The RF Impedance Of A Probe In A Plasma With Anisotropic Electron Neutral Collision Frequencies

Piyas Chowdhury, Phanindra S. Rayapati, Edmund A. Spencer, and Saeed I. Latif
University of South Alabama, Mobile, Al 36688, USA (pc2223@jagmail.southalabama.edu, pr2222@jagmail.southalabama.edu, espencer@southalabama.edu, slatif@southalabama.edu)

***Abstract*—The impedance curve for a dipole antenna immersed in the ionospheric plasma can be used to infer the plasma properties such as electron density n_e and electron neutral collision frequency ν_{en}. In the previous research, it is always assumed the ν_{en} identical around the dipole. However, at upper altitudes above 200 km, ν_{en} can be anisotropic, with different values parallel and perpendicular to the ambient magnetic field of the earth. Here we propose the idea of two perpendicular dipole antennas to measure the nonuniform parameters due to anisotropic environment. FDTD simulations have been done to demonstrate the impedance magnitude and phase curve for different values of collision frequencies under parallel and perpendicular orientations of a dipole antenna with respect to the ambient magnetic field. The fact that the parallel component of collision frequency is greater or smaller than the perpendicular component can be recognized through the simulations, and hence through complementary measurements made in the ionosphere with two dipoles, one parallel to the earth's magnetic field, and the other perpendicular to it.**

I. Introduction

Using a plasma impedance probe has become a commonly used technique for measuring the plasma parameters, such as absolute electron density n_e and electron neutral collision frequency ν_{en}, in the ionosphere. In sounding rocket mission, radio frequency (RF) sweeping impedance probes (SIP) are more reliable due to being less affected by spacecraft charging above the electron plasma frequency while ion sheath effects are negligible [1]. By sweeping a sinusoidal voltage for a range of frequencies as well as measuring the current, the SIP measures the small signal AC impedance for the short monopole or dipole antenna immersed in the cold magnetized plasma.

Most previous research works assumed the uniform electron neutral collision frequency around the impedance probe [2], [3]. In the anisotropic space environment, this collision frequency may not be identical. At higher altitudes, above 200 km, the neutral densities drop off rapidly, and the parallel and perpendicular temperatures of the electrons start to be different. This in turn affects the mobility of the electrons and hence the collision frequencies with the remaining neutrals.

We will be capable of extracting the anisotropic effect if we use two dipole antenna: one parallel to the ambient magnetic field and the other perpendicular. In this work, we utilize the FDTD simulation method to investigate this complementary two-dipole hypothesis for the anisotropic medium. To simulate the effect, in the first case the ambient magnetic field is oriented parallel to the probe, and in another case, the field is directed perpendicular to the antenna. In each case, we calibrated the code implementing different electron neutral collision frequencies with respect to the ambient magnetic field (B_o).

II. Ionospheric Conductivities

As a motivation for our study, we briefly describe the influence of the electron neutral collision frequencies on the determination of the Pederson and Hall conductivities in the earth's ionosphere. These conductivities in turn allow the accurate prediction of the currents that flow in the ionosphere that produce magnetic field perturbations measured on the ground. In the presence of a cold magnetized plasma considering electron motions only, the steady-state Langevin equation can be written as [4],

$$-e(\mathbf{E}+\mathbf{u_e}\times\mathbf{B_o})-m_e\nu_c\mathbf{u_e}=0 \tag{1}$$

where $\mathbf{B_o}$ is the ambient magnetic field and from the above equation, an expression for the electron current $\mathbf{J}$ can be derived as,

$$\frac{m_e\nu_c}{n_e e}\mathbf{J}=e(\mathbf{E}+\mathbf{u_e}\times\mathbf{B_o}) \tag{2}$$

For our analysis, we will consider B_o constant and take ν_c different with respect to the ambient magnetic field in the parallel ($\nu_{||}$) and perpendicular ($\nu_\perp$) directions. Solving eqn.(2) we obtain,

$$\begin{pmatrix}J_x\\J_y\\J_z\end{pmatrix}=\begin{pmatrix}\sigma_P & -\sigma_H & 0\\ \sigma_H & \sigma_P & 0\\ 0 & 0 & \sigma_{||}\end{pmatrix}\begin{pmatrix}E_x\\E_y\\E_z\end{pmatrix} \tag{3}$$

In eqn.(3), it has been observed that the Pederson conductivity becomes $\sigma_P=\sigma_\perp=\frac{\nu_\perp^2\sigma_A}{\nu_\perp^2+\Omega_{ce}^2}$, and the Hall conductivity becomes $\sigma_H=\frac{\nu_\perp^2\Omega_{ce}\sigma_A}{\nu_\perp^2+\Omega_{ce}^2}$ where, $\sigma_A=\frac{n_o e^2}{m\nu_\perp}$, $\sigma_{||}=\frac{n_o e^2}{m\nu_{||}}$. In the derivation of the eqn.(3), we consider that the ambient field $\mathbf{B_o}$ is aligned with z-axis. The Pederson and Hall conductivities are different for an anisotropic collision operator compared to isotropic collisions. The perpendicular component is the dominant factor for σ_P and σ_H.

III. Numerical Model And Simulation Results

A full mathematical description of the Plasma Fluid FDTD numerical code that is used in this work can be found in [5]. In the FDTD simulation, Maxwells equations are executed using leap-frog method algorithm, whereas the Auxiliary Differential Equations (ADE) have been applied to linearize and simulate the electron momentum and continuity equations. The code is modified in this work to allow for parallel and perpendicular collision frequencies.

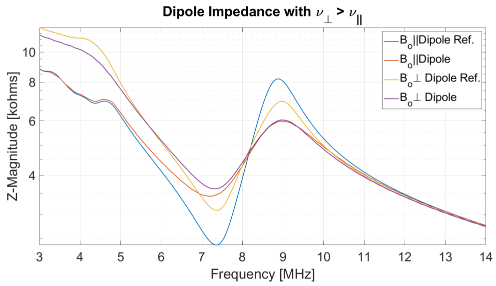

Fig. 1: Dipole impedance magnitude curve when $\nu_{\perp} > \nu_{||}$. The blue and orange curves are when the collision frequency is isotropic, and for the dipole oriented parallel or perpendicular to B_0 respectively.

In the simulation, the plasma parameters are configured as follows: the plasma frequency f_{pe}=5MHz, the cyclotron frequency f_{ce}=7.5MHz and the electron neutral collision frequency $\nu_{en} = 0.1 f_{pe}$ and therefore, the upper hybrid frequency would be f_{uh}=9.01MHz. For the anisotropic condition, we changed collision frequency with respect to B_o such as $\nu_{\perp}$ = $2\nu_{en}$ or $0.5\nu_{en}$ and always $\nu_{||}$=ν_{en}. In this regard, we simulate our plasma environment for two different scenarios; B_o parallel to dipole antenna or perpendicular. In each case, we generate impedance magnitude and phase for the demonstration. Also, we took $\nu_{||}$=ν_{en}=$\nu_{\perp}$ as the reference for the analysis. The dipole antenna remains aligned with the z-axis.

Our purpose here is to show whether the simulation shows a difference when the perpendicular and parallel collision frequencies are the same, or when one is larger or smaller than the other. In the figures, the blue curve is for isotropic ν_{en} when the dipole is parallel to B_o, and the orange curve is for the isotropic case with the dipole perpendicular to B_o. The red and magenta curves show the anisotropic cases $\nu_{\perp} > \nu_{||}$ in Fig.1 and Fig.2, or $\nu_{\perp} < \nu_{||}$ in Fig.3 and Fig.4, under parallel or perpendicular dipole orientation to B_0.

For the magnitude curves, we see that the envelope of the anisotropic cases differ under each of the conditions $\nu_{\perp} > \nu_{||}$ or $\nu_{\perp} < \nu_{||}$, in the region around f_{uh}. When $\nu_{\perp} < \nu_{||}$, the magnitude envelope are above both isotropic impedance curves, for parallel as well as perpendicular dipole orientation. However, when $\nu_{\perp} > \nu_{||}$, the opposite is true.

We also observe that f_{uh} in each case exhibit differences. When $\nu_{\perp} < \nu_{||}$, the f_{uh} for the anisotropic cases are almost the same as the isotropic cases, for corresponding dipole orientations with respect to B_0. However, when $\nu_{\perp} > \nu_{||}$, f_{uh} is equal to the case with perpendicular dipole orientation isotropic case, but higher than the parallel isotropic case.

For the phase curves, we have a slightly different outcome. When $\nu_{\perp} < \nu_{||}$, the phase maximum that lies between f_{ce} and f_{uh} are above and below the parallel isotropic phase curve. However, when $\nu_{\perp} > \nu_{||}$, the anisotropic curve phase maximums are both below the isotropic cases.

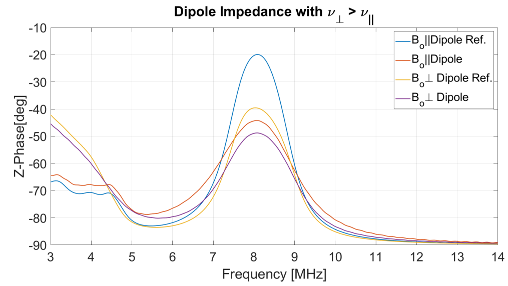

Fig. 2: Dipole impedance phase curve when $\nu_{\perp} > \nu_{||}$.

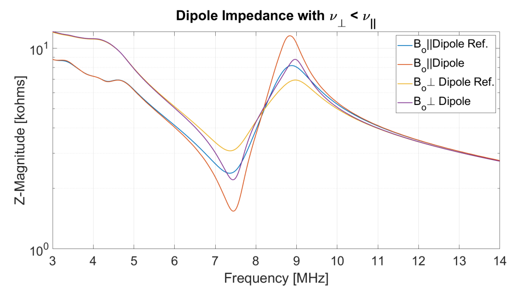

Fig. 3: Dipole impedance magnitude curve when $\nu_{\perp} < \nu_{||}$.

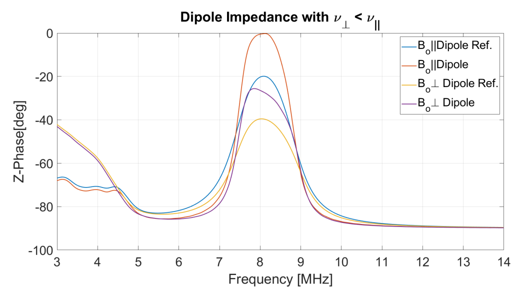

Fig. 4: Dipole impedance phase curve when $\nu_{\perp} < \nu_{||}$.

IV. Conclusions And Future Work

We have shown that it is possible to detect whether a medium is isotropic in collision frequencies, or anisotropic. Furthermore, we also observe that it is possible to distinguish whether the parallel component of the collision frequency is lower or higher than the perpendicular component of collision frequency, from both the magnitude and phase information. As a next step we will include temperature effects into the simulation.

References

[1] B. Oliver, R. Clements, and P. Smy, "Experimental investigation of the low-frequency capacitive response of a plasma sheath," *Journal of Applied Physics*, vol. 44, no. 10, pp. 4511–4517, 1973.

[2] E. Spencer, S. Patra, T. Andriyas, C. Swenson, J. Ward, and A. Barjatya, "Electron density and electron neutral collision frequency in the ionosphere using plasma impedance probe measurements," *Journal of Geophysical Research: Space Physics*, vol. 113, no. A9, 2008.

[3] E. Spencer and S. Patra, "Ionosphere plasma electron parameters from radio frequency sweeping impedance probe measurements," *Radio Science*, vol. 50, no. 9, pp. 853–865, 2015.

[4] J. A. Bittencourt, *Fundamentals of plasma physics*. Springer Science & Business Media, 2013.

[5] J. D. Ward, *The numerical modeling of an antenna in plasma*, 2006.