherical sensors measure a current that increases linearly with probe voltage ($\beta = 1$), and cylindrical sensors measure an increase that goes with the square root of the probe voltage ($\beta = 1/2$). The requirement of probe dimensions being smaller than the Debye length is hard to meet in practice for ionospheric measurements, where the Debye length varies from a few mm to several cm. Because of this as well as because of contamination, the actual probe characteristics often differ from the approximated OML theory expressions. In fact, Piel *et al.*[8] and Barjatya *et al.*[4] have shown that that although the general expression remains the same, the β factor varies even for a specific probe geometry. At the same time, recent work by Bekkeng *et al.*[15] and Chen[16] has shown that the approximated expressions are indeed valid, both in space and in laboratory plasma, as long as the probe design adheres to keeping the dimensions smaller than any Debye length encountered. Thus, we have chosen to use the approximated OML theory current collection expressions in the model, not only because they are easier to implement, but also because effects on the I-V characteristic due to deviation from OML expressions are expected to be smaller than that caused by contamination or by surface to probe area ratio. This is tested next by a qualitative comparison with *in situ* measured data, where the probe dimensions were comparable or larger than the Debye length encountered during the rocket flight.

Figure 2 shows the measured I-V characteristics from a spherical probe sweep measurement during a nighttime

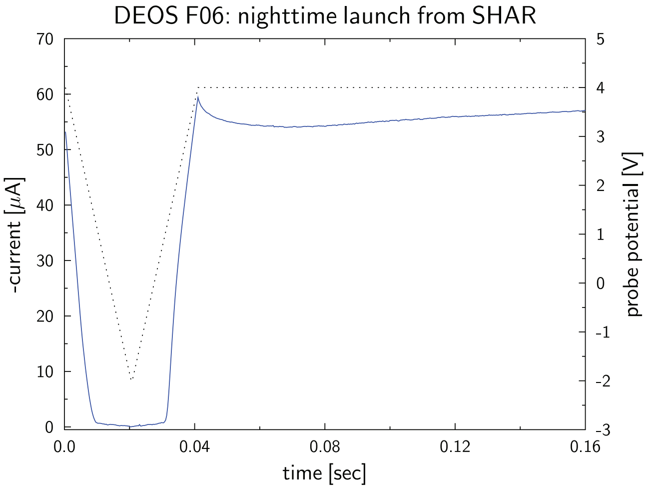

FIG. 2. Probe current versus time after the start of the sweep. Also shown is the applied probe potential. The slight current increase after 0.08 s is a spin effect.

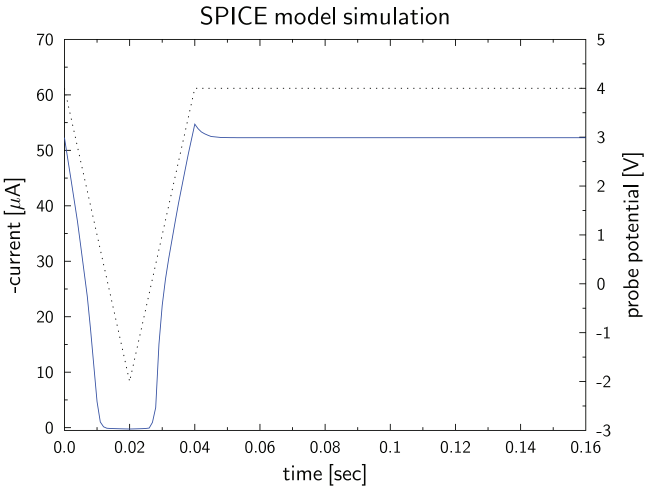

FIG. 3. SPICE model simulation results for $N_e = 7 \times 10^{11}/\text{m}^3$ and $T_e = 1300$ K. Dotted line: applied potential.

launch from Sriharikota Range (SHAR), India (Dynamics of the Equatorial Ionosphere over SHAR (DEOS) F06). There are two features that pop-out in the plot: one, the electron saturation region shows a nonlinear increase with applied voltage, and two, the current decays even though the potential is held constant at the end of up-sweep. The analysis in Ref. 8 finds that the contamination on the spherical Langmuir probe on the DEOS F06 rocket payload can be characterized by a parallel combination of $R_p = 30\ \text{k}\,\Omega$ and $C_p = 0.1\ \mu$F. We use these values in our SPICE model, and simulate the −2 V to 4 V sweeps for the density and temperature combination that was derived from the DEOS data after contamination corrections as outlined in the Piel *et al.*[8] paper. The model simulation results are shown in Figure 3, which match qualitatively fairly well with measured current. Thus, while our model using the approximate OML theory expression in a case where probe dimensions are larger than the Debye length cannot accurately quantitatively simulate the observed currents, it should be sufficient to qualitatively describe the effects of contamination on fixed bias probe measurements.

In addition to probe surface contamination, a small payload-to-probe surface area ratio also leads to poorly determined plasma parameters from a swept-bias Langmuir probe's measured I-V curves. Szuszczewicz has shown that a swept-bias Langmuir probe should have a ratio of payload surface area to the probe area of 10000 to guarantee no change in payload floating potential during probe sweep.[17] In a recent

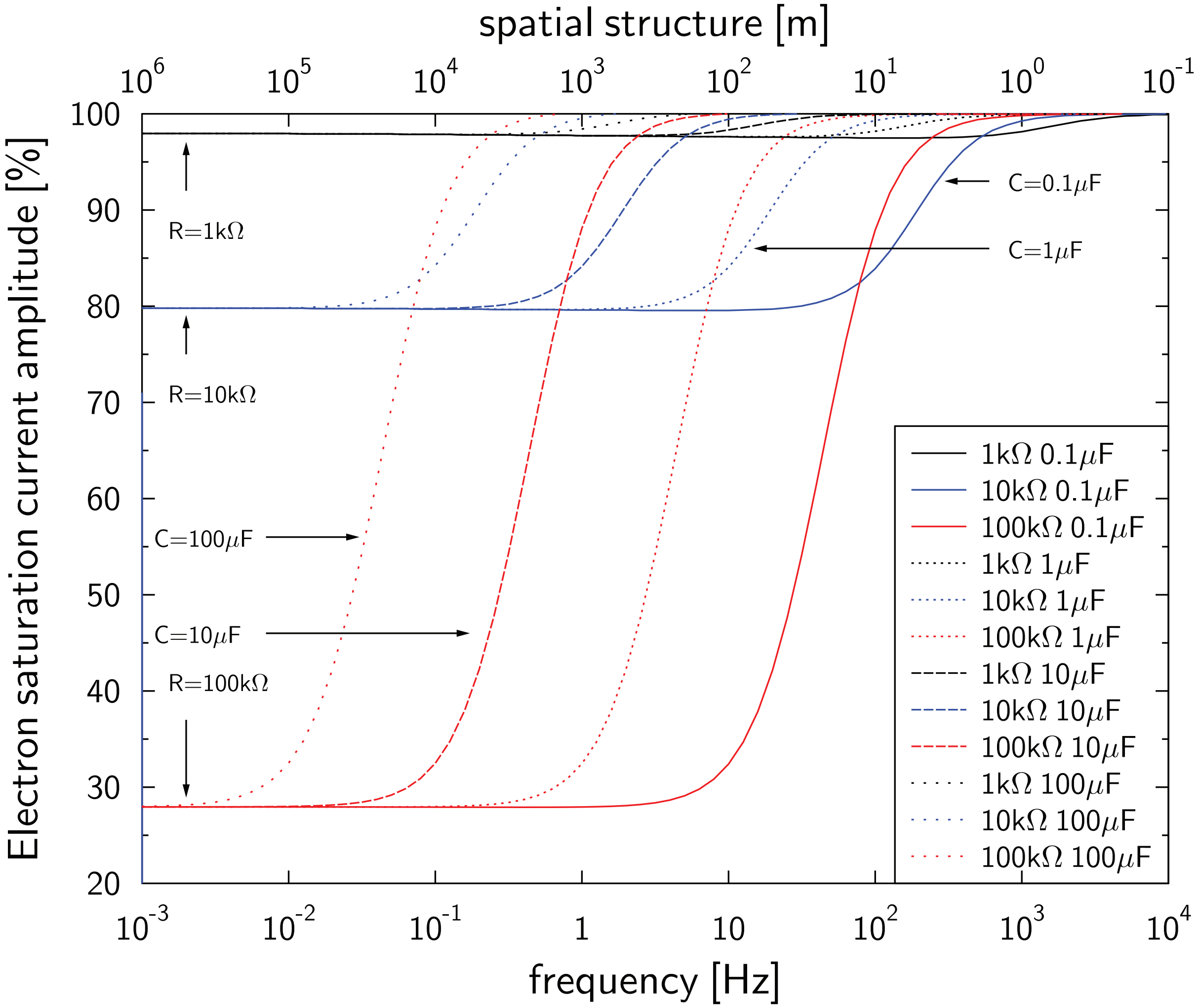

FIG. 4. Spice model simulation of a spherical Langmuir probe biased at +5 V in the electron saturation region. The simulation used $N_e = 10^{12}/\text{m}^3$ and $T_e = 2000$ K. A density fluctuation of 10% was simulated at different frequencies as shown in the x-axis.

experiment, Shimoyama *et al.* have shown[18] that a small surface ratio of 124 causes an underestimation of electron density by 50%. However, a small payload-to-probe surface area ratio has a lesser effect on fixed-bias Langmuir probe data set. This is because the payload will float to whatever potential is required to maintain current balance between fixed bias probe and the payload surface. Thus, the only effect seen by the fixed bias probe will be a smaller measured current because the probe is now not operating as far in the saturation region as it was intended to be. The only instance a fixed bias probe will fail is when the surface ratio is so small that the payload floating potential shifts significantly enough to impede the fixed bias probe from operating in the saturation region. We maintained a payload-to-probe surface area ratio of 2000 in our simulations, which is typical of most sounding rockets.

III. CONTAMINATION EFFECTS ON FIXED-BIAS LANGMUIR PROBES

While contamination effects on a swept-bias probe are easy to diagnose and account for in post-flight data analysis, they cannot be assessed in a fixed-bias Langmuir probe data set. The largest effect on a fixed-bias probe would occur when the ambient density is fluctuating at a rate much slower than the RC time constant of the probe contamination, in particular for the DC current. We model this effect by simulating a 10% sinusoidal fluctuation in the plasma density at varying frequencies from 1 mHz to 10 kHz. The simulation results for a fixed-bias probe operating in the electron saturation region (+5 V) are plotted in Fig. 4. We use contamination resistances of 1 kΩ (black lines), 10 kΩ (blue lines), and 100 kΩ (red lines), and contamination capacitances of 0.1 μF (solid), 1 μF, 10 μF, and 100 μF (dot). We simulate the density and temperature that is found in the *F*-region ionosphere: plasma density of 10^{12} m^{-3} and a plasma temperature of 2000 K. The bottom x-axis of the figure shows the fluctuation frequency, while the top x-axis shows the spatial scale of density structure that corresponds to the frequency assuming a rocket velocity of 1 km/s. The y-axis is presented as a percentage of amplitude change, where we have assumed the current amplitude at higher frequency (i.e., smaller scale structure) as 100%. Figure 5 is a similar plot but for a fixed-bias probe operating in the ion saturation region (−5 V) with a 10 times larger probe area to collect a comfortably measurable current.

As mentioned before, relative density measurements derived from fixed-bias probes are periodically cross calibrated/normalized to absolute density measurements from

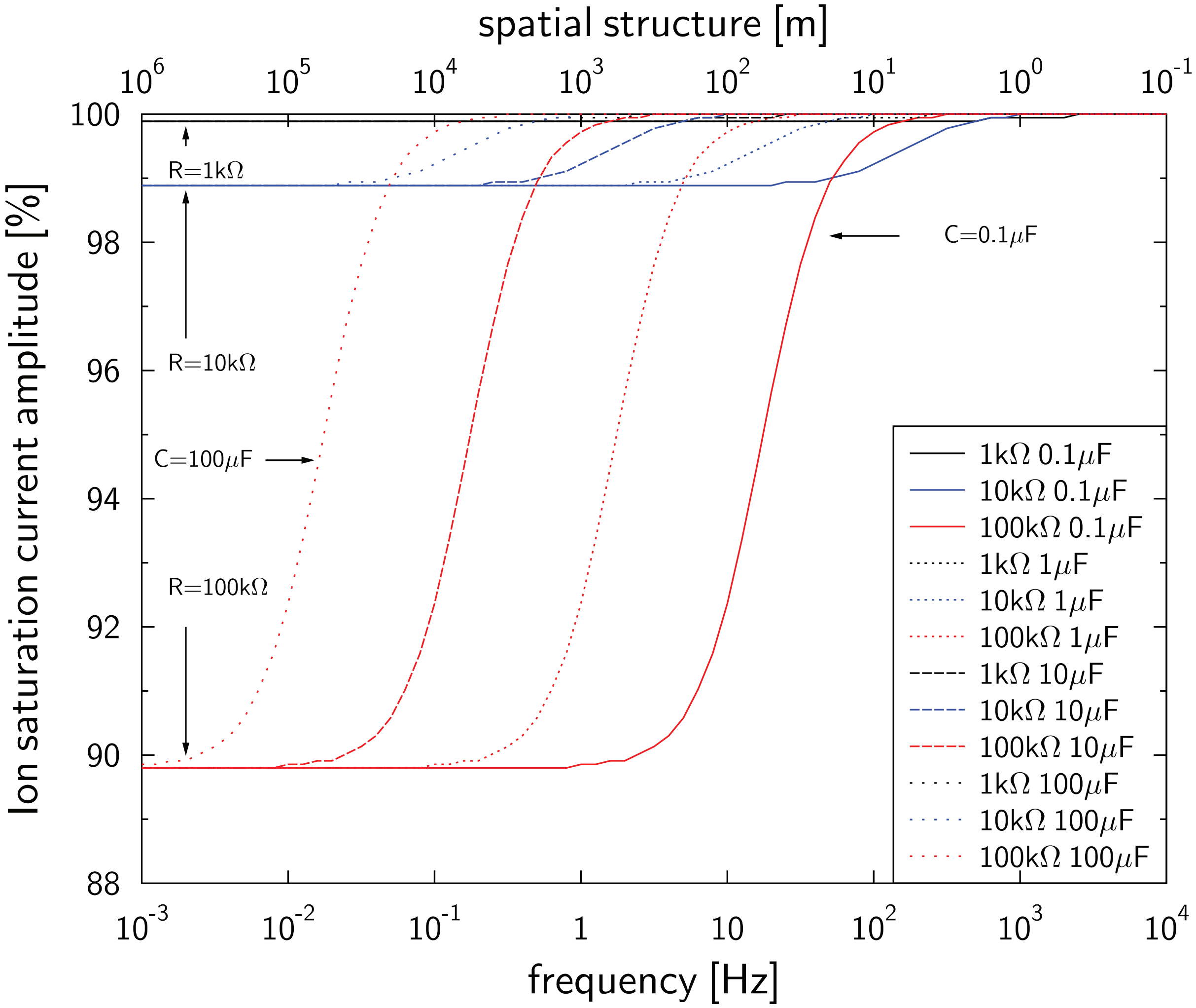

FIG. 5. Same simulation parameters as in Figure 4, but with the Langmuir probe biased at −5 Vin the ion saturation region.

other instruments. Such a calibration/normalization is usually done outside the plasma turbulence zone where the altitude-density profile is smooth, i.e., large spatial scale or low frequency (left side of Figure 4). If such a normalization is done for a fixed-bias probe operating in electron saturation region then the results shown in Figure 4 imply that the apparent magnitude of turbulence can be as much as factor of three larger than actuality. The contamination resistance determines the magnitude of the fluctuation amplification, whereas the contamination capacitance determines the cross-over frequency, i.e., the larger the contamination resistance, the larger the observed amplitude of the small scale spatial fluctuations, and the larger the contamination capacitance, the larger the spatial scale density fluctuation where the magnitude amplification starts occurring. Figure 5 shows us that a fixed-bias probe operating in ion saturation region has a smaller such effect. This is to be expected as the observed current in ion saturation region is an order of magnitude smaller than that in electron saturation region. It is important to note here that Figure 4 is unique to the chosen probe area and plasma density. If we simulate a lower plasma density and a smaller sized probe then the collected current becomes smaller, resulting in the smaller amplification of fluctuations, but an amplification nevertheless.

Due to the nature of operation of fixed-bias probes, it is not possible to isolate and remove contamination effects. However, confirmation of these effects in the actual spectra of density fluctuations acquired with fixed-bias Langmuir probes could be made through comparisons of, for example, simultaneous high time resolution plasma density measurements through impedance probes that track the upper hybrid frequency. Note that these contamination effects on fixed-bias Langmuir probes pose a problem only for those missions that aim to identify the size of plasma density fluctuations, and not those missions where the sole objective is to identify the altitudes where the turbulence exists. In fact, this accentuation of small scale density fluctuations may be an asset in the latter case.

IV. CONCLUSION

In most cases, Langmuir probes used on sounding rockets are contaminated. Even if care has been taken to wipe the probes with alcohol, internally heat them while on the launch-pad, and nitrogen purge the payload, the probes can still be quickly contaminated in the atmosphere after launch. This contamination severely affects measurements with swept Langmuir probes, which can lead to large errors in the determination of plasma parameters. The contamination parameters can be determined from the probe measurements when the sweep function includes both an up- and down-ramp, and sufficient settle time between the ramps. Based on the determined contamination constants, we can calculate the potential that the plasma sees. In this manner, the correct plasma parameters can be determined from swept-bias probes.

As shown in this paper, probe contamination also affects fixed-bias measurements. The presence of contamination may not pose a noticeable problem in cases where the fixed-bias probe is frequently cross-calibrated with an independent density measurement during the flight and/or the instrument is only used for "DC" density measurements. It creates a problem specifically for those missions where the fixed-bias Langmuir probes are used to study plasma turbulence and the magnitude of the density gradients. If the fixed-bias Langmuir probe data are normalized to absolute density measurements outside the turbulence zone then this would increase the apparent amplitude of the fluctuations in the turbulence zone. Thus, the degree by which the amplitude of the fluctuations in the turbulence zone has been enhanced as a function of spatial small scale structure will not be readily determined. If the probe is never operated in a sweep mode, the contamination will probably remain undetected and fluctuation magnitude measurements will be unreliable. However, if the sole purpose of the fixed-bias probe measurements is the location of small scale density fluctuations along the payload trajectory, then the contamination effects may actually be helpful as this would make even the smallest scale density changes easily noticeable in the data. This paper also shows that contamination effects are comparatively benign for fixed-bias probes operating in ion saturation region, with the caveat that the measurement electronics have to be more sensitive as the ion saturation current is an order of magnitude smaller than electron saturation current. Nevertheless, since the contamination parameters are expected to change only slowly during a sounding rocket flight, it should be sufficient to measure the contamination by sweeping the probe a few times during the flight, especially near the apogee where the rocket velocity is slow.

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