Low Frequency Characteristics of Electric Wire Antenna onboard Scientific Spacecraft

Tomohiko Imachi[1], Ryoichi Higashi[2], Mitsunori Ozaki[3], Satoshi Yagitani[3]
[1]Information Media Center, Kanazawa University
Kakuma-machi, Kanazawa, Ishikawa pref., 920-1192, Japan, imachi@imc.kanazawa-u.ac.jp
[2]Ishiakwa National College of Technology
[3]Graduate School of Natural Science and Technology, Kanazawa University

Abstract **For satellite observation of the electric fields of waves, a dipole antenna using a wire (wire antenna) is often used. For calibration of a wire antenna, the effective length is a problem. In our present research, we clarified that the characteristics of the effective length depends on the frequency and the structure of the wire antenna, such as the wire insulator and the shape of tips by holding "rheometry" experiments[1]. In this paper we describe about "DPS method" on which we calculated the characteristic of the effective length theoretically.**

I. INTRODUCTION

Observation of plasma waves in space is an important task for scientific satellites. The electromagnetic waveform detected by an electromagnetic sensor on the satellite is transformed to a voltage by the sensor, is converted to digital data by A-D conversion during the observation equipment, and then transmitted to the earth by telemetry. Hence, in order to accurately determine the magnitude of the original electromagnetic field, the calibration of the observation equipment and the sensor must be accurate. Most of the transfer function needed for this purpose is acquired in ground tests prior to launching of the satellite. However, the effective length (h_{eff}) of the electric field sensor cannot be accurately obtained in the ground test. If the electric field is E (V/m) and the antenna output voltage is V (V), the effective length is an extremely important parameter providing the ratio of the two:

$$V = h_{eff} \cdot E \tag{1}$$

For observation of the electric field component of the wave, a dipole antenna using a wire (the wire antenna) is often used. Since sensitivity must be assured at frequencies of several kilohertz and below for plasma wave observation, the total length of the wire is extremely large, ranging from tens of meters to 100 m. Since the surrounding environment at the time of observation is plasma medium, it is difficult to acquire the needed characteristics in a ground test.

II. RHEOMETRY EXPERIMENT

In order to study the transition of the effective lengths of the wire antennas, the authors performed a rheometry experiment [1]. The experimental setup is shown in Figure. 1.

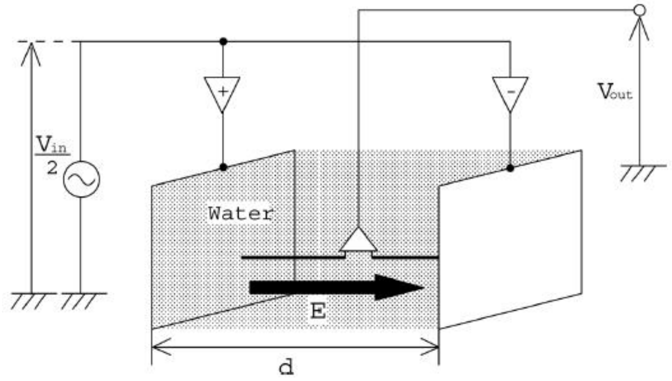

Figure 1. Setup for a "rheometry" experiment..

In this experiment, a signal is applied to two electrodes placed in parallel in water so that a quasi-static electric field is generated between the electrodes. This field is considered as the electric field component of an electromagnetic wave and is received by an antenna whose output voltage is measured. If the distance between the electrodes is d and the amplitude of the signal is V_{in}, then the amplitude of the generated electric field is

$$E = V_{in}/d \tag{2}$$

Therefore, if the output voltage is V, the effective length becomes

$$h_{eff} = \frac{V}{E} = \frac{Vd}{V_{in}} \tag{3}$$

In free space, the impedance between the elements of a dipole antenna is purely capacitive and is extremely large at low frequencies, however, by adding conductivity in parallel to capacitance when the antenna is immersed in water, measurement is made possible. In contrast, the electric lines of force in water cannot escape into the air by passing through the water surface, because the permittivity of water is about 80 times that in air. As a result, an extremely uniform electric field can be formed in water.

Since this experiment models the electric field component of an electromagnetic wave by a quasi-static electric field, the measurable frequencies are limited. The wave length must be much longer than the antenna length where the phase does not vary for a location shift of about the antenna length. On the other hand, if the frequency is too low, no electric field may be formed as the water is polarized. In the experiments reported in this paper, measurements were performed at frequencies of 10 Hz to 100 kHz for an antenna with 0.3 m length.

For the experiment, the three types of antennas shown in Figure. 2 were prepared and measurements of variations of the characteristics due to differences in structure were performed: (1) The antenna without insulation, so that the entire length of the wires (copper) was exposed to the water, (2) the antenna with its sides insulated so that only the cross sections of the two ends were exposed to the water, and (3) the antenna with aluminum spheres attached on both ends of the wires with their sides insulated. The wire diameter was 1.3 mm. A differential amplifier with input impedance consisting of a parallel connection of 10 MΩ and 2 pF between the wires was inserted.

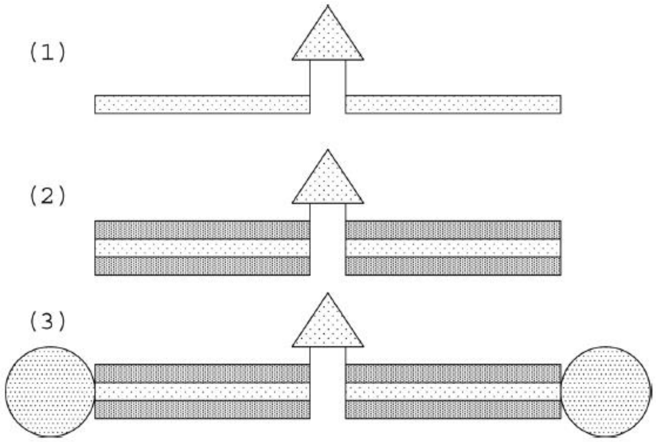

Figure 2. Antennas applied to the experiment: (1) without isolations; (2) insulated cylindrically and exposed to the water at both tips; (3) with sphere probes at both tips.

Figure 3 shows the experimental results. The horizontal axis of the figure represents frequency over the range of 10 Hz to 100 kHz. The vertical axis represents h_{eff}/L where L is antenna length. If the value is 1, the effective length and the wire length are equal. " Naked" denotes the case without insulation, "Cylindrical" denotes insulation only over the sides, and "With Probe" denotes the structure with spherical probes.

As shown in Figure. 3, three entirely different characteristics are obtained for the three antennas. There is no observable phase difference between the input waveform and the output waveform. Below we present a theoretical analysis of the results based on an equivalent circuit.

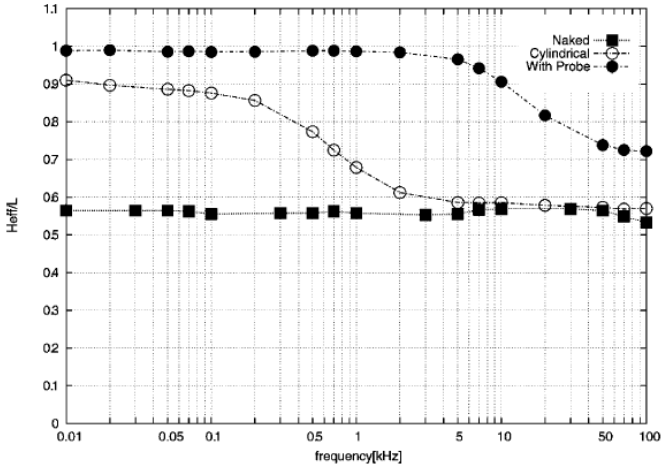

Figure 3. Experimentally measured effective lengths.

III. DPS METHOD

The circuit elements located on the wire are considered to be those in Figure. 4. The insulating coat is considered as a capacitance C_1 between the wire core and the water and is connected in series to the grounding resistor R_1 of the wire through the water. Grounding resistances exist from the wire cross section and the probe surface and are designated as R_M and R_P.

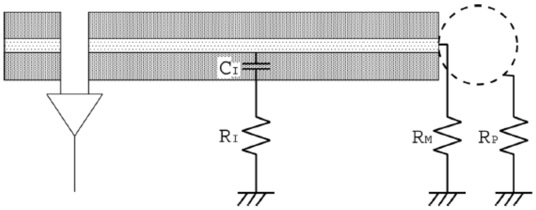

Figure 4. Equivalent of impedance of a wire.

When a wire antenna is placed parallel to a uniform static electric field, a potential difference arises as the location is moved away from the center, where the potential is 0, and a differential amplifier is installed. The potential becomes the maximum at the end. This phenomenon can be expressed by an equivalent circuit in which many voltage sources are connected in parallel through impedances as shown in Figure. 5. Then, the voltage of each source is $(L/2)EV$ if the voltage is 0 V at the center and the length of the wire on one side is $L/2$ m. The voltage variation along the wire is linear. Hence, if the center is the 0th and the end is the n-th, the voltage V_k at the k-th supply is

$$V_k = \frac{k}{n} \cdot \frac{L}{2} E \tag{4}$$

Then the potential of the wire core is V in Figure. 5, which becomes the input voltage to one side of the differential amplifier. In the following discussions, the value of this V is evaluated.

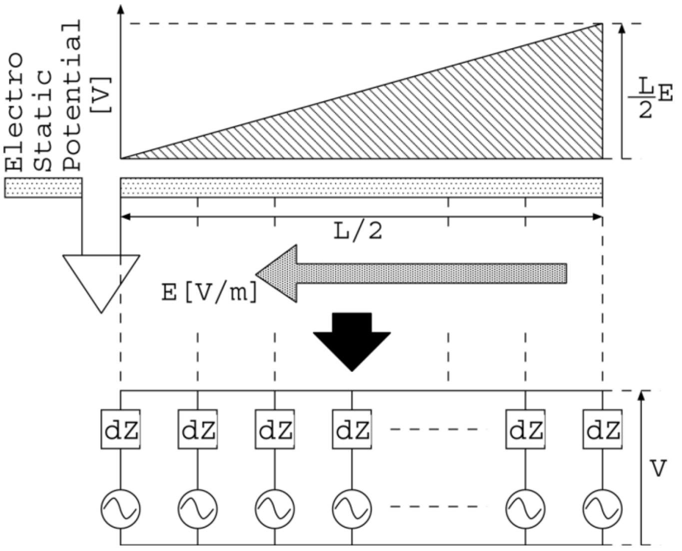

Figure 5. Basic concept of DPS method

For example, let us consider the case in which coatings exist only on the sides of the wire. If the impedance of the coating is Z_I and the impedance of the end surfaces where the conductors are exposed is Z_M, then the equivalent circuit is as shown in Figure. 6.

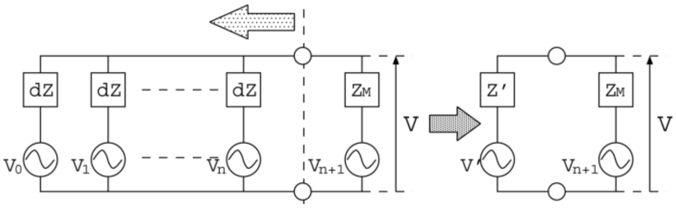

Figure 6. An equivalent circuit for the case of a cylindrical insulator.

Here,

$$V' = \frac{\sum_{k=0}^{n} V_k}{n+1} \tag{5}$$

$$Z' = \frac{dZ}{n+1} \tag{6}$$

$$dZ = (n+1)Z_I \tag{7}$$

When the output voltage is derived by means of the Ho-Thévenin theorem, we have

$$\begin{aligned} V &= V_{n+1} + \frac{Z_M}{\frac{dZ}{n+1} + Z_M}\left(\frac{\sum_{k=0}^{n} V_k}{n+1} - V_{n+1}\right) \\ &= \frac{\frac{dZ}{n} V_{n+1} + \frac{Z_M}{n}\sum_{k=0}^{n} V_k}{Z_M + \frac{Z_M + dZ}{n}} \end{aligned} \tag{8}$$

Where

$$V_k = \frac{k}{n}\cdot\frac{L}{2}E \tag{9}$$

$$V_{n+1} = \frac{L}{2}E \tag{10}$$

Therefore,

$$\begin{aligned} V &= \frac{\frac{dZ}{n}\cdot\frac{L}{2}E + \frac{Z_M}{n}\sum_{k=0}^{n}\frac{k}{n}\cdot\frac{L}{2}E}{Z_M + \frac{Z_M + dZ}{n}} \\ &= \frac{\frac{dZ}{n} + \frac{Z_M}{2} + \frac{Z_M}{2n}}{Z_M + \frac{Z_M}{n} + \frac{dZ}{n}}\cdot\frac{L}{2}E \end{aligned} \tag{11}$$

If n goes to infinity,

$$\frac{Z_M}{n} \to 0 \tag{12}$$

$$\frac{dZ}{n} = \frac{(n+1)Z_I}{n} \to Z_I \tag{13}$$

Hence,

$$V|_{n\to\infty} = \left(1 - \frac{1}{2}\frac{Z_M}{Z_I + Z_M}\right)\frac{L}{2}E \tag{14}$$

As described above, by regarding the electric field to be “distributed potential source”, we can calculate the output voltage of a wire antenna with complex structure. We call this “DPS (Distributed Potential Source) “ method.

IV. APPLYING DPS METHOD TO THE EXPERIMENT RESULT

Let up apply DPS method to the rheometry experiment. In the case of naked wire, *dZ* is dominated by the grounding resistance of the sides of the wire. If the output voltage *V* is calculated in Figure. 5, we obtain

$$V = \frac{\sum_{k=0}^{n} V_k}{n+1} \tag{15}$$

Therefore, the output voltage is

$$\begin{aligned} V &= \frac{1}{n+1}\cdot\sum_{k=0}^{n}\frac{k}{n}\cdot\frac{L}{2}E \\ &= \frac{L}{4}E \end{aligned} \tag{16}$$

The output voltage of the differential amplifier is twice, namely, $L/2 \cdot E$, and the effective length is

$$h_{eff} = \frac{L}{2} \tag{17}$$

On the other hand, when the impedance of the exposed metal portions is only the grounding resistance R_M and the impedance of the insulating parts on the sides is a series connection $R_I + 1 / j\omega C_I$ of the capacitance of the coating C_I and the grounding resistance R_I; then the output voltage is the following according to Eq. (14)

$$V = \left(\frac{1 + j\omega C_I (R_I + \frac{R_M}{2})}{1 + j\omega C_I (R_I + R_M)} \right) \frac{L}{2} E \qquad (18)$$

Since there is little phase difference, only the amplitude characteristics are evaluated. The absolute value of V is

$$|V| = \sqrt{\frac{1 + \omega^2 C_I^2 (R_I + \frac{R_M}{2})^2}{1 + \omega^2 C_I^2 (R_I + R_M)^2}} \frac{L}{2} E \qquad (19)$$

The output voltage of the differential amplifier is twice the above and hence the amplitude characteristics of the frequency dependence of the effective length are given by

$$h_{eff} = \sqrt{\frac{1 + \omega^2 C_I^2 (R_I + \frac{R_M}{2})^2}{1 + \omega^2 C_I^2 (R_I + R_M)^2}} \cdot L \qquad (20)$$

When probes are attached to both ends, the equation for deriving the effective length is Eq. (20), with R_M replaced by the grounding resistance R_P, which has a smaller value. Therefore, the effective length is

$$h_{eff} = \sqrt{\frac{1 + \omega^2 C_I^2 (R_I + \frac{R_P}{2})^2}{1 + \omega^2 C_I^2 (R_I + R_P)^2}} \cdot L \qquad (21)$$

Figure 6 shows the result of DPS method calculation according to Eq. (17), (20) and (21) applying the actual physical parameters of the experiment environment. The solid lines show the calculation results, and the symbols shows the measurement results.

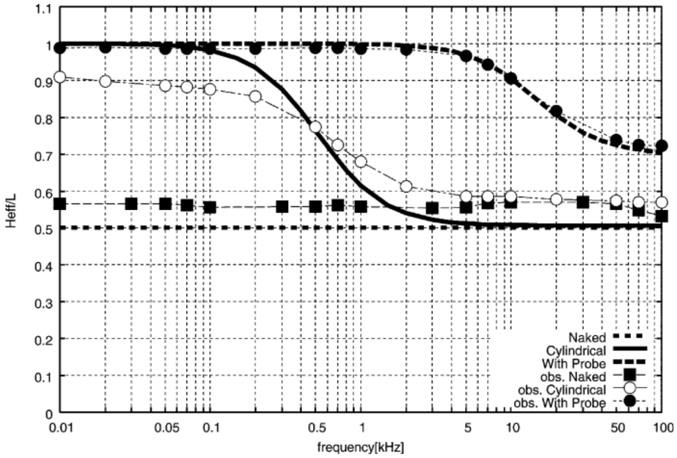

Figure 6. The result of theoretical calculation by using DPS method.

When the numerical values and the measured values are compared in each case, the frequencies at which the effective length starts decreasing at all cases agree well.

V. CURRENT WORK

Currently, we are working on an advanced rheometry experiment. The advanced factors are the following: (1) improvement of accuracy, (2) clarification of the applicable limit and (3) diversification of the antenna model. In the current result, the transit frequencies are consistent, however, the value of the effective length have some difference, between the experiment and DPS calculation. We try to clarify the cause of the difference and take better result by improvement of accuracy of the experiment. To clarify the applicable limit, we use the computer simulation. By reproducing the experimental environment on the computer, we identify the requirement for the experiment, such as the tank size, the water depth and so on. For diversification of the antenna model, we make models of antenna that have complicated structure, such as Hockey Pack antenna.

In parallel, we make a detail analysis about the experiment result by using computer simulations. By simulating the detail structure of potential distribution around the antenna models, we try to clarify the mechanism of the effective length determination, comparing to DPS calculation.

VI. CONCLUSION

In this paper, we made explain about the rheometry experiment and DPS calculation method. By using DPS method, we can calculate the effective length of a wire antenna at low frequencies, and the result is clarified to be consistent to the result of the rheometry experiment.

Currently, we are working on an advanced experiment, and the computer simulation. We will show the result of them in near future.

As a future work, we try to apply DPS method calculation to the wire antenna aboard actual scientific spacecraft.

REFERENCES

[1] T. Imachi, et al., “Rheometry Experiment for a Wire Antenna Aboard Spacecraft at Low Frequencies”, Vol. J89-B, No. 4, April 2006, pp. 552–559.