FDTD Simulations Of The Impedance Of A Dipole Antenna in A Plasma

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***Abstract*—The impedance of a dipole antenna in the earth's ionospheric plasma is dependent on the ambient plasma properties such as electron density and electron neutral collision frequency. Depending on the length of the dipole, it is possible to not only measure the plasma properties, but in addition, receive plasma waves that are found propagating in the ionosphere. Here we report on some FDTD simulations of a dipole antenna in a cold plasma, and present some approximate expressions that can be used to analyze this behavior. When the dipole antenna resonant wavelength $\lambda/4$ and associated frequency is far from the upper hybrid, cyclotron and plasma frequencies of the local plasma, the expressions work fairly well. However, when the length of the antenna is such that it's resonant wavelength coincides or is close to the plasma resonances, the expressions fail, and a full-wave FDTD simulation has to be performed to extract meaningful plasma data.**

I. Introduction

A plasma impedance probe is an instrument that derives the absolute electron density and other plasma parameters by applying a known input voltage, usually sinusoid, across the probe terminals, varying the input frequency, and measuring the current through the probe at each frequency to obtain the impedance of the plasma-probe configuration. In a magnetized cold plasma at electron scales $\omega \approx \omega_{pe}$, certain resonances can be clearly observed which are proportional to the electron cyclotron frequency Ω_{ce} and the upper hybrid resonance ω_{uh}. These two frequencies are related to the the absolute electron density n_e through the relations $\omega_{uh}^2 = \omega_{pe}^2 + \Omega_{ce}^2$ where $\Omega_{ce} = eB_0/m_e$ is the electron cyclotron frequency, and $\omega_{pe} = n_e e^2/m_e\epsilon_0$ is the electron plasma frequency. The electron charge, electron mass and permittivity of free space are e, m_e, and ϵ_0 respectively. By sweeping through a physically relevant range of frequencies for a particular plasma, the impedance magnitude and phase characteristics can be used to infer n_e and other parameters such as the electron neutral collision frequency ν. This is the method employed on sounding rocket experiments [1],[2]. In these instances, the probe is called a Sweeping Impedance Probe (SIP). Examples of SIP measurement from a sounding rocket matched to theory and simulations can be found in [2].

If the impedance probe boom is made longer, it will be able to efficiently receive plasma waves that exist in the ionosphere. The key factor in achieving this functionality is to tune the dipole antenna impedance that is minimum at approximately $\lambda/4$ to coincide with the received signal frequency of interest. Although reciprocity does not hold generally in an anisotropic medium, for a magnetized plasma it holds when the ambient magnetic field B_0 is reversed in sign [3].

II. Antenna-Plasma Impedance Theory

The instrument measures impedance to electron electrostatic modes ($\vec{k} \parallel \vec{E}$), electron electromagnetic modes ($\vec{k} \cdot \vec{E} = 0$) as well as electron plasma modes propagating at arbitrary angles [4]. The dispersion relations governing each of these modes can be obtained through algebraic manipulation of the fourier transformed relations.The electrostatic resonance parallel to $\vec{B_0}$, ($\vec{k} \parallel \vec{E}$), $T_e = 0$, is given by,

$$\omega^2 = \omega_{pe}^2 \tag{1}$$

The electrostatic resonance perpendicular to $\vec{B_0}$ ($\vec{k} \parallel \vec{E}$), $T_e = 0$ is the Upper Hybrid Resonance given by,

$$\omega^2 = \omega_{pe}^2 + \Omega_{ce}^2 \tag{2}$$

These resonances are emphasized depending on probe orientation parallel or perpendicular to the ambient magnetic field $\vec{B_0}$. The electromagnetic resonance that is most clearly observable in the impedance curves is the resonance due to the right hand circularly polarized wave propagating along $\vec{B_0}$. Solving for this particular mode gives,

$$\frac{c^2 k_z^2}{\omega^2} = \frac{\omega_{pe}^2}{\omega(\Omega_{ce} - \omega)} \tag{3}$$

which yields a clearly observable resonance trough at $\omega = \Omega_{ce}$,. This is where energy is most effectively coupled into the plasma. Of the three linear resonances described, the Upper Hybrid Resonance (UHR) frequency resonance and the cyclotron frequency resonance are the most clearly observable. When the probe dimensions are much smaller than the shortest wavelengths of interest, we can derive the basic behavior by considering a parallel plate capacitive structure immersed in a plasma. The analysis does not include the self-consistent induction field from Faradays law. The perpendicular impedance, $Z_\perp(s) = V(s)/I_\perp(s)$ is given by,

$$Z_\perp(s) = \frac{\Omega_{ce}^2 + (s+\nu)^2}{sC_0[(s+\nu)^2 + (\omega_{pe}^2 + \Omega_{ce}^2)] + C_0\nu\omega_{pe}^2} \tag{4}$$

we note the appearance of the upper hybrid frequency, $\omega_{uh}^2 = \omega_{pe}^2 + \Omega_{ce}^2$, as a resonance in the impedance when $\nu = 0$.

When the antenna is electrically long, the natural antenna resonances start to move down the frequency spectrum intil they coincide with the regions where the plasma resonances occur. When the first minimum is about twice the plasma upper hybrid frequency, we can approximate the behavior by superposing a transmission line approximation for the dipole to a second order approximation of the plasma response, given by,

$$Z(L) = \left(\frac{\omega_{n2}^2}{sC_0\omega_{n1}^2}\right)\left(\frac{s^2 + 2\eta_1\omega_{n1}s + \omega_{n1}^2}{s^2 + 2\eta_2\omega_{n2}s + \omega_{n2}^2}\right) j\cot(kL) \quad (5)$$

When the antenna length is long enough such that the resonances overlap, the approximation above fails, and we resort to FDTD simulations to obtain the antenna behavior.

III. Simulation Results

Maxwells equations are simulated using the standard Yee lattice and leap-frog method, while the electron momentum and continuity equations are linearized and simulated employing the Auxiliary Differential Equations (ADE) technique. Details can be found in [5]. If in the vacuum case we let the dipole antenna impedance be approximated by an open circuited transmission line, the first impedance minimum (Antenna resonance) will occur when the applied frequency $f = c/4L$ where c is the speed of light, and L is the probe arm length. For example, when the dipole is 5 meters in length, $L = 2.5$ m, and the minimum should occur when $f = 30$ MHz using a transmission line approximation. In the simulation, when no plasma is present, the actual dipole antenna gives the minimum to be about 24.95 MHz. This is shown in Fig. 1. The simulated response of the antenna when the plasma is present, is also shown in Fig. 1. For all cases shown, the plasma parameters are as follows: The plasma frequency $f_{pe} = 5$ MHz, the cyclotron frequency $f_{ce} = 7.5$MHz, and the electron neutral collision frequency $\nu_{en} = 0.1 f_{pe}$. The upper hybrid frequency will be $f_{uh} = 9.01$MHz. We observe a clear impedance minimum at 7.5MHz corresponding to f_{ce}, and a clear maximum at 9.1MHz corresponding to f_{uh}. A barely discernible bend in the impedance curve occurs at f_{pe}.

In Fig. 2 and Fig. 3, we show three different curves, for different lasma frequencies, together with the vacuum case. This is the case when the dipole antenna resonance overlaps the plasma resonances. The plasma cyclotron frequency minimum appears to be shifted from 7.5 MHz to about 5.8 MHz, but it is not coincident with the antenna resonance in vacuum, and a second minimum occurs after the upper hybrid frequency, around 10.5 MHz. Although this behavior does not follow equation 5, we are still able to obtain the plasma parameters, as long as we run full wave simulations to match against data. Data will be available from a NASA USIP 2U CubeSat that will be launched from the ISS in 2020.

Acknowledgement

References

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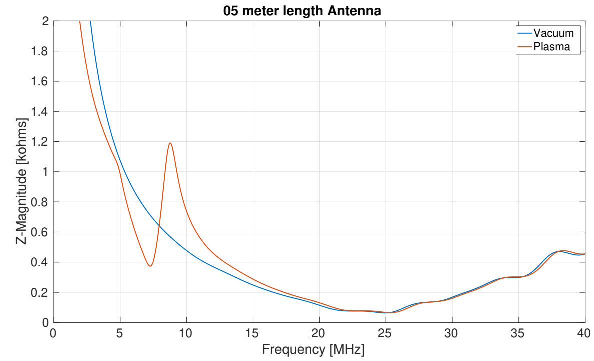

Fig. 1. Impedance of a 5m dipole immersed in a cold plasma from a FDTD simulation. Cyclotron and upper hybrid frequencies are observable. Antenna resonance is far from plasma resonances.

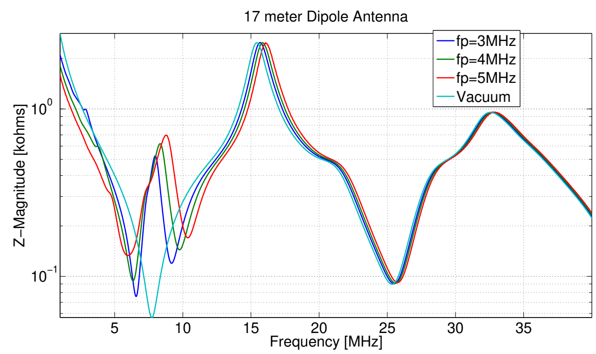

Fig. 2. Impedance magnitude of a 17 m dipole in a plasma for 3 different plasma frequencies.

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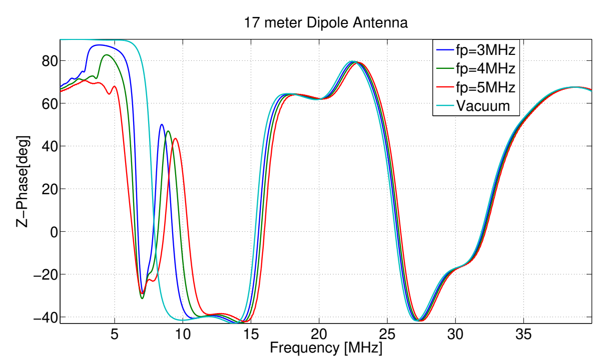

Fig. 3. Impedance phase of a 17 m dipole in a plasma for 3 different plasma frequencies.