Journal of the Earth and Space Physics, Vol. 45, No. 4, Winter 2020, P. 237-244

DOI: 10.22059/jesphys.2019.269440.1007063

First mesospheric in-situ measurement in Iran using sounding rockets and plasma impedance probe (PIP)

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(Received: 18 Nov 2018, Accepted: 14 May 2019)

Abstract

This paper reports on the progress for the first development of rocket probe for in-situ measurement of ionospheric plasma parameters in Iran. The designed probe known as Plasma Impedance Probe (PIP) will be used to measure the electron density, electron-neutral collision frequency, background magnetic field, and temperature in the mesospheric and in the altitude range of 70 km to 150 km. This paper presents a review of the current plan on design, analysis, fabrication and laboratory tests of the PIP. Specifically, the theoretical calculations as well as numerical simulations on the characteristics of the PIP is provided and discussed. The effect of several background parameters in the ionospheric region on the radiation characteristics of the immersed antenna in the background plasma is presented. The possible reduction technique in order to analyze the observational data and derive background ionospheric parameters is provided. The requirements for the implementation of the designed probe are investigated. The possible applications of the PIP in complex plasma are introduced.

Keywords: Plasma impedance probe, Ionosphere, in-situ measurement, sounding rocket.

1. Introduction

The local measurements of atmospheric, ionospheric and magnetospheric parameters using a probe on rockets and satellites, which is known as in-situ observations, has a long history in the field of space science and remote sensing. The history of these observations goes back to the post world war II era. The technologies associated with in-situ probes and instruments have been advanced over the years significantly such that they can provide very accurate observations of natural and artificially created phenomena in the near earth environment.

One of the simple and applicable probes that have been used in several missions by NASA and other institutions is the Plasma Impedance Probe (PIP) (Balmain, 1964; Baker et al., 1966; Bishop and Baker, 1972; Oya, 1966; Oya and Aso, 1969; Oya and Obayashi, 1967; Oya and Morioka, 1975; Carlson, 2004; Ward et al., 2005; Ward, 2006; Blackwell et al., 2005a, b, 2007; Spencer et al., 2007). The plasma impedance probe consists of an antenna with sweeping frequency within the range of background ionospheric plasma frequency. As the rocket passes through the ionosphere and based on the time scale of each frequency sweep, the resonance condition associated with electron plasma frequency, electron gyro-frequency, and electron-neutral collision frequency. This probe has passed the measurement capabilities within highly variable region of the ionosphere such as Aurora (Spencer et al., 2008; Abe et al., 2006; Wakabayashi and Ono, 2006; Jayram et al., 2008).

There are several other in-situ probes that can be used on rockets or satellites for local measurements of plasma and ionospheric parameters, which are not the subject of this paper. One major probe, which is widely being used, is the Langmuir probe that is well known as a basic instrument for measurement of ionospheric parameters such as electron density. This probe is designed to determine the electron temperature, electron density, and electric potential of plasma. This probe uses a constant or time-varying electric potential between the various electrodes or between them and the surrounding plasma. While this technique can provide an accurate measurement of plasma parameters, the direct contact of the probe with the plasma and shielding effect could limit the performance and applications of such probe. Therefore, the PIP that is the subject of current paper has a great advantage over the

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common in-situ probes both on simplicity and flexibility aspects.

This paper presents the theoretical analysis of PIP with varying background ionospheric parameters. The capability assessment of this probe for measuring ionospheric parameters is investigated by varying background parameters. A complicated computational model is discussed and used for accurate determination of plasma parameters. A data reduction technique to analyze the measured parameters is presented. The planned laboratory experiments are also discussed.

2. Plasma Impedance Probe (PIP)

The plasma impedance probe has received attention of the researchers for in-situ observations of the mesosphere and ionosphere. As discussed before, the main goal of the PIP is to measure the induced variation of the antenna input impedance, which is a result of changes in the background electron density, electron temperature, as well as orientation with respect to the background magnetic field.

These electrically short antennas in free space have a fundamental impedance of

$$Z_{antenna} = \frac{-j}{\omega C_0} \quad (1)$$

where ω is the transmission frequency, and C_0 is the characteristics capacitance of the antenna. The simplest approximation of the effect of plasma on an antenna is obtained by treating the plasma as a dielectric.

$$\epsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2}\right) \quad (2)$$

In this expression, electron plasma frequency is $\omega_p = {ne^2}/{\epsilon_0 m_e}$. Immersed antenna in plasma can be treated as a parallel plate capacitor filled with a dielectric

$$C = \epsilon_r C_0 = \left(1 - \frac{\omega_p^2}{\omega^2}\right) C_0 \quad (3)$$

If the plasma is modeled as a lossy dielectric, due to electron-neutral collisions (ν_{en}), the relative permittivity becomes

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\upsilon_{en}} \quad (4)$$

In the case of lossy (collisional) plasma, the impedance of the antenna not only has a modified reactive component (X) of the impendence, but also adds a resistive component (R). The plasma parameters such as electron density and collision frequency can be obtained from the following expressions.

$$n_e = \frac{\omega^2 m_e \varepsilon_0}{q^2}\left[\frac{\Delta X + \frac{\Delta R^2}{\Delta X}}{\Delta X + \frac{\Delta R^2}{\Delta X} + \frac{1}{\omega C_0}}\right]$$

$$v = \frac{\omega \frac{\Delta R}{\Delta X}}{1 + \omega C_0\left(\Delta X + \frac{\Delta R^2}{\Delta X}\right)} \quad (5)$$

Measuring the difference from a free space value results in

$$\Delta Z = Z_{total} - Z_{free\ space} = \Delta R + j\Delta X \quad (6)$$

3. Balmain Theoretical Model

Balmain (1964) was the first to develop a relatively simple expression for an antenna in a magnetized plasma. For an antenna immersed in a cold, collisional magnetized plasma

$$Z_{in} = \frac{1}{j\omega\pi\varepsilon_0 L'}\left(ln\frac{L'}{R'} - 1\right) \quad (7)$$

For a short dipole in a plasma by only replacing the effective half length (L) and radius (R), The dielectric tensor contains essentially all of the information about the electromagnetic properties of a plasma.

$$L' = L\sqrt{\epsilon_1 T} \quad (8)$$

$$R' = \frac{R}{2}\left(\frac{\epsilon_1\sqrt{\epsilon_3}}{\sqrt{T}} + \sqrt{\epsilon_1\epsilon_3}\right) \quad (9)$$

$$T = \epsilon_0 \sin^2\theta + \epsilon_1 \cos^2\theta \quad (10)$$

where θ denotes the incident angle of the DC magnetic field. The dielectric tensor for a cold, collisional, magnetized plasma

$$\overline{\overline{\epsilon_r}} = \begin{pmatrix} \epsilon_1 & -j\epsilon_2 & 0 \\ j\epsilon_2 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_3 \end{pmatrix} \quad (11)$$

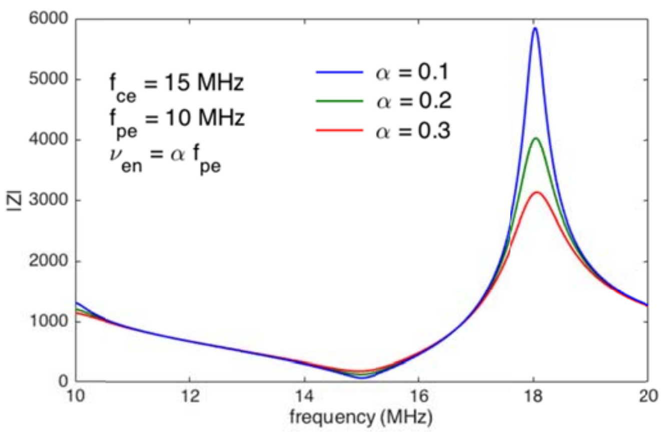
$$\epsilon_1 = 1 - \frac{\omega_{pe}^2(1 - j^{\upsilon}/_{\omega})}{\omega^2(1 - j^{\upsilon}/_{\omega})^2 - \Omega_{ce}^2} \quad (12)$$

$$\epsilon_2 = \frac{\omega_{pe}^2\left({}^{\Omega_{ce}}/_{\omega}\right)}{\omega^2(1 - j^{\upsilon}/_{\omega})^2 - \Omega_{ce}^2} \quad (13)$$

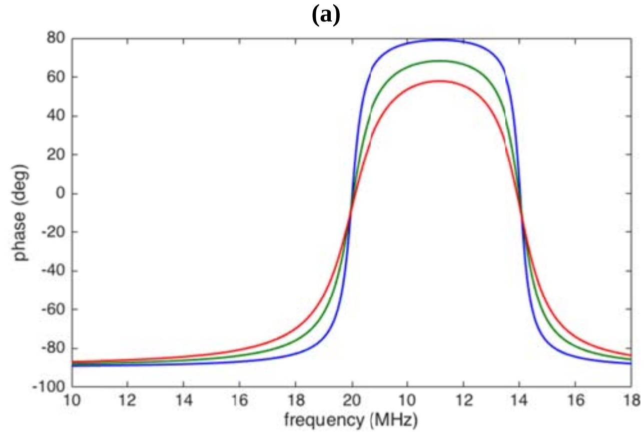
$$\epsilon_3 = 1 - \frac{\omega_{pe}^2}{\omega^2(1 - j^{\upsilon}/_{\omega})^2} \quad (14)$$

The theoretical results using the above-mentioned expressions for various ionospheric conditions are shown in Figures 1 and 2. Specifically, the variation of electron neutral collision frequency on the characteristic curve of antenna input impedance amplitude and phase versus frequency is shown in Figure 1. Figure 1 presents the effect of electron-neutral collision frequency (υ_{en}) on the input impedance characteristic curve. It should be noted that υ_{en} is an important parameter in the Earth's ionosphere and can be used to measure the neutral density. According to Figure 1, as the collision frequency increases the amplitude of the maximum and minimum amplitudes will be reduced. This effect can completely be differentiated from the above-mentioned parameters. Therefore, the spectrum of the antenna characteristic input impedance can be employed to determine the ionospheric plasma parameters with a good accuracy. The input impedance phase data in the frequency domain also validates this effect.

As can be seen in Figure 2, while the minima associated with electron gyro-frequency remains at a fixed point, the maxima location will be shifted according to the upper-hybrid frequency. The peak of the maximum amplitude also becomes stronger by increasing the electron plasma frequency as the electron neutral collision frequency coefficient reduces. This is consistent with the theoretical results presented in Figure 1. On the other hand, with increasing electron gyro-frequency the minima location will be shifted to the right as well as the electron plasma, which provides a great opportunity to discriminate the two effects. Another signature observed in the theoretical results is a peak in the spectrum of the input impedance associated with electron plasma frequency. This also provides a unique opportunity to distinguish the effect of electron plasma frequency and electron neutral collision frequency.

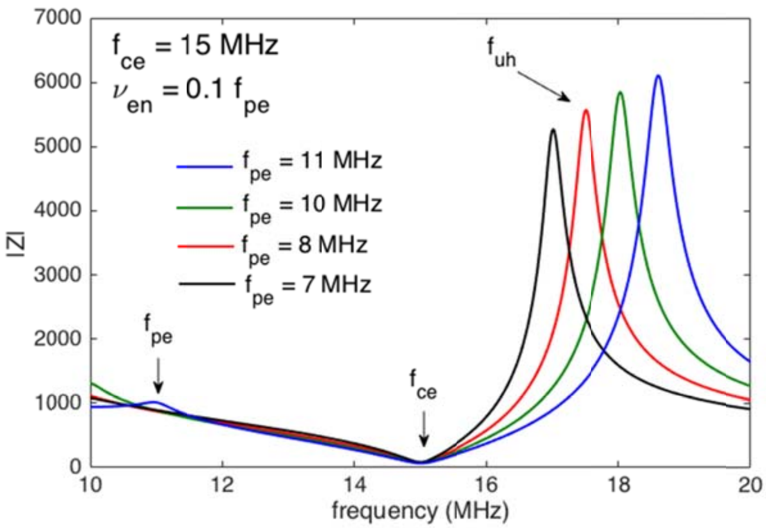


(a)

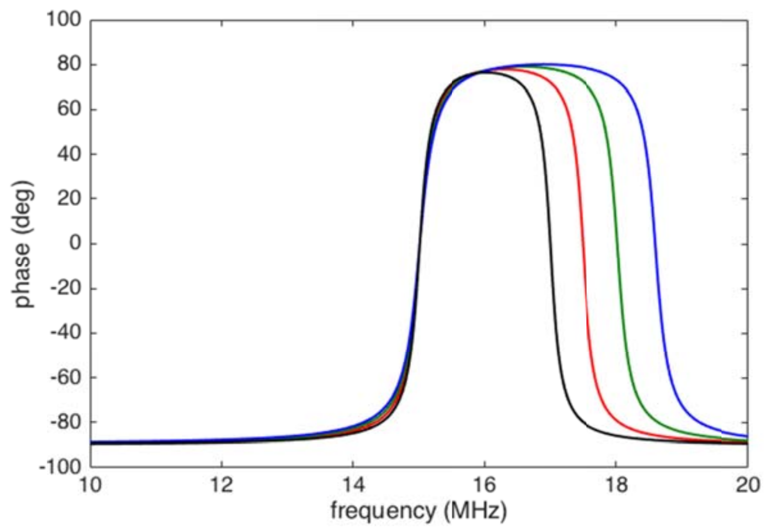


(b)

Figure 1. Variation effect of electron density (electron plasma frequency) on antenna input impedance a) amplitude and b) phase using Balmain theoretical model associated with varying electron neutral collision frequency.



(a)



(b)

Figure 2. Variation effect of electron-neutral collision frequency on antenna input impedance a) amplitude and b) phase using Balmain theoretical model associated with varying electron plasma frequency.

4. Plasma-Fluid Computational Model

While Balmain theoretical model can provide a rough estimate on input impedance of the antenna, a sophisticated computational model to include the temporal behavior of antenna radiation characteristics in the presence of ionospheric plasma will be required. This approach will enhance the exact measurement of ionospheric parameters.

The computational model used in this study is based on the fluid-plasma combined with the Maxwell's equations. The multi ion species plasma is treated with continuity and momentum equations for the plasma density (n_s) and velocity (u_s), respectively. The Maxwell's equations are solved to obtain the time variation of the electric field (E) and magnetic fields (B) generated by the antenna immersed in the plasma. $\upsilon_{S\alpha}$ denotes the collision frequency between the two ion species, and U and m_s represents the velocity and mass for each ion species. As shown below, Equations (14), (15), and (16) are the Maxwell's equation, which are used to determine the variation of electric field, magnetic field and plasma current densities, respectively. Equations (17) and (18) are the continuity and momentum expressions for plasma densities and velocities, respectively, and in the presence of external fields.

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{14}$$

$$\nabla \times B = \epsilon\mu \frac{\partial E}{\partial t} + \mu J \tag{15}$$

$$J = \sum_s q_s n_s u_s \tag{16}$$

$$\frac{\partial n_s}{\partial t} + \nabla.(n_s u_s) = P - L \tag{17}$$

$$m_s n_s \left(\frac{\partial u_s}{\partial t} + (u_s.\nabla)u_s\right) = u_s q_s(E + u_s \times B) - \nabla P_s - m_s n_s \sum_{\alpha \neq s} v_{s\alpha}(u_s - u_\alpha) \tag{18}$$

In order to investigate the input impedance characteristics as the transmission frequency varies, several frequencies should be considered to derive the response of the antenna parameters to the surrounding plasma. Therefore, the antenna response to the derivative of a Gaussian signal is calculated in the simulations to reduce the computational time. The simulated input impedance is then taken in to the spectrum domain to study the response versus frequency. The numerical results using the full computational model of an antenna radiating in the plasma environment is shown in Figure 3.

The figure represents the variation of antenna radiation characteristics including input impedance with varying background electron plasma temperature. According to this figure, it can be seen that electron temperature only starts to play a significant role for energies higher than 5eV that is much higher than the temperatures observed in the ionosphere (T_e << 1eV). Therefore, this probe is capable of determining the effect of high energy electrons. This would expand the applications of the probe to study the active geomagnetic condition in the upper Earth environment as well as the laboratory.

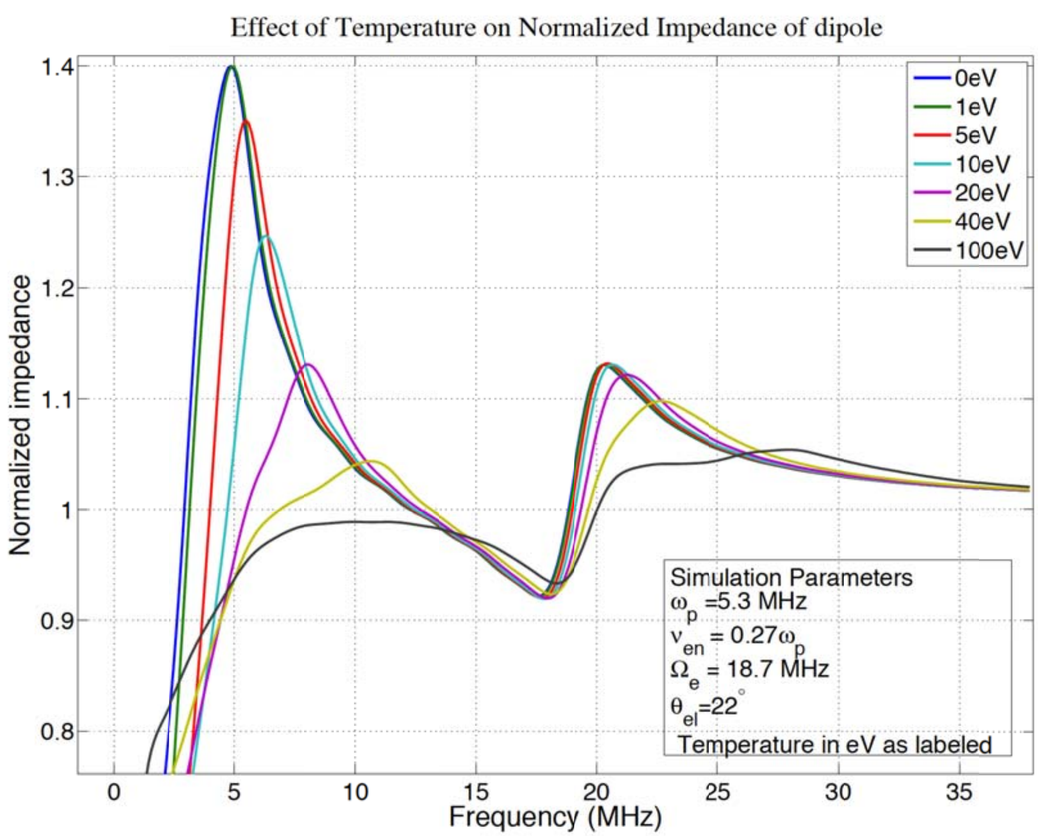


Figure 3. Impedance of a dipole antenna in a homogeneous plasma for different values of electron temperature as simulated by PF-FDTD.

5. Data Reduction

The data reduction technique is designed to measure local parameters of the ionosphere as the rocket passes through this region. This technique will use the observed input impedance and compares it with the theoretical model as well as the computational model in order to determine the altitude profile of electron density and electron neutral collision frequency. It should be noted that υ_{en} is an important parameter to be used for calculating the background neutral density in the mesosphere. Considering the size of required calculations to estimate ionospheric background parameters on each altitude section, the data reduction process will be done using the comparison of the observations with Balmain theoretical model. In this technique, the value of the input impedance including phase and amplitude versus frequency will be used against the Balmain theoretical results in order to determine the possible range of ionospheric parameters. Specifically, the matching criterion of 1) the similarity of the slope input impedance curve versus frequency at frequencies higher than ω_{uh}, 2) the entire curve behavior such as minima and maxima frequencies, and 3) a weighted combination of both will be considered in this study. Then, the estimated values of background plasma parameters through Balmain model will be imported to the computational model in order to determine the exact value of electron density, electron-neutral collision frequency, magnetic field strength and temperature at the corresponding altitude. It should be noted that similar matching criterion will be considered for the comparison of numerical results with the experimental observations.

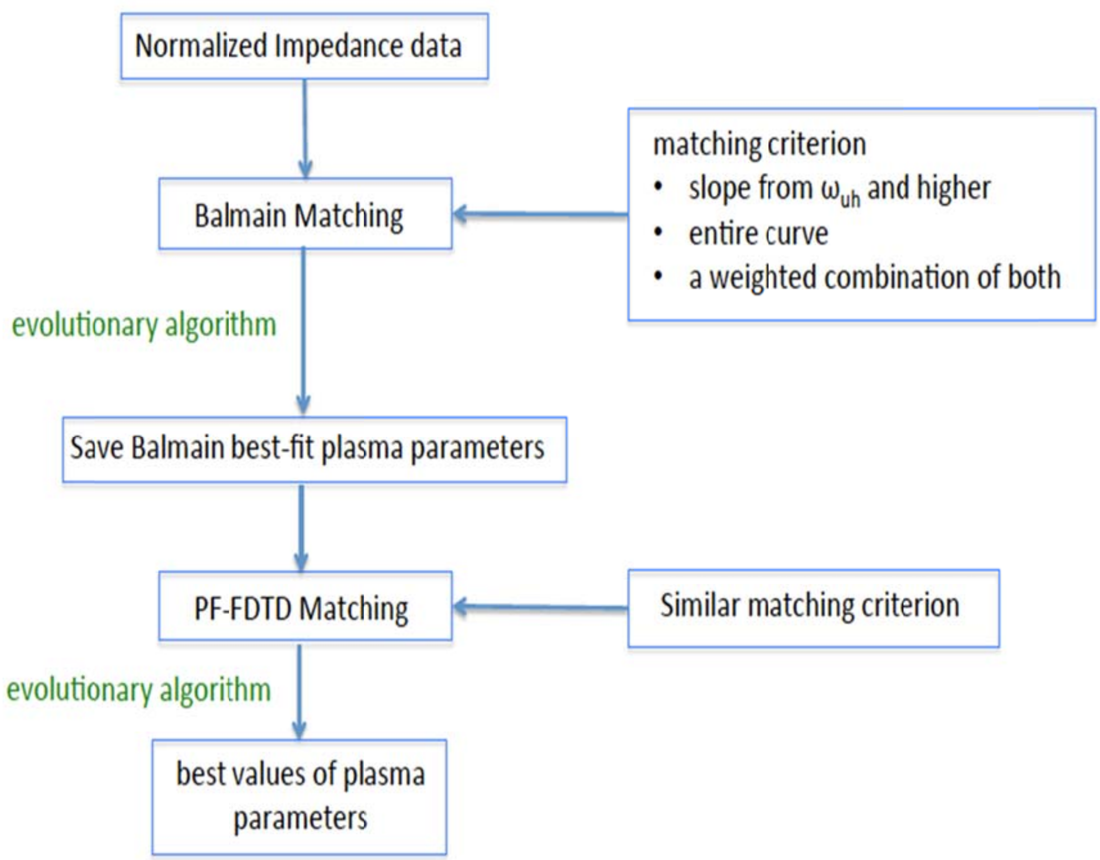


Figure 4. Data reduction technique using the measured impedance data and comparison with the Balmain theoretical model and PF-FDTD model.

6. Conclusion

The theoretical and computational modeling of antenna radiation characteristics such as input impedance in the presence of plasma is investigated for the first upcoming in-situ mesospheric measurement using sounding rockets in Iran. The plasma impedance probe (PIP), an immersed antenna in plasma has been used for local measurements of plasma layer parameters such as plasma density, collision frequency, magnetic field strength and temperature in the near Earth environment.

The background ionospheric parameters will produce a clear signature on the characteristic impedance of antenna versus transmission frequency, which provides a measurement technique for in-situ measurements in the ionosphere using PIP on sounding rockets. It has been shown in this paper that the unique signature of electron-plasma frequency, gyro-frequency and electron-neutral collision frequency on the characteristic impedance of the antenna is distinguishable and can be employed to measure the background ionospheric parameters. A data reduction technique to be used in the actual experiment for measuring background ionospheric parameters is discussed. It has been shown that the best practical approach is to determine an estimated value of parameters using the comparison of Balmain theoretical results and observations. A detailed computational modeling will be used next for exact determination of background parameters.

As part of the pre-mission tests, laboratory experiments are planned to examine the performance of the electronic parts as well as the data reduction algorithm. Having access to magnetized plasma vacuum chamber for the laboratory experiments to verify the PIP observations is critical. There are several plasma laboratory facilities that suit well for the purpose of this study.

The electronics and other parts of the probe are under development. Altitude resolution and corresponding frequency sweep time are being decided. The authors of this paper are currently investigating the broader applications of the plasma impedance probe in complex plasma and in the presence of dust particles for the first time. This study is expected to be used to diagnose natural dust layers in the near Earth environment as well as the laboratory.

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