Proceedings of ISAP'04, Sendai, JAPAN

CHARACTERISTICS OF ELECTRIC WIRE ANTENNAS ONBOARD SCIENTIFIC SPACECRAFT

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1. Introduction

Plasma wave observations are among the many valuable scientific measurements made onboard satellites. The electromagnetic sensors onboard satellites generate output voltages related to the imposed electromagnetic fields and the measurements of these voltages are transmitted to the earth in the telemetry data after amplification and A/D conversion. We must know the transfer function between the input physical quantity and the output digital data in order to accurately calibrate the electromagnetic fields from the telemetry data. We can determine much of the transfer function by static testing, but the wire antennas used as electric field sensors onboard scientific satellites have further complications. The "effective length" is an important parameter of a wire antenna. The output voltage V for an electric antenna subject to an imposed electric field E (measured in V/m) is written as $V = h_{eff} \cdot E$ where h_{eff} is the effective length. It is very difficult to determine the exact value of an effective length by static testing, because the wire antenna needed to observe low frequency plasma waves down to several 100 Hz becomes very long. For example, "Akebono" has 60 m tip-to-tip antennas and "Geotail" has 100 m tip-to-tip antennas. Additonally, the antenna characteristics in geospace are different from those in the earth's atmosphere. For these reasons, it is very difficult to obtain rigorous results from static testing.

In recent studies, the effective lengths have been usually assumed to be L for DC (static) electric fields and $\frac{L}{2}$ for AC (wave) electric fields, where L is the tip-to-tip length of a wire dipole antenna[2]. This means that the effective length depends on the frequency of the wave.

In this research, we determine the characteristics of the effective length of the wire antenna at low frequencies by experimentally using "Rheometry,"[3] and then theoretically by analysis of the equivalent circuit. The results of the measurement show and this is confirmed that the effective length depends on the structure of the antenna at low frequencies by the theoretical analysis.

2. Rheometry experiment

"Rheometry" is a method to determine the antenna characterisitics of a wire antenna using a scale model set in water. The antenna characterisitics are determined from the antenna output voltage measured as a function of input electric field. The experimental setup is shown in Fig.1. Two stainless plates are used as electrodes at either end of a water tank made of plastic. A quasi-static electric field is created between them by applying an AC voltage generated by a signal generator. The effective length of the antenna is obtained from the applied voltage and

ISBN: 4-88552-206-4 C3055©IEICE

the output voltage of the antenna at the center of the tank by the equation $V = h_{eff} \cdot E$. Here, V is the output voltage of the antenna, E is the electric field intensity in the water (the input voltage divided by the distance between the two electrodes). The antennas we used are as follows: (1) long thin solid cylindrical wire covered by an insulator except at the tip,(2) long thin solid cylindrical wire with no insulator,(3)long thin solid cylindrical wire covered by an insulator except for the spherical probes at both tips. We measured the characteristics of these antennas at frequencies from 10 Hz to 100 kHz. The measurement results are shown in Fig.2.

The effective lengths of (1) and (3) take the value of the total length of the antenna at low frequencies. This is because the electric potential difference of the antenna's tips emerge directly as the output voltage. The transition where the value of (1) converged to the value of (2) (nearly $\frac{L}{2}$) at high frequency can be explained by the effect of the capacitance of the insulator, i.e. as the frequency becomes higher, the impedance of the capacitance decreases, and the effect of insulator is reduced therefore (1) approaches the condition of (2).In the case of (3), the value of the effective length is higher than for the other two cases. Because the ground resistance of the probe is much lower than the ground resistance of the wire tip and is not very much higher than the ground also resistance of the side surface of the wire, the contribution of the voltage of both antenna tips is high when the effect of the coating is reduced.

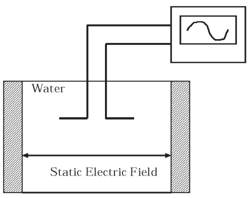

Fig.1:Set up for "Rheometry" experiment.

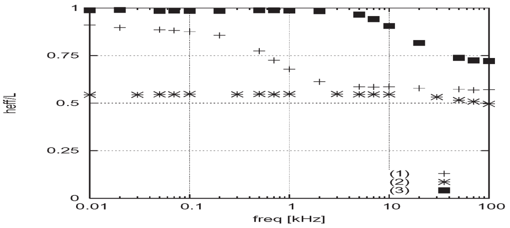

Fig.2:Expreimentally measured effective length of wire antennas.

3. Theoretical analysis

We theoretically computed the effective lengths by using equivalent circuits. The insulator has the capacitance C_I between the wire and the water, the ground resistance of the side surface of the wire is R_I, and the ground resistance of the tip of the wire is R_M.

When the wire antenna is arranged to be parallel to the direction of the electric field, the electrostatic potential increases linearly along the wire. The effects of the static potential can be considered as distributed, ground parallel voltage generators, as shown in Fig.3. When the ground is defined to be at the center of the antenna, the voltage of each voltage generator is $\frac{L}{2}E$ at the tip and is connected linearly between the tip and the center. Therefore, when there are $n+1$ voltage generators as V_k (k=0,1,$\cdots$ n) along one of the wires is expressed as

$$V_k = \frac{k}{n} \cdot \frac{L}{2} E \tag{1}$$

So we can determine the effective length by considering this voltage distribution.

3.1 Without an insulator

In Fig.3, calculating the output voltage V

$$V = \frac{\sum_{k=0}^{n} V_k}{n+1} \tag{2}$$

The output voltage becomes the average of all the voltage generators. So

$$V = \tfrac{L}{4} E \tag{3}$$

The output voltage of a differential amplifier connected to the base of two wires is twice this voltage, so that the effective length becomes.

$$h_{eff} = \frac{L}{2} \tag{4}$$

3.2 Insulated cylindrically

When the impedance of the side surface of the wire is Z_I and that of the wire tip is Z_M, the equivalent circuit becomes as shown in Fig.4, where

$$V' = \frac{\sum_{k=0}^{n} V_k}{n+1}, \quad Z' = \frac{dZ}{n+1}, and \quad dZ = (n+1)Z_I.$$

In this case, the output voltage is expressed as

$$V = \frac{\frac{dZ}{n}V_n + \frac{Z_M}{n}\sum_{k=0}^{n} V_k}{Z_M + \frac{Z_M+dZ}{n}}. \tag{5}$$

Then, when the impedance of the wire tip Z_M is the ground resistance, and the impedance of the side surface of wire is a serial circuit of the capacitance of the insulator and the ground resistance of the side surface of the insulator, the output voltage V is expressed as

$$V = \left(\frac{1 + j\omega C_I (R_I + \frac{R_M}{2})}{1 + j\omega C_I (R_I + R_M)} \right) \frac{L}{2} E. \tag{6}$$

The effective length is expressed as follows.

$$h_{eff} = \sqrt{\frac{1 + \omega^2 C_I^2 (R_I + \frac{R_M}{2})^2}{1 + \omega^2 C_I^2 (R_I + R_M)^2}} \cdot L. \tag{7}$$

In the case of the spherlcal probe at the tip of the wire, the ground resistance of the wire tip R_M is replaced with the ground resistance of the probe, so the effective length becomes

$$h_{eff} = \sqrt{\frac{1 + \omega^2 C_I^2 (R_I + \frac{R_P}{2})^2}{1 + \omega^2 C_I^2 (R_I + R_P)^2}} \cdot L. \tag{8}$$

3.3 Results of calculations

Four curved lines shown in Fig.5 are the results of the theoretical calculations. Comparing the experimentally measured values with the calculated values, we can that there is little difference, especially the frequency of transition as the effective length is almost same. According to these results, the effective length depends on the structure of the antenna at low frequencies and as the frequency becomes higher, the value of effective length converges to $\frac{L}{2}$.

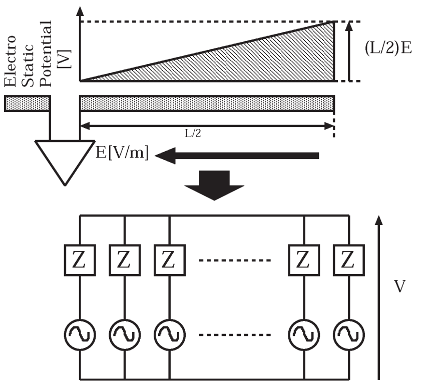

Fig.3: An equivalent circuit of a i

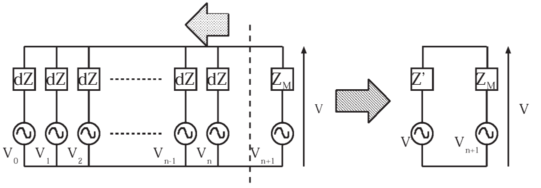

Fig.4: An equivalent circuit for the case of a cylindrical insulator.

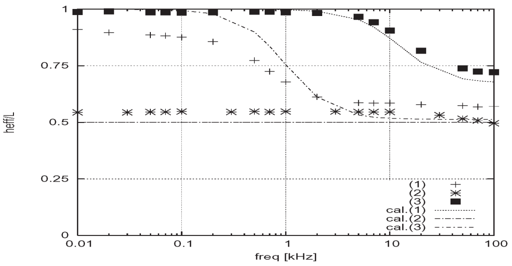

Fig.5: Comparison between the experiment and the calculations.

4. Effect of the antenna sleeve

An antenna on an actual scientific spacecraft has a metal mesh sleeve to reduce the noise from the spacecraft body. Here, the effect of the antenna sleeve on the effective length is considered by using a theoretical model.

The voltage on the sleeve area is 0, so no voltage generator should be placed in this area as in Fig.6. The ground resistance of this area should be considered independent from the other parts. The sleeve part has only the capacitance of the wire insulator C_{IS}, while the capacitance of the other part of wire side surface is C_I, the ground resistance of the side surface of insulator is R_I, and the ground resistance of the wire tip is R_M. In this case, the effective length is expressed as

$$h_{eff} = \sqrt{\frac{1+\omega^2 C_I^2 (R_I + aR_M)^2}{(1-\omega^2 C_I C_{IS} R_I R_M)^2 + \omega^2 (R_M C_{IS} + R_I C_I + R_M C_I)^2}} \tag{9}$$

where a=$\frac{5}{8}$: Sleeve from base to $\frac{L}{4}$,
a=$\frac{3}{4}$: Sleeve from base to $\frac{L}{2}$,and
a=$\frac{7}{8}$: Sleeve from base to $\frac{3L}{4}$.

The results of the calculations and the measurements for the sleeve antennas are shown in Fig.7. The symbolsare the result of measurement, and the lines are the results of the theoretical calculations. Both show that the values of the effective lengths decrease from $\frac{L}{2}$ at higher frequencies. This is thought to be due to he fact that the impedance between the wire core and the sleeve becomes 0, so the wire core is grounded because of the decrease of the capacitance in the insulator C_{IS} at high frequency.

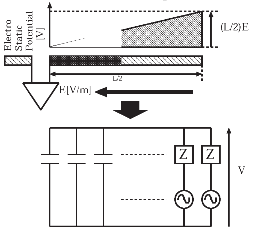

Fig.6: An equivalent circuit for the case of a sleeve.

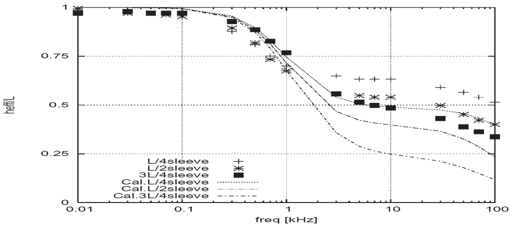

Fig.7: The result of the experiment and the calculation for the case of a sleeve

5. Summary

We confirmed the frequency dependence of the effective length of dipole antennas. In the case without insulators, the potential of the midpoint of each element is observed free from frequency dependence. As the antenna is insulated cylindrically, the output voltage is the potential difference at both antenna tips at low frequencies, and converges to the same $\frac{L}{2}$ value as for the un-insulated case. The reason is that insulating coating is capacitance, so as the frequency become high, the effect of coating is reduced, and its structure becomes same structure without insulators. In this paper, we analyzed the frequency dependence of the effective length by rheometry experiments and theoretical calculations using equivalent circuits. The results of experiment, were in the case of cylindrical insulated, the effective length becomes $\frac{L}{2}$ for the AC electric field, and L for DC.

In the future we will take into account the effect on the effective length of the plasma around the spacecraft.

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