PLASMA IMPEDANCE PROBE DIAGNOSTICS: MODEL AND DATA

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Abstract

The electrical impedance of an antenna exposed to the space environment is dependent upon the parameters of the space plasma in which it is immersed. This effect can be used as a diagnostics for electron density, collision frequencies, etc. Utah State University has recently flown a number of Plasma Impedance Probes on sounding rockets with NASA including dipoles, monopoles, and patch antennas. There are several analytic theories for the impedance of monopole or dipole antenna in space plasma. There are no analytic theories for a patch antenna. Utah State has developed a Plasma Fluid Finite Difference Time Domain (PF-FDTD) simulation that can be used to model various antenna geometries. Antenna impedance data from various geometries are presented and compared with analytic and the PF-FDTD simulation. Preliminary results of the extraction of electron density, electron neutral collision frequency, and electron temperature along the rocket trajectory are presented.

Introduction

The impedance characteristics of an antenna immersed in ionospheric plasma have been extensively studied. Balmain [1] developed one of the most well known theories. He treated the cold plasma as an anisotropic dielectric and assumed a proscribed triangular current distribution along the antenna. Under an electrostatic assumption Balmain was able to compute the induced fields around the antenna from which the input impedance was calculated through conservation of power. His relatively simple expression relates the electron density, electron neutral collision frequency, and the DC magnetic field to the input impedance of an antenna. This theory has been used to deduce ionospheric plasma parameters from antenna impedance measurements and shows relatively good agreement with measurements for frequencies above about twice the cyclotron frequency [Cite]. Other theories have been developed for warm plasmas [2] and the extension to electrically long antennas [3]. Nakatani and Kuehl developed a theory for warm kinetic magnetized plasmas but could only provide closed form solutions for propagating frequency regions [4]. A very complete theory has been produce by Meyer-Vernet [5] for warm, unmagnetized plasmas that has application to the solar wind but not the ionosphere.

Recently a Plasma Fluid Finite Difference Time Domain model (PF-FDTD) has been developed. The model numerically solves, through use of finite differencing techniques, the 5-moment fluid equations for magnetized plasma. This enables a full wave, self consistent, calculation of the fields and currents on the antenna, from which input impedance of the antenna can be determined. While memory, processor speeds, and the Courant condition limit the frequency resolution of the simulation, it still remains possible to observe both electron and ion plasma resonances effects on antenna impedance. The PF-FDTD also enables the analysis of the current distribution along the length of the antenna, and provides a design tool to optimize the plasma effects on the probe [6].

This paper presents an overview of some of the recent measurements by Utah State University of antenna systems in magnetized ionospheric plasmas. These measurements have been obtained on three different sounding rocket programs in 1998, 2003, and 2004. The analysis of these data sets are on going and some preliminary data is presented within this paper including observations of the impedance of dipole antennas in the D and E regions of the ionosphere at electron plasma and cyclotron as well as ion resonance frequencies. We also present observations of a monopole and surface patch antenna at electron frequencies. We note that all of these antenna geometries show strong effects on input impedance due to the presence of ionospheric plasma.

SAL flight and data

The Sudden Atom Layer (SAL) payload was launched February 1998 at 20:09 LT from Puerto-Rico into the nighttime D- and E- regions. The experiment was conducted in conjunction with Cornell University and the University of New Hampshire. Measurements were made in the D and E regions of the ionosphere or from about 90 km to about 115 km. The mission was a study of neutral metallic layers, such as sodium, which spontaneously occur at the base of the ionosphere (90 km) and are routinely observed by LIDAR.

The antenna for these measurements consisted of two booms deployed 180 degrees apart with a 3 meter tip to tip length and a 2.54 cm diameter. The last 52.5 cm of booms were used as the active elements of the antenna. The antenna was driven with a 1 volt sinusoidal signal at forty different fixed frequencies from 200 kHz to 12 MHz. The magnitude of the current flow to the antenna was recorded at each of these frequencies in a sweep lasting 5 ms.

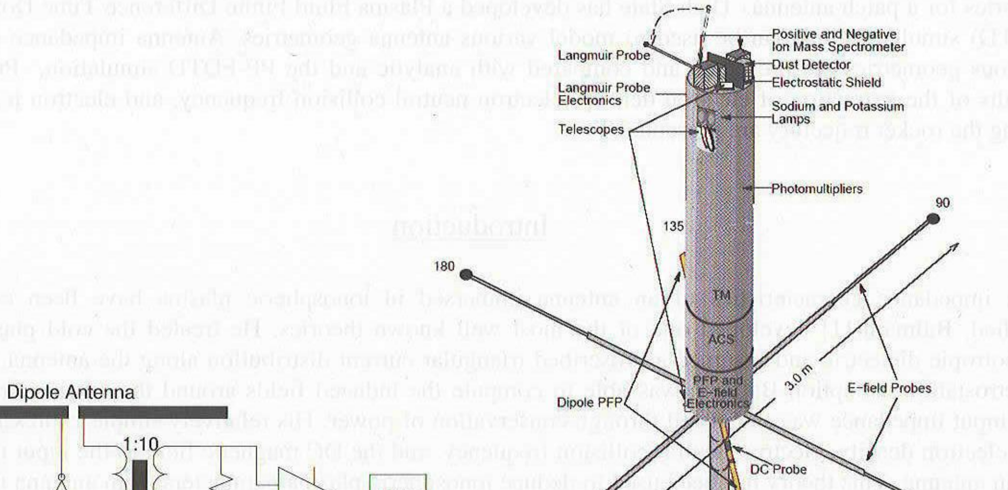

Figure 1 Instrumentation for SAL and payload layout.

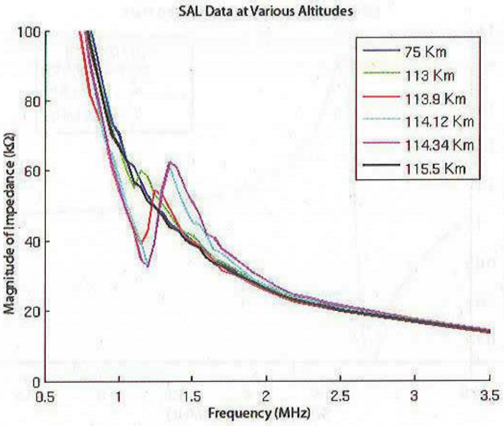

Figure 2 Sample data from SAL at different altitudes. Data at 75 km is used as the free space impedance measurement of the antenna or Z_{ref}.

The current flowing to the antenna was monitored using a RF current transformer as illustrated in **Figure 1**. The load impedance, on the transformer consisted of a 1 KΩ resistor in parallel with a 3 pF capacitor. The instrument was calibrated pre-flight without the dipole antenna using a series of resistors and capacitors. The measured data at several different altitudes is shown in Figure 2.

The data analysis approach was to compare the measured data to theory for antenna impedance in cold collisional magnetized plasma. A non-linear least squares fit was used to find the unknown plasma parameters of plasma frequency, electron cyclotron frequency and electron neutral collision frequency. The data can be considered a combination of three impedances; the antenna free space impedance, Z_o, the contribution due the plasma, Z_p, and instrumentation plus shunt contributions, Z_i.

$$\text{Data} = \left| Z_i + Z_o + Z_p \right|$$

The free space impedance plus instrument effects were best fit as a parallel R-L-C circuit, Z_{ref}, where C=2.85 pF, L=41.2 mH, and R=206 KΩ.

Balmain's theory for the impedance of an antenna in cold, collisional, magnetized plasma was used as a model. The impedance of this model is a function of three parameters; the plasma frequency, ω_p, the electron cyclotron frequency, Ω_e, and the electron neutral collision frequency ν_e.

$$Z_{Balmain}(\omega_p, \Omega_e, \nu_e) = Z_p + Z_o$$

The ratio of change, due to the ionospheric plasma, from free space impedance was computed by normalizing the data with a sweep at low altitude where the contribution of the plasma to the impedance would be small.

$$\frac{\text{Data}}{\text{Data}_{ref}} = \left| \frac{Z_i + Z_o + Z_p}{Z_i + Z_o} \right| = \left| \frac{Z_p}{Z_i + Z_o} + 1 \right|$$

This normalized data was fit using a least squares approach with a normalized to free space model

$$\left| \frac{Z_{Balmain}(\omega_p, \Omega_e, \nu_e) - Z_o}{Z_{ref}} + 1 \right|$$

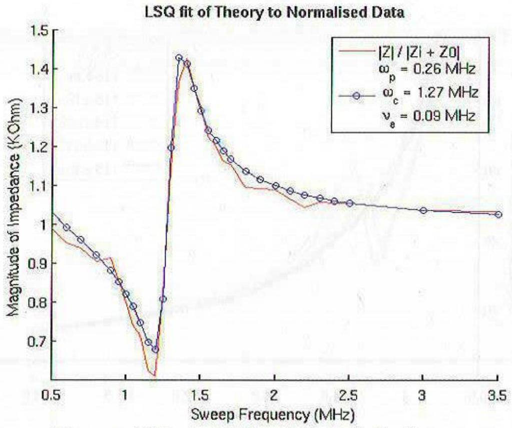

Figure 3 Data fit by Balmain's theory

where Z_o was computed from Balmain's theory for $\omega_p \to 0$. An example data sweep and fit are shown in Figure 3.

Electron density was computed from the fit for plasma frequency and is plotted along with the current from the DC probe in Figure 4. The DC probe data has been normalized to the impedance data at maximum density. The signatures of the metallic atom layer at about 92 km altitude in both the up and down legs are clearly observable. We believe the payload charged while passing through the layer such that the DC probe experienced a ground reference shift and did not observe a strong signature of the layer. The strong spin modulation in the data from both instruments is due to the sensing element passing through the spacecraft wake.

E-Winds Flight and Data

On July 1, 2003, two different Plasma Impedance Probes where flown on a series of four sounding rockets that were launched at 3:19, 5:41, 6:50 and 7:07 UT on July 1, 2003 from Wallops Island, Virginia into the nighttime D- and E-regions, in conjunction with the University of Texas at Dallas (UTD) and Clemson University. These rockets were part of the "Sequential Rocket Study of Nighttime Descending Layers" (E-Winds). The first instrument operated at electron frequencies (0.5 to 20 MHz) while the second operated at ion frequencies (1-60 kHz). Both instruments used a quasi logarithmic distribution of 256 sample frequencies, with the ion sweeping at a much lower rate. The PIP operating at electron frequencies provided data throughout the flight while it was not until the probe entered a dense layer, that the Ion frequency probe measured something similar to the lower hybrid resonance as seen in the PF-FDTD simulations. Sample data from the electron and ion instruments are shown in Figure 5.

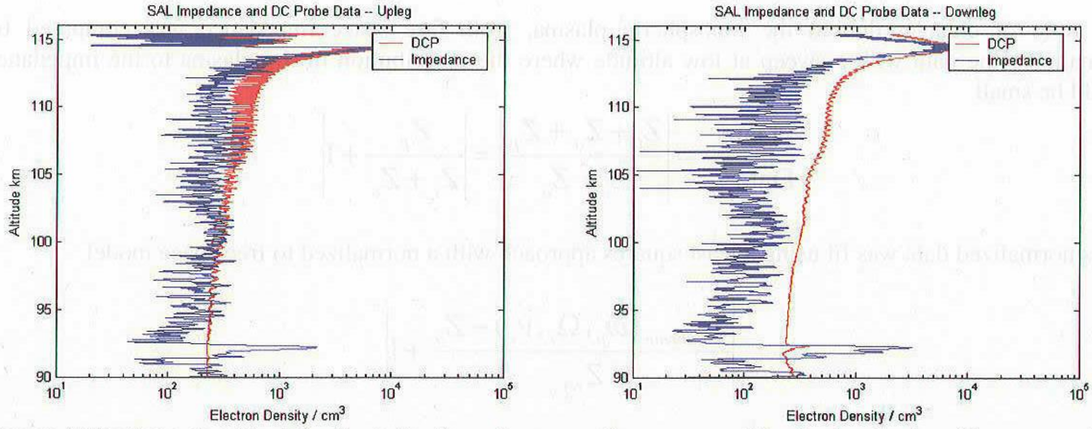

Figure 4 Electron density data from the impedance probe compared to electron saturation current.

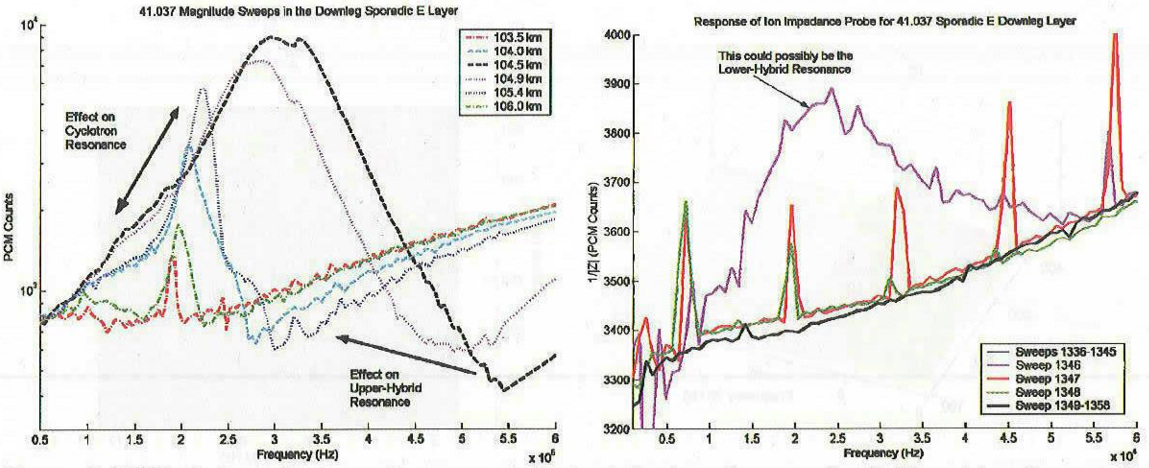

Figure 5 E-Winds impedance probe measurements at electron frequencies (left) and ion frequencies (right).

Kwajalein Flight and Data

On August 7, 2004 and August 15, 2004, two types of Plasma Impedance Probes where flown as part of NASA's Rocket Investigation "Winds Scattering Layers in the Bottom side Equatorial F-Region Ionosphere". These launches were conducted at Kwajalein Flight Facility, South Pacific, in conjunction with the University of Texas at Dallas (UTD) and Clemson University. The first PIP was a monopole boom stowed inside a faring / nose cone for the first 98 km of the flight and then exposed for the remainder. The second PIP made use of an experimental patch antenna that was mounted on the side of the rocket and is exposed for the entire flight. The configuration of these probes is shown in Figure 6.

The monopole used a distribution of 256 sample frequencies; the patch used 32 frequencies sampled at the same rate as the dipole. Data from both instruments are shown in Figure 7. Data for the monopole antenna are saturated at high altitude where the impedance of the antenna became very large and therefore the current drawn from the instrument very small. Thus the double humped features in the impedance sweeps above 400 km are suspect. The comparison between the patch impedance magnitude and the monopole impedance magnitude show similar features thus enabling the concept of using a surface path antenna for future impedance probes.

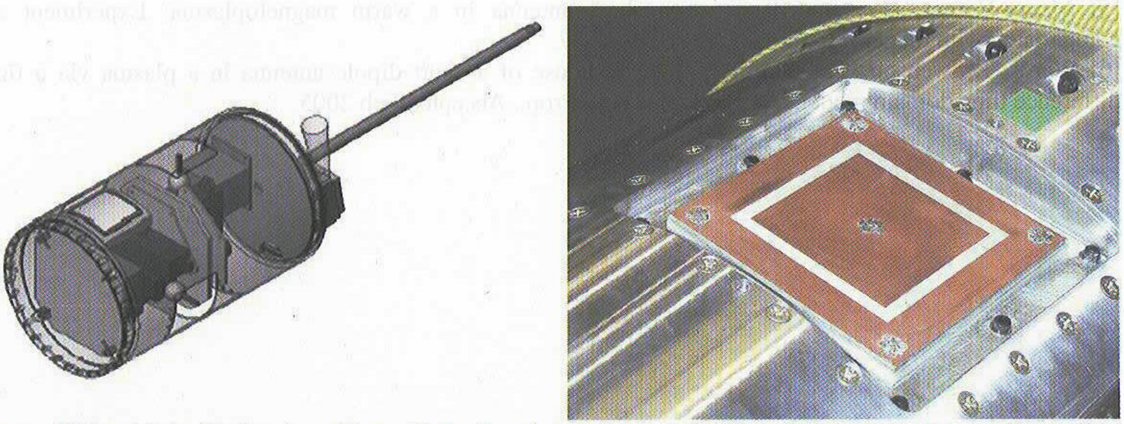

Figure 6 Kwajalein Payload configurations showing monopole (left) and surface patch configuration (right).

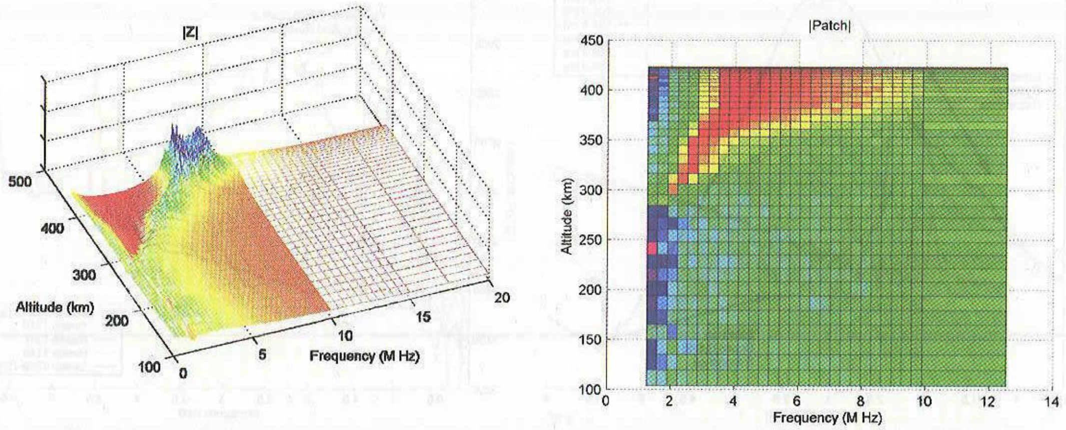

Figure 7Data from Kwajalein instruments. Left; plot of impedance for monopole antenna. Right; plot of impedance sweeps for experimental patch antenna

Summary

Within this paper we have presented a brief qualitative overview of a number of impedance probe data sets obtained on sounding rockets both low in the nighttime D- and E-regions of the ionosphere and high in the F-region where changes from the free space impedance are dramatic. These data sets were obtained with dipole, monopole, and surface patch antennas. At electron frequencies all the data show similar fetchers that have been previously described by Balmain [1]. Observations at lower frequencies where ion resonances would be expected to become important have been made. Further analysis will be needed to verify these results. Utah State is currently exploring these data sets and developing a PF-FDTD code to analyze geometries, such as the patch, and frequency regions where analytic theories do not apply.

References

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