A Circuit Model for the Interaction of an RF Impedance Probe with Ionospheric Plasmas in the E-Layer and F-Layer Ionosphere Regions

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***Abstract*—We analyze Sweeping Impedance Probe (SIP) measurements which were made by the payload of the STORMS sounding rocket, launched from Wallops Island, Virginia, in 2007. The objective of the STORMS mission was to establish whether density irregularities observed in midlatitude spread F could arise from ionospheric coupling to terrestrial weather. The instrument measures both the magnitude and phase of the AC impedance from 100 kHz to 20 MHz in 128 frequency steps, performing 45,776 sweeps over the entire flight. Using a fluid formulation for the impedance of the plasma, we modify the interaction by introducing a sheath capacitance and additional conductivity elements in order to fit circuit models against the data obtained at different altitudes. From these measurements, we will be able to infer both the absolute electron density and the electron neutral collision frequencies throughout the flight trajectory. The models have to be altered as the payload moves through different ionospheric layers because the sheath capacitance and parallel conductivities become prominent depending on the local properties of the ionosphere around the probe structure. Our model is found to robustly and consistently fit to the data, accounting for all the observations over both the upleg and downleg of the payload trajectory.**

I. Introduction

Nowadays, it is a common technique to use a plasma impedance probe for measuring the plasma parameters in the ionosphere in particular the absolute electron density n_e and electron neutral collision frequency ν_{en}. To obtain plasma electron densities in the ionospheric E and F layers, the dipole configurations of plasma impedance probes have been used on sounding rocket missions [1], [2]. In this regard, radio frequency (RF) sweeping impedance probe (SIP) are more robust compared to DC Langmuir type instruments because the AC instrument is not influenced by the potentials induced by spacecraft charging at time scales above the electron plasma frequency when the ion motion and the sheath effects are negligibly small [3].

The SIP measures the small signal AC impedance of a monopole or dipole antenna traveling through the plasma by varying a sinusoidal voltage over a defined range of frequencies and reading the resultant current measured at the terminals. Under a cold fluid approximation, the impedance that is obtained as a function of frequency contains resonant regions that are connected to the plasma frequency f_{pe}, the electron cyclotron frequency f_{ce}, and the upper hybrid frequency f_{uh}. The resonances can be roughly represented by the usual fundamental series and parallel RLC circuit resonances from electric circuit theory. The combined impedance of the antenna immersed in the ambient plasma is normalized with respect to the impedance when placed in a vacuum, which is typically only capacitive when the antenna probe dimensions are short compared to cold fluid plasma electrostatic and electromagnetic wavelengths. When the normalized impedance magnitude curve is analyzed, the series resonance around f_{ce} produces a minimum in impedance magnitude, while the parallel resonance around f_{uh} produces a maximum in the impedance magnitude. Using a relation between f_{ce}, f_{pe}, and f_{uh}, we can obtain the absolute plasma density directly.

In [4], the authors explained the SIP data analysis which was measured by the instrument payload suite on the STORMS rocket mission, that was launched from Wallops Island, Virginia, in 2007. In that paper, they described and analyzed the impedance magnitude and phase data obtained from a monopole probe structure that was integrated into the Tropical STORMS payload. The SIP measured impedance phase and magnitude on the upleg and downleg, reaching maximum altitudes close to 400 km.

At the lower altitudes (around 100 km and up to 200 km) the instrument made measurements that could be roughly explained by the standard cold plasma fluid theory in both magnitude and phase. Above 261 km both the magnitude and phase data could not be easily understood because the series resonance was shifted unnaturally and anomalous damping effects appeared that could not be analyzed with the basic cold plasma fluid theory. Interestingly, they were able to obtain the variation of electron density and electron neutral collision frequency with respect to altitude by interpreting the zero

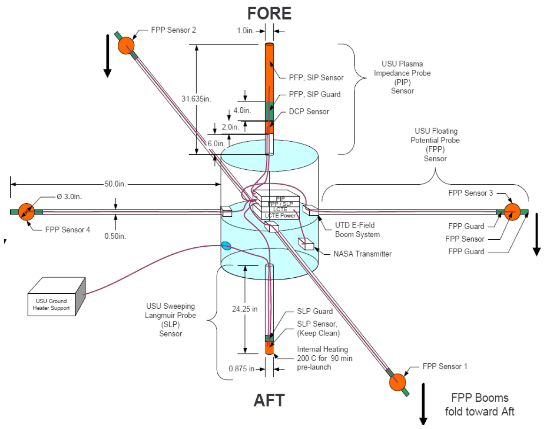

Fig. 1. The physical structure of the STORMS daughter payload of the mission. The SIP can be seen at the top of the payload shaped as a monopole antenna. The monopole points at some angle with respect the payload velocity vector. The daughter payload was built to spin around the FORE axis so that wake effects are minimized.

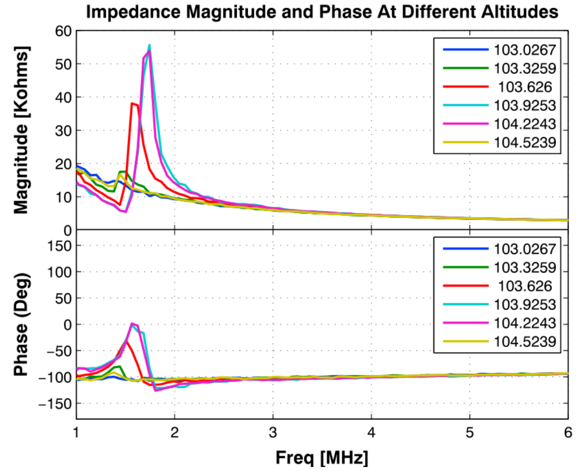

Fig. 2. SIP data for sweep numbers 5150, 5160, 5170, 5180, 5190, and 5200 from 103 to 105 km in the E layer. When plasma density increases were detected at these altitudes, the impedance curves could be interpreted with the standard cold plasma fluid theory.

crossing in the phase data only.

In this work, we will analyze the additional damping in the impedance curve mentioned in [4] by proposing two analogous circuit models. In addition to the sheath capacitance and plasma impedance, the parallel enhanced conductivity is added in the proposed models to fit their impedance curves with the STORMS SIP data developed for the different altitudes.

II. Background Study

The Tropical STORMS mission was launched on 30 October 2007 from Wallops Island, Virginia (37.95^0N, 284.53^0E, 67.5^0 dip angle) at 00:12 local time. The rocket trajectory reached apogee near 394 km. The mission was to study the possible coupling between terrestrial weather systems and the ionosphere that may result in density irregularities associated with midlatitude spread F (MSF). We refer the reader to Earle et al.[5] for further details on the science objectives of the mission. The scientific payload consisted of a mother-daughter configuration with instrument provided by the University of Texas-Dallas and Utah State University/Space Dynamics Laboratory [6]. The daughter payload (Fig.1) designed by Utah State University consisted of a Plasma Frequency Probe (PFP), sweeping impedance probe (SIP), a DC Langmuir Probe (DCP), a Sweeping Langmuir Probe, and four Floating Potential Probe sensors.

In [4], authors analyzed the SIP data into three categories: measured data around 100km to 105km (Fig.2); showing transitioned in the character of the curves around 265km(Fig.3); and the impedance curve around the peak density at 314km(Fig.4). In particular, the authors utilized phase curves data alone especially the zero crossing to match the electron density profile closely with the HFC (High Frequency Capacitance) method [2].

At altitudes between 100 km to 105 km in the ionosphere E layer, the fits between data and analytical solutions followed the cold plasma theory closely and consistently. From Fig.2, it is obvious that, as the plasma density increases, the impedance magnitude curve shifts right, grows larger in amplitude at the upper hybrid resonance, then shifts left and becomes smaller as the plasma density decreases.

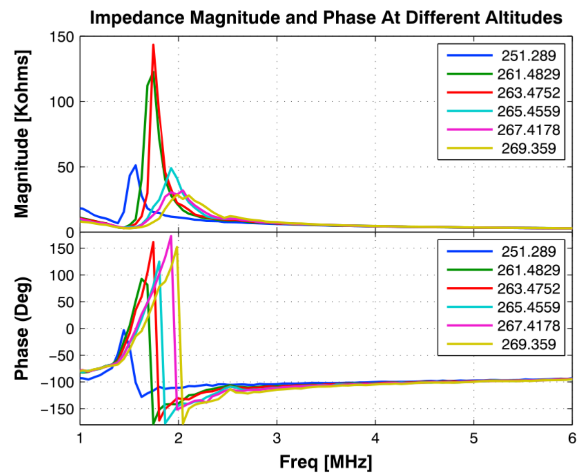

Fig. 3. SIP data for sweep numbers 11000, 11500, 11600, 11700, 11800 and 11900 from 251 km to 269 km in the F layer. A change in the shape, from increasing Q factor to a sudden decrease in Q factor can be observed in the magnitude data as the instrument goes above 265 km. The impedance data could not be fit to the standard cold plasma fluid theory at these altitudes.

From Fig.3, a transition in the characteristic curves, damping, is visible at altitudes between 251 km to 269 km in the F layer. Up to a certain distance, the amplitudes of the magnitude plots are growing but there is an abrupt decrease after 261 km. As the curve peaks as well as zero crossing shifts to the right, it can be assured that there is a gradual plasma electron density enhancement despite the damping of impedance magnitudes. However, since the neutral densities are decreasing rapidly with altitude, the collision frequencies and hence the damping factor should reduce with increasing

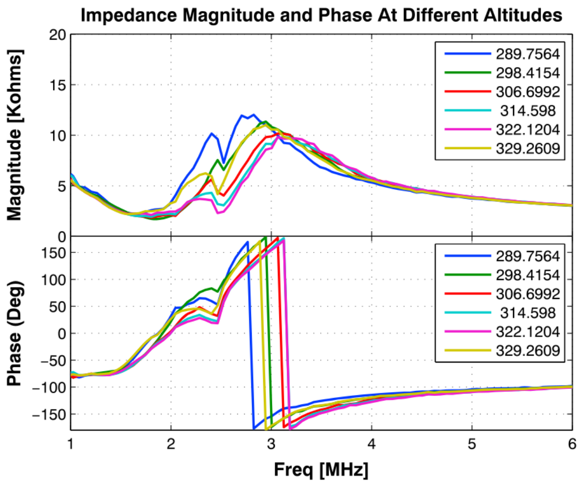

Fig. 4. SIP data for sweep numbers 13000, 13500, 14000, 15000, and 15500 from 289 to 329 km in the F layer. Here the Q factors were anomalously low, even though the effects due to collisions between the electrons and neutrals should be continuously decreasing at exponential rates with respect to altitude. However, the phase curves still have the sharp zero-crossing associated with f_{uh}.

altitude. This is not evidenced in the data.

The trend of this damping behavior in the impedance curve(Fig.4) further continues until the spacecraft reaches its apogee of 400km in the F layer. As the plasma density decreases, the impedance curve shifts right to left after certain altitudes.

More detailed explanation and analysis of these three plots Fig.2, Fig.3 and Fig.4 can be found in [4].

III. Proposed Circuit Model

The circuit models we developed here are used to match the impedance curve that could not be explained in [4] due to the damping mechanism. The concept of those models was also inspired from the direct conductivity demonstrated in Figure 13 of [5].

In circuit model-1(Fig.5), we tried to include the conductivity in addition to the sheath capacitance C_S [7] and plasma impedance Z_p in the demonstration of the probe plasma interaction. It is assumed that this conductance is due to the high mobility electrons in the plasma layer and is responsible for the parallel conductance with Z_p. With this in mind, a resistance R is connected in parallel with the plasma impedance altogether in series with sheath capacitance. To understand the basic operation and mathematical theory of SIP and PlP(Plasma Impedance Probe), we refer the reader to the articles [8], [4], [9]. But here we are going to show the basic realization of the proposed circuit models. The impedance of the plasma in the s-domain ($s = j\omega$, $\omega = 2\pi f$) is represented by:

$$Z_p = \left(\frac{K}{sC_o}\right)\left(\frac{\omega_{uh}^2}{\omega_{ce}^2}\right)\left[\frac{s^2 + 2\zeta_{ce}\omega_{ce}s + \omega_{ce}^2}{s^2 + 2\zeta_{uh}\omega_{uh}s + \omega_{uh}^2}\right] \quad (1)$$

where $\omega_{uh}^2 = \omega_{pe}^2 + \omega_{ce}^2$ and the subscript 'ce' indicates damping and resonant frequencies related to the electron cyclotron resonance, the subscript 'pe' indicates resonant frequencies related to the plasma electron resonance, and the subscript 'uh' indicates damping and resonant frequencies related to the upper hybrid resonance. Also, C_o is the vacuum capacitance of the probe structure and K is an adjustable amplification factor.

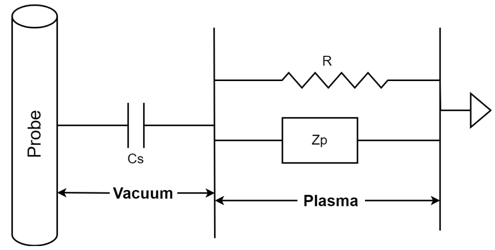

Fig. 5. Model-1 of the probe plasma interaction where it is assumed that high mobility electrons in parallel to plasma impedance. But the value of R is infinity in E-layer and lower level of F-layer until the transition of damping behavior begins

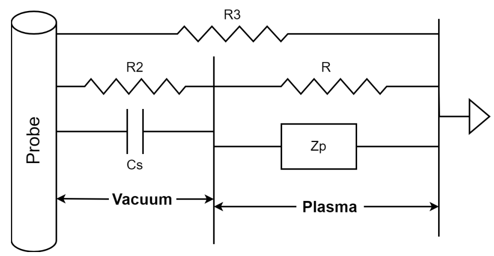

Fig. 6. Model 2 of the probe plasma interaction at upper altitudes of F-layer.Here, it is assumed that free high mobility particles are not only in the plasma region but also in the sheath capacitance layer and probe body to the ground.

Up to a certain altitude, the R is infinity and there is no additional damping in the impedance curve in SIP data due to conductivity. At lower altitude of the E layer, there is no sheath capacitance but after a certain point a series capacitance C_S due to the sheath structure around the probe structure has appeared [7] and the total impedance (Z_T) has become as,

$$Z_T = \frac{1}{sC_S} + Z_p \quad (2)$$

At around 250-270 km in the F-region(transition region), the character of the impedance measurements strongly indicates the appearance of an anomalous conductivity that increases the damping even though electron-neutral collisions rapidly decrease. It is assumed that there must be a secondary species of high-mobility electrons present in the plasma for which a low level of conductivity is induced. Hence, a parallel leakage resistance R was introduced in the model-1 and therefore, total impedance (Z_T) has been modified to,

$$Z_T = \frac{1}{sC_S} + \frac{RZ_p}{R + Z_p} \quad (3)$$

At higher altitudes of the F layer, after around 270 km, we could not fit the impedance curve of circuit model-1 with SIP data. After several analyses, it is assumed that there is high

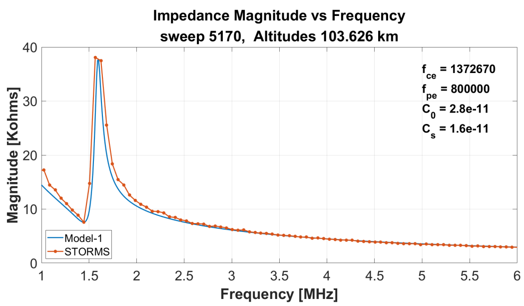

Fig. 7. Impedance magnitude curve using model-1 compared to STORMS data in the E layer for the sweeps 5170 at 163.63km. For this curve fitting, we took leakage resistance R as infinity and it matched with STORMS data for f_{ce} and f_{uh}

damping not only for high-mobility electrons in the plasma layer but also in the sheath layer and for the conductive secondary species from the probe body to the ground. For this purpose, we modified the circuit into model-2 of Fig.6 by adding two more resistances: R_2 in parallel C_S and R_3 from the probe body to the ground. Therefore, the modified total impedance for circuit model-2 is given by,

$$Z_T = \frac{R_3(Z_1 + Z_2)}{R_3 + (Z_1 + Z_2)} \tag{4}$$

where,

$$Z_1 = \frac{RZ_p}{R + Z_p}, Z_2 = \frac{R_2 Z_S}{R_2 + Z_S}, Z_S = \frac{1}{sC_S}$$

It should be noted that all three conductivities were necessary for the proper functioning of the model when we attempt to fit the impedance expressions to the data.

IV. Model Result and Analysis

In the analysis, mostly we have to include sheath capacitance to fit the model plot with SIP data. The proposed model-1 and model-2 have been effective from the transition region and upper altitudes in the F-layer. Furthermore, zero crossings from the phase plot are used as the main criteria to fit the curve in the upper hybrid frequency, f_{uh}.

From Fig.7, by using eqn. (2) it is observed that the impedance curve matched using fluid formation theory including a sheath capacitance in the E-Layer at 103 km, and without this sheath effect, it does not give good results across the entire frequency range of measurements.

Fig.8 and Fig.9 show that there is an increase in the impedance magnitude curve from 251km to 263km due to rapidly decreasing collisions and gradual density enhancement, as would be expected from eqn. (2). At altitude, 263 km, the curve showed (Fig.9) the maximum quality factor Q at the transition altitudes. Though there is the continuation of plasma density enhancement, Fig.11 demonstrates the transition of impedance magnitude and damping behavior at 265km. Due to the low collisions, the curve should have had an even larger Q than that observed at 263 km. From the analysis of eqn.(3) for the model-1, a leakage resistivity (R) of 65kΩ

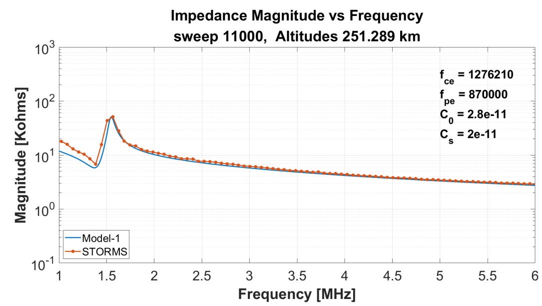

Fig. 8. Impedance magnitude curve using model-1 compared to STORMS data in the F layer for the sweep 11000 at 251.29km. Here, also enhanced conductivity is neglected, and the simulation curve for the model-1 matched with STORMS data in most of the frequency range

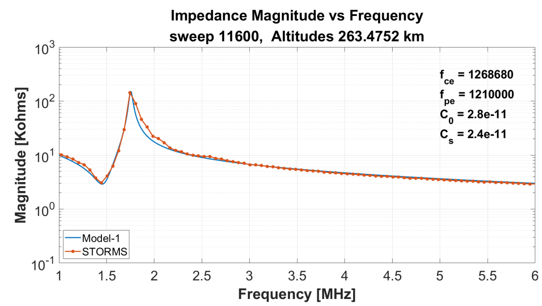

Fig. 9. Impedance magnitude curve using model-1 compared to STORMS data in the F layer for the sweep 11600 at 263.48km. At this time, also there is no enhanced conductivity and magnitude increases with respect to Fig.8 as there is low collision frequency due to the plasma density enhancement. The simulated curve for model-1 matched mostly with STORMS data.

had to be introduced in parallel with the plasma impedance to account for the damping behavior of STORMS data. There is a gradual increase of enhanced conductivity as the height increases meaning in turn the value of R has to be reduced.

Using model-1, we could not fit the curve due to high damping behavior as is seen in Fig.11 tail mismatching at 298km. Hence, the model alone was not sufficient enough to match with additional damping at high frequencies for the higher altitudes in the F-layer and prompted a further modification to the model-1.

To solve these mismatches, we modified the circuit models in various designs and were able to overcome the anomalies in higher altitudes by using model-2 (Fig.6). By implementing the eqn. (4) of model-2, we were able to fit the impedance curve at high frequencies for the higher altitudes of the F-layers.in Fig.12. Here, we Introduced three conductivities R, R_2, R_3 due to the presence of high mobility electrons and obtained a good fit across the entire frequency range of measurements. For instance, by analyzing eqn.(4),in Fig.12 we applied three leakage resistances 18kΩ, 5kΩ, and 28kΩ in parallel with plasma impedance, sheath capacitance and probe body to ground respectively to meet the additional damping behavior of Fig.11. Indeed, this model was feasible for fitting the plot until the apogee of the flight trajectory at 394 km.

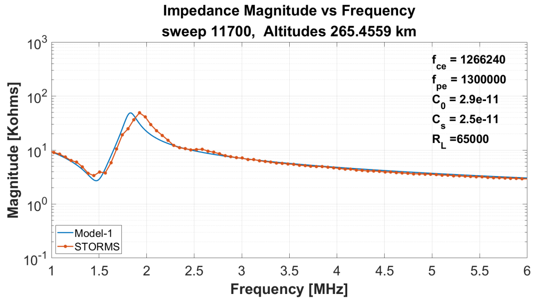

Fig. 10. Impedance magnitude curve using model-1 compared to STORMS data in the F layer for the sweep 11700 at 265.46km. It is the transition region as the magnitude decreases regarding Fig.9 which should be increased due to the gradual Density enhancement. To fit the curve, we fully utilized the model-1 to meet the damping behavior implying the leakage resistance(R) 65kΩ with parallel to Z_p

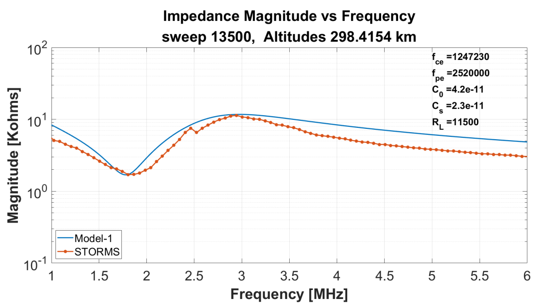

Fig. 11. Impedance magnitude curve using model-1 compared to STORMS data in the F layer for the sweep 13500 at 298.42km. Due to more additional damping in STORMS data, the plot of the model-1 couldn't fit as before due to tail mismatching at the higher frequencies

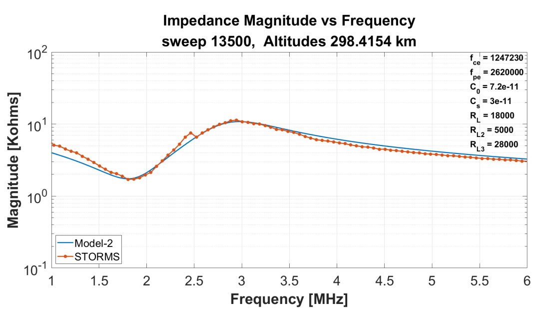

Fig. 12. Impedance magnitude curve using model-2 compared to STORMS data in the F layer for the sweep 13500 at 298.42km. The simulated result of model-2 shows that enhanced conductivity in the plasma layer, sheath layer, and probe body to the ground can demonstrate the high damping of Fig.11. Here, analyzing eqn.4, we implied leakage resistances $R = 18k\Omega, R_2 = 5k\Omega, R_3 = 28k\Omega$

V. Conclusion

The design of two circuit models has been proposed in this paper to explain the damping behavior in the STORMS sounding rocket mission data. Here, we found out that this damping may be caused by high mobility electrons in the ionospheric F-layer. There is an alteration from Model-1 to Model-2 from the transition region to higher altitudes due to the dependence of enhanced conductivity on the local criteria of the ionosphere around the probe body. Using the derived model in this work, we are able to obtain the electron density and the damping due to the electron neutral collision frequencies over the flight path of the sounding rocket payload. We are also able to obtain a measure of contributions due to other effects. In future research, we will seek out the reason and explanation behind this enhanced conductivity in the ionosphere F-layer due to secondary high-mobility species.

Acknowledgment

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