Numerical Simulation of a combined Time Domain Impedance Probe And Plasma Wave Receiver System For Small Satellite Applications

Sai Krishna Vadepu, Edmund Spencer, Riley Mayes
Department of Electrical and Computer Engineering
University of South Alabama
Mobile, Alabama, USA
sv1522@jagmail.southalabama.edu, espencer@southalabama.edu, ram1724@jagmail.southalabama.edu

***Abstract*— A Plasma Impedance Probe measures electron density and electron neutral collision frequencies in the ionosphere. This instrument has been tested on a sounding rocket flight and is now being further developed to fly on a NASA Undergraduate Student Instrument Program (USIP) cubesat to be launched out of the ISS in 2019. Here we report on the development of a new combined PIP and plasma wave instrument from a computational perspective. The new instrument can be used on cubesat platforms to measure local electron parameters, and also to receive or transmit electron scale waves. Two dipole antennas will be used. One is optimized for impedance measurements, while the other is optimized for transmitter-receiver performance. Here we use Finite Difference Time Domain (FDTD) simulations of an electrically long antenna immersed in a magnetized plasma to analyze the configuration.**

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. These two frequencies are related to the absolute electron density n_e through the relations

$$\omega^2_{uh} = \omega^2_{pe} + \Omega^2_{ce} \quad (1)$$

where $\Omega_{ce} = eB_0 / m_e$ is the electron cyclotron frequency, and $\omega_{pe} = n_e e^2 / m_e \varepsilon_0$ 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 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. It is commonly used in laboratory experiments, and this is the method employed on sounding rocket experiments [1],[2]. Examples of Sweeping Impedance Probe 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 a minimum at approximately λ/4 to coincide with the wave length of the received signal 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 [3]. We thus are interested in how the antenna impedance in a cold magnetized plasma varies as a function of dipole length.

II. Plasma Fluid Finite Difference Time Domain Simulations

In our simulations, the antenna is immersed in a cold, magnetized and collisional plasma using a fluid approximation, and further, that the frequency content ω of any excitation of the plasma is much higher than the ion plasma frequency, ω_{pi}, such that ion dynamics can be neglected. Since the electron thermal velocities are much higher than the spacecraft velocity, we also neglect the spacecraft velocity V_s. The dynamical equations for electron motion in the region around the probe are then given by the continuity and momentum equations with Maxwell's equations. The code used was developed by [4].

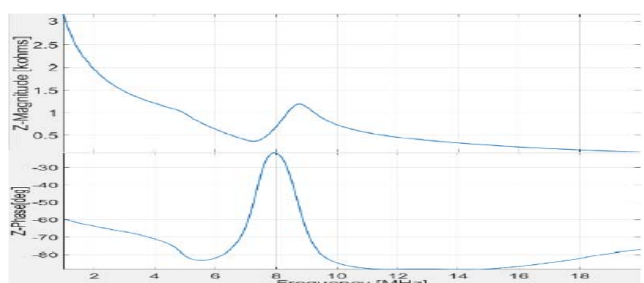

Figure1: Impedance magnitude and phase obtained from the FDTD Simulations by dividing the Fourier transform of voltage with the Fourier transform of current. The plasma frequency is 5Mhz, the cyclotron frequency is 7.5Mhz, and the upper hybrid frequency is 9.1Mhz.

III. Results for a FDTD simulations for a long dipole antenna immersed in a cold magnetized plasma.

When working as a plasma wave receiver the dipole must be optimized to receive waves at the antenna resonant frequency. Here the dipole impedance is used as a proxy for antenna efficiency. A long dipole immersed in a cold magnetized plasma can to first order be approximated by a transmission line with its characteristic impedance Z_0 replaced with the plasma dielectric response. When the plasma resonances are far away from the first antenna resonance, the impedance is approximately given by,

$$Z(x) = \frac{1}{sC_0}\left(\frac{\omega_{n2}^2}{\omega_{n1}^2}\right)\left(\frac{s^2 + 2\zeta_1\omega_{n1}s + \omega_{n1}^2}{s^2 + 2\zeta_2\omega_{n2}s + \omega_{n2}^2}\right)(j\, cot(kx))$$

ω_{n1}, ζ_1 correspond to the cyclotron resonance, while ω_{n2}, ζ_2 correspond to the upper hybrid resonance. However, as the antenna resonance approaches the plasma resonances, this quasi-superposition is no longer valid.

In all our cases the antenna (dielectric material) is placed in a computational volume of a 5.6meter cube, (140*140*130 cells, with each cell size, dx=dy=dz= 0.4m), with Plasma Frequency (fpe): 5MHz, Collision Frequency: 0.5MHz. Cyclotron Frequency (fce): 7.5MHz, and Upper hybrid frequency (fuh): 9.1MHz.

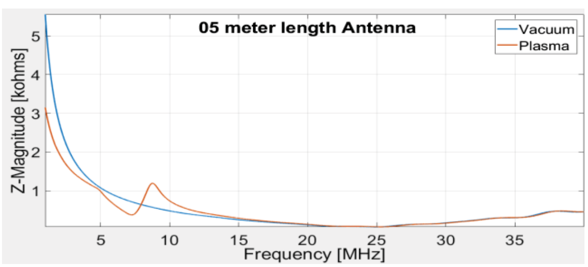

Figure2: Impedance of a 5m dipole the FDTD simulation. Note that the cyclotron and upper hybrid frequencies are observable when the antenna resonance is far from plasma resonances.

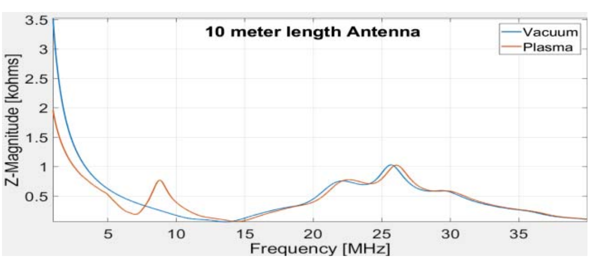

Figure3: Impedance of a 10m dipole the FDTD simulation. Note that the cyclotron and upper hybrid frequencies are observable when the antenna resonance is far from plasma resonances.

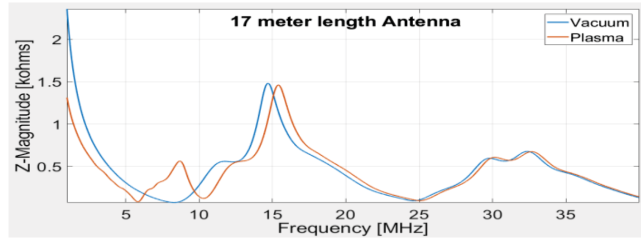

Figure4: Impedance of a 17m dipole from the FDTD simulation. Here cyclotron frequency not clearly apparent and the upper hybrid frequency is shifted. Here Antenna resonance almost coincides with the original upper hybrid frequency at 9.1Mhz.

For different lengths of antennas, the minimum impedance is shifts towards the electron cyclotron frequency as the length increases. We observe in Fig. 2 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. 3, the antenna resonance is at 14.4MHz, but we are still able to observe the plasma resonances, and the plasma parameters can be accurately found from observation of the resonant frequencies. However, in Fig. 4, the behavior changes dramatically. Now 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 10.5MHz. When the antenna resonances coincide with the plasma resonances, the total impedance cannot be obtained by a simple superposition of the impedances. This means that we will have to run a complete numerical simulation or create an equivalence table to estimate the plasma parameters whenever a long dipole is used as a Plasma Impedance Probe.

IV. Conclusion

We have explored the performance of a dipole antenna immersed in a plasma for frequencies comparable to the antenna dimensions. Using these results as a starting point, we can further optimize the antenna for probe-receiver performance, or possibly introduce a different antenna topology to increase receiver bandwidth. This is left for future work.

V. References

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