4-11-2018

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Scholarly Commons Citation
Barjatya, A., & Merritt, W. (2018). Error Analysis of Multi-Needle Langmuir Probe Measurement Technique. *Review of Scientific Instruments, 89*(4). https://doi.org/10.1063/1.5022820

Review of Scientific Instruments

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Cite as: Rev. Sci. Instrum. **89**, 043507 (2018); https://doi.org/10.1063/1.5022820
Submitted: 18 January 2018 • Accepted: 27 March 2018 • Published Online: 11 April 2018

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REVIEW OF SCIENTIFIC INSTRUMENTS **89**, 043507 (2018)

Error analysis of multi-needle Langmuir probe measurement technique

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(Received 18 January 2018; accepted 27 March 2018; published online 11 April 2018)

Multi-needle Langmuir probe is a fairly new instrument technique that has been flown on several recent sounding rockets and is slated to fly on a subset of QB50 CubeSat constellation. This paper takes a fundamental look into the data analysis procedures used for this instrument to derive absolute electron density. Our calculations suggest that while the technique remains promising, the current data analysis procedures could easily result in errors of 50% or more. We present a simple data analysis adjustment that can reduce errors by at least a factor of five in typical operation. *Published by AIP Publishing.* https://doi.org/10.1063/1.5022820

I. INTRODUCTION

Langmuir probes are the most commonly used instruments for plasma density diagnostics on sounding rockets and satellites. The technique is simple: a metallic sensor immersed in plasma is applied a voltage V and the collected current I is measured. The resulting I-V curve is then analyzed to determine various plasma parameters such as electron and ion density, electron temperature, and spacecraft floating potential.[1] The instrument can be implemented in primarily two ways. First, and most commonly, as a fixed-bias probe wherein the voltage is kept constant relative to the spacecraft chassis ground. As the collected current is directly proportional to density, this implementation results in high cadence relative density measurement as long as there are no significant spacecraft charging events and the plasma temperature remains in a fairly narrow range (usually within few hundred Kelvin). The second way is a sweeping Langmuir probe where the voltage is swept from some negative bias to a positive bias, thereby recording the entire I-V curve. As one sweep can only give one measurement of each plasma parameter, the sweeping potential implementation of the Langmuir probe has lower cadence measurement of plasma parameters. Both implementations are susceptible to surface contamination,[2,3] although only the sweeping probe adversely affects other electric probes on the spacecraft by swinging the spacecraft floating potential, especially when the spacecraft-to-probe surface area ratio is smaller than few thousand times.[4] Thus, in order to avoid affecting the payload floating potential, fixed bias probes are largely favored to measure relative plasma density.

Multi-Needle Langmuir Probe (mNLP) is a relatively new technique that uses multiple fixed bias Langmuir probes to derive absolute plasma density that is independent of spacecraft charging.[5] This instrument technique has been used on several sounding rockets[6,7] and is also being implemented for CubeSats and small satellites. This paper first presents a brief overview of the technique and then elucidates how the current data processing of the mNLP can lead to significant errors. We then propose an alternate method of data analysis that is expected to work better.

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II. MULTI-NEEDLE LANGMUIR PROBE TECHNIQUE

The electron saturation current collected by a Langmuir probe operating in an Orbital Motion Limited (OML) regime is given by the following equation:

$$I_e = n_e e A\sqrt{\frac{k_B T_e}{2\pi m_e}}\left(1+\frac{e(\phi-\phi_p)}{k_B T_e}\right)^{\beta}, \tag{1}$$

where e, n_e, T_e, and m_e are the charge, density, temperature, and mass of electrons, k_B is the Boltzmann constant, A is the surface area of the probe, ϕ is the applied potential relative to ϕ_p plasma potential, and the variable β is set to 0, 0.5, or 1 based on the probe geometry of flat plate, cylinder, or sphere, respectively.

Operating in OML regime requires the probe diameter to be much smaller than the Debye sheath. The multi-needle Langmuir probe accomplishes that by using less than 1 mm diameter needles as fixed bias Langmuir probes. The mNLP technique relies on the fact that for cylindrical Langmuir probes, the square of the saturation current has a linear relationship with the applied relative potential. One can then derive absolute electron density using only the measurements at discrete points in electron saturation region. The equations governing the process are

$$I_e^2 = \frac{(n_e e A)^2}{2\pi m_e}\left(k_B T_e + e(\phi-\phi_p)\right), \tag{2}$$

$$\frac{dI^2}{d\phi} = M = \frac{n_e^2 e^3 A^2}{2\pi m_e}, \tag{3}$$

$$n_e = \sqrt{\frac{2\pi m_e M}{e^3 A^2}}. \tag{4}$$

This is the method used by Jacobsen *et al.*[5] in a paper covering data analysis of the mNLP instrument aboard the ICI-2 sounding rocket mission. Typically anywhere from 3 to 8 needles are used to create a line fit between square of the measured current and the relative potential difference between the applied potential. The unique benefit of the mNLP technique is that only the potential difference between the applied potentials to the needles is relevant, making this technique relatively immune to spacecraft charging as long as sufficient number of needles (≥3) are operating in the electron saturation region. As rockets and satellites typically charge −1 V to −2 V in nighttime ionospheric conditions, needles biased higher than 3.5 V should not be affected by spacecraft charging.

III. DATA ANALYSIS DISCUSSION

Several papers[1,2,8] have shown that the value of β in Eq. (1) rarely follows OML theory values. It is important to note that the papers referenced here had probe size larger than the expected Debye length so the departure of β from OML theory predicted values was to be expected. The entire premise of the mNLP technique is that the very thin "needle" probes are much smaller than the Debye length and consequently behave in the OML regime with the collected current following the $\beta = 0.5$ curve in the saturation region. One way to show that the probe measurements conform to OML expressions is by showing the linearity of the I^2 measurements with respect to the applied voltage. Jacobsen *et al.*[5] have shown 6 such instances throughout an ionospheric rocket flight. They have shown the correlation coefficients of a linear fit of I^2 measurements to V vary between 0.997 and 0.9993. Similarly, Friedrich *et al.*[9] have noted that the ECOMA 7, 8, and 9 flights had the I^2 vs V linear correlation coefficients between 0.97 and 0.99, but do not mention how that translates into error bars on the density calculation. This paper investigates the magnitude of error in derived absolute plasma density even when the I^2 vs V linear fit correlation coefficients are as good as seen on ICI2 and ECOMA 7, 8, and 9 flights.

Using Eq. (1), we simulated electron saturation currents at four different voltages similar to ICI2: 2.5, 4, 5.5, and 10 V, using three combinations of electron temperature and density that are representative of various regions and conditions within the ionosphere: 800 K and 1×10^9 m^{-3}, 1200 K and 1×10^{11} m^{-3}, and 2000 K and 1×10^{12} m^{-3}. The simulated current values at these four potentials were generated with β value varying between 0.45 and 0.85. We then calculated the linearity of the I^2 measurement vs potential difference between the points. This is shown in Fig. 1. For these three combinations of density and temperature, the linearity fit of these four points is largely the same across the different β values and only varies slightly for higher β values. It is crucial to note that for $\beta = 0.6$, the coefficient of correlation is 0.9998 or better in all three cases. This is better than the best correlation case shown in the paper of Jacobsen *et al.*[5], which was 0.9993. Thus, it is reasonable to assume that the β value observed *in situ* during ICI2 rocket flight was unlikely to be 0.5. For these combinations of temperature and density, the Debye length is expected to vary from 3 mm to 60 mm, which is an order of magnitude or larger than the ICI2 mNLP needle radius of 0.25 mm.

After these data were simulated, we used Eq. (4) to derive the electron density, i.e., the densities were derived assuming $\beta = 0.5$. The resulting densities were then compared with the simulation input densities for error. This comparison is shown in Fig. 2. As expected, for the currents simulated with β value fairly close to 0.5, the use of Eq. (4) results in very little error. But if the simulated β value deviated even 10% (to 0.55), then the error in calculated density using mNLP technique

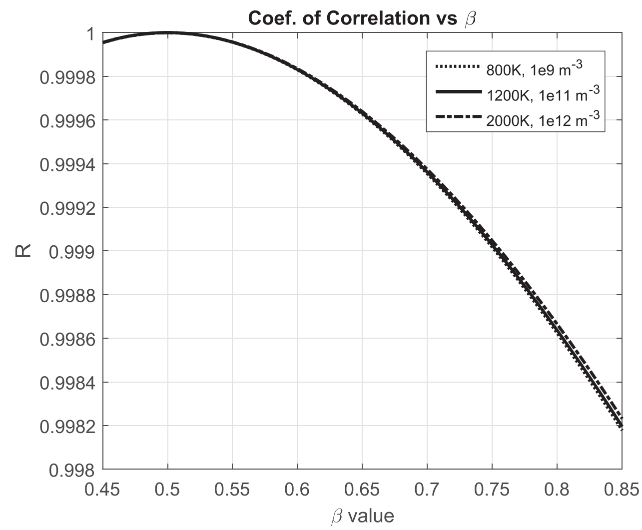

FIG. 1. Pearson coefficient of correlation for a range of β values for three combinations of density and temperature. Note the negligible variation between three combinations of density and temperature, which only marginally changes at higher β values.

can easily approach 30% or more. With $\beta = 0.6$, the error in derived density can be as large as 70%, even though the four I^2 points show excellent linearity, as was indicated in Fig. 1.

Note that we have not simulated any spacecraft charging in these plots. A worst case spacecraft charging of −2.5 V, such as seen by Bekkeng *et al.*,[6] will have adversely affected the 2.5 V biased needle measurement and further worsened the linear fit. In fact, Bekkeng *et al.*[6] not only ignored the 2.5 V needle data point but also the 4 V needle point as those data were corrupted. They derived electron density using the mNLP technique [i.e., Eq. (4)] with only two needles. In the Earth's mesosphere, the densities are lower and hence the Debye length

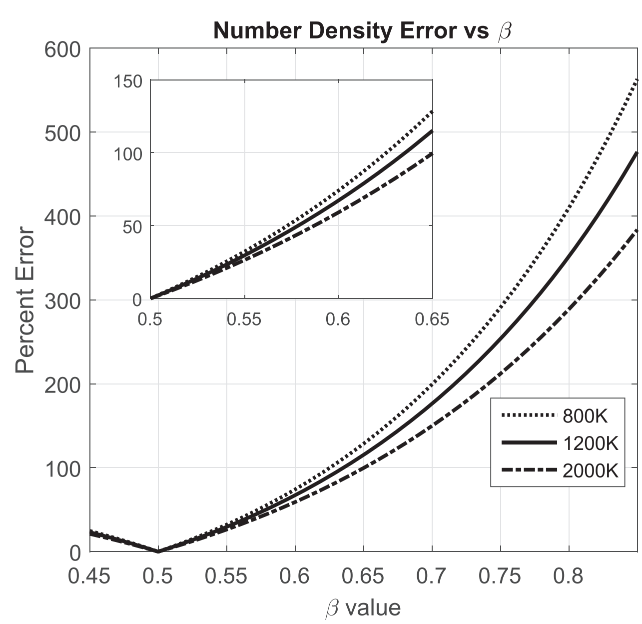

FIG. 2. Number density error for varying values of β. The inset is a zoomed section from $\beta = 0.5$ to $\beta = 0.65$.

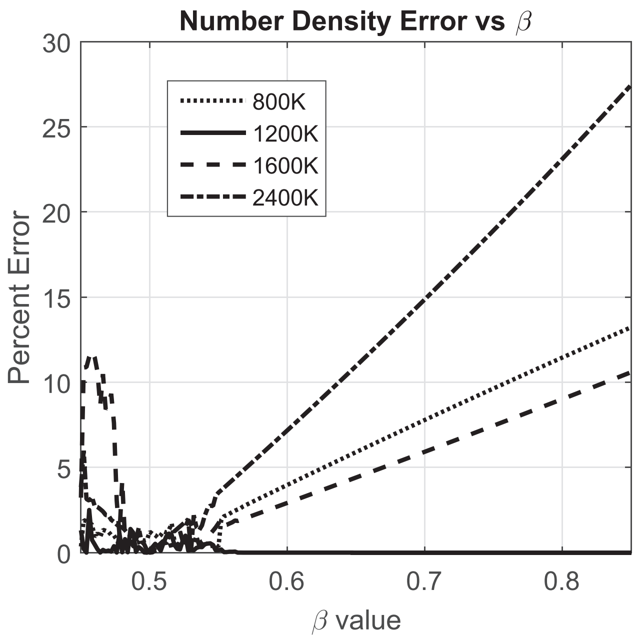

FIG. 3. Number density error when fitting for β over three points: 4 V, 5.5 V, and 10 V. Note that the error is nearly zero when the assumed temperature is exactly the same for simulated current values, i.e., 1200 K. A 100% error in assumed T_e (i.e., 2400 K) only results in 7.5% error in derived n_e at $\beta = 0.6$.

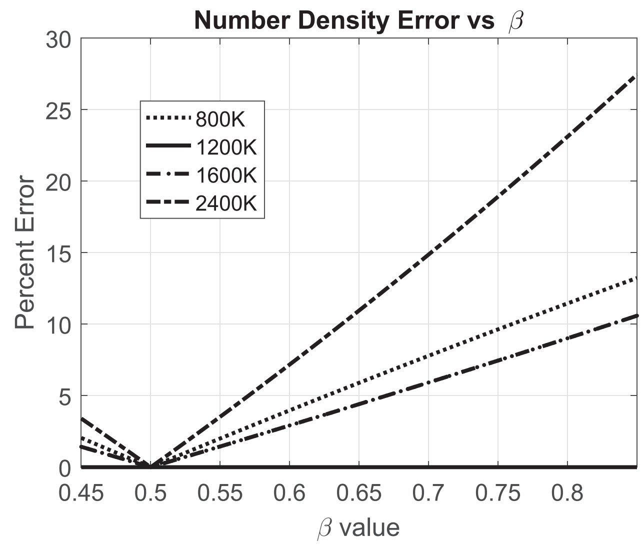

FIG. 4. Number density error when fitting for β over four points: 3.3 V, 4 V, 5.5 V, and 10 V. The fits are a lot cleaner for lower β values and the error in calculated density continues to be much lower than when assuming $\beta = 0.5$.

is much larger. Thus, one would expect the mNLP instrument to behave in the OML regime and the observed β value to be closer to 0.5. Despite a large Debye length, the mNLP derived density was a factor of 2 (i.e., 100%) different when compared with Faraday rotation derived absolute density.[9] However, once normalized to the Faraday rotation density numbers at 97 km, the mNLP derived densities were within 15%-20% of the Faraday rotation derived density profile. This normalization defeats the purpose of using mNLP instrument as an absolute density measurement and requires another instrument to be present onboard the rocket/satellite to provide the absolute density measurement to which mNLP data could be normalized to.

In light of the above, we instead propose using a β fitting technique similar to Barjatya *et al.*[2] and Barjatya *et al.*[1] We have four unknowns: β, n_e, T_e, and ϕ_p (i.e., spacecraft charging). We propose that the four measurement points (or more) from a mNLP-type instrument be used to fit for these four unknowns in a least-squares sense to the OML current collection equation (1). Although four points are sufficient for fitting for four unknown parameters, but assuming a worst case scenario where the lowest biased 2.5 V needle is corrupted by spacecraft charging and only three points/needles are available, we fit for β, n_e, and ϕ_p over measurements at 4, 5.5, and 10 V. We do the fits "assuming" various temperatures that deviate from the simulated temperatures by ±50% and +100%. And finally, also note that we generated the simulated currents using a spacecraft charging value of –2.5 V. The resulting error between derived densities and input densities after fitting for β, n_e, and ϕ_p is shown in Fig. 3. Note that the error drops down significantly as compared to doing an analysis assuming that $\beta = 0.5$ (see Fig. 2). This is even true when the assumed temperatures are significantly off from the temperatures used to simulate the currents. This is to be expected because saturation current regime is fairly independent of electron temperature. Note that at $\beta = 0.5$ the T_e term cancels out, thus the error is less dependent on the assumed T_e value when closer to $\beta = 0.5$ and worsens with temperature as the observed β value increases.

We next simulated currents on four voltages 3.3 V, 4 V, 5.5 V, and 10 V and fit for β, n_e, and ϕ_p. This is shown in Fig. 4. As there are more points than there are unknowns, the fits are much cleaner. So we recommend that any future implementations of mNLP type probes use at least four points that are not corrupted by spacecraft charging. The more the better, albeit that comes at a cost of increased data to downlink.

IV. CONCLUSION

We have shown here that the existing analysis method for mNLP probes, which assumes the square of the measured needle currents has a linear relationship to applied potential, can result in significant errors in the calculated absolute electron density. This error is a result of the assumption that the electron saturation current varies with $\beta = 0.5$. Our work has shown that even a 10% error in β observed by the needles can result in 30% or more error in the calculated density. In a real scenario, the needle current measurements at discrete points in the electron saturation region will be corrupted by inherent electronic noise as well as any wake effects, thereby increasing the resulting error percentage. Additionally, if the needles are spatially separated, then any local density variations have the potential to vary the β value seen by individual needles, thereby further increasing the error in calculated density. Nevertheless, the error that one gets by least-squares fitting for β, n_e, and ϕ_p and hence deriving absolute electron density will be far less than assuming the β to be 0.5. We also suggest that any mNLP implementation includes at least four needles that are biased above the spacecraft charging potential such that they are clearly in the electron saturation region.

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