SOME MEASUREMENTS OF AERIAL IMPEDANCE IN THE IONOSPHERE

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Résumé. — *On a mesuré l'impédance d'un dipôle filiforme de 20 mètres de longueur totale, à une hauteur de 125 km dans l'ionosphère de nuit. Ces mesures ont été faites à 60 kHz et à une fréquence variée entre 1,4 et 1,8 MHz et passant par la gyrofréquence. Les résultats obtenus sont interprétés à partir de la théorie de* Kaiser *et sont en bon accord avec cette théorie. On en déduit une estimation de la densité électronique et de la fréquence de collision.*

Abstract. — *The admittance of a wire dipole of overall length 20 m was measured at a height of approximately 125 km in the night-time ionosphere. Measurements were obtained at 60 kHz and at a frequency swept over the range 1.4 MHz to 1.8 MHz so as to include the gyrofrequency. The results are interpreted in terms of a theory due to* Kaiser, *and fair agreement is obtained. The electron density and collision frequency in the plasma surrounding the aerial are estimated.*

Резюме. — Был измерен импеданц нитеобразного диполя общей длины 20 метров, на высоте 125 км в ионосфере, ночью. Эти измерения были сделаны в 60 кгц и в частоте изменявшейся между 1,4 и 1,8 Мгц, включая гирочастоту. Полученные результаты интерпретированы исходя из теории Кайзера и находятся в хорошем согласии с этой теорией. Отсюда выведена оценка электронной плотности и соударной частоты.

Introduction

The interpretation of measurements using radio receiving equipment in space vehicles, such as the radio astronomy experiment in satellite S-52, requires some knowledge of the impedance of a dipole aerial immersed in the ionospheric plasma. There have been several theoretical approaches to this problem none of which is completely satisfactory, and checks with experiment are desirable. Deschamps [1962] and Bain [1963] have treated the case of an isotropic medium. Their results are valid only when the operating frequency is much larger than the gyrofrequency. Kaiser [1962] and Bramlay [1962] have extended this analysis to an anisotropic medium and Mlodonsky and Garriott [1962] have calculated the impedance of a dipole at very low frequencies. The development of the apparatus for satellite S-52 afforded an opportunity of testing these theories. A mechanism for extending a wire dipole from the rotating satellite was modified for use in Skylark rocket. A length of wire 20 m overall could be deployed and the most suitable application seemed to be to check the variation of its impedance at a low frequency and at a frequency near the gyrofrequency where a large dispersion was expected. Two impedance measuring devices were connected to the aerial one operating at 60 kHz and the other at a frequency swept over the range 1.4 to 1.8 MHz. The gyrofrequency in the E-region of the ionosphere at Woomera, where the rocket flight was made, is approximately 1.52 MHz.

The Antenna System

The antenna consists of two 10 m lengths of stranded nylon copper braided wire. The wire is contained on an insulating drum during launch, which can be turned at a predetermined time by a small electric motor. A rubbing connection is made with two silvered brass cones through which the wires pass. This allowed measurements to be made during deployment of the aerial. The rocket head was released from the motor at a height of 75 km. The roll rate of the round was accelerated to 7.5 radians/s between 90 km and 110 km where

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aerial deployement was started. The rate of deployment was approximately 0.25 m/s.

The 60 kHz Impedance Device

This consists of an L, C oscillator matched into an eight section delay line of characteristic impedance 2.1 kΩ. The aerial is connected to the delay line through a transformer which enables the line to be matched by 70 kΩ, the approximate value of the reactance of the aerial system in free space. A high impedance detector is connected to each point of the delay line and the outputs from these are telemetered to ground and recorded there in the usual way. The standing wave pattern on the delay line provides a measure of the complex impedance at its terminals. It is 0.6 λ long at 60 kHz so that two maxima or minima can be observed. A similar system was used by Haycock and Baker [1961].

The Swept Frequency Impedance Device

The swept frequency device operates on different principles. In this case the L, C oscillator is swept in frequency. The tank circuit capacitor consists of four reverse biassed zener diodes in parallel, driven with a varying voltage from a simple time base. Zener diodes are used because they have a suitably large junction capacitance. The output from the oscillator is presented between one wire of the aerial system and the rocket body ; the current flowing in the other wire is amplified and passed through a resistor and capacitor in series. The current through the aerial system in phase with the driving voltage produces a proportional " in phase " voltage across the resistor. The " in phase " component of the voltage across the capacitor is proportional to the current through the aerial system in quadrature with the driving voltage, that is, the current through the susceptive component of aerial admittance. These " in phase " components of the voltages across the resistor and capacitor are detected using phase sensitive detectors (ring demodulators). The direct voltages at the detector outputs are proportional to the conductance and capacitance of the aerial system respectively. They are amplified to a suitable level for presentation to the telemetry system.

In order that measurements can be made simultaneously by both devices a duplexer is used. The swept frequency device is connected to the aerial wires through two parallel tuned circuits which have a low impedance at frequencies in the range 1.4 to 1.8 MHz and a high impedance at 60 kHz. A choke for the higher frequencies is also placed in series with the 60 kHz device to reject the waveform of the other.

Rocket Flight : System Performance

Skylark 81 A was launched from the Woomera range at 0040 hours local time en October 4, 1963. Ionograms were taken at intervals of 15 minutes throughout the flight. The precession angle of the rocket head is at present unknown. It can be estimated when the results of measurements by magnetometers and rate gyros carried in the rocket become available. The motion of the rocket head throughout the flight was quite regular showing that the wires had deployed correctly and not become entrained by the head. It is assumed that the wires rotated in a plane about an axis almost parallel with the total angular momentum vector of the rocket head.

At the end of its deployment a fault occurred in the aerial system which had the effect of short-circuiting it ; thus no measurements were obtained above a height of 128 km. For the previous 10 s the overall length of the aerial system was increasing between 15 m and 20 m. Four sweeps were made by the swept frequency device in the same interval. The ionograms indicate that at the height where measurements could be made the electron density was quite small. The F layer was overdense only at heights greater than 200 km for frequencies greater than 500 kHz. However, the electron density at 128 km could have been affected by sporadic E observed on the ionograms at a lower level.

The payload was recovered after the flight and the apparatus was found to be in good condition. It was possible to make some recalibration of the electronic apparatus and to discover the cause of the fault which occurred in the aerial system.

The accuracy of the telemetry system is better than 1 %. Two calibration levels are provided against which to compare the output voltages of the equipment in the rocket. Input voltages to the telemetry lie between 0 v and + 4.5 v. By comparison between the two calibration levels and between measurements made during the flight and on the ground the errors in reading the telemetry records can be estimated. The random error is estimated to be less than ± 0.03 V, and the systematic error to be less than 2 %.

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Aerial Impedance Near the Gyrofrequency

The measured values of aerial admittance, after correction for various stray capacitances which occur between the aerial wires inside the rocket body, are shown in Figure 1. The frequency scale is not linear. The accuracy of the frequency markers shown is ± 0.02 MHz. Random errors in the results are estimated to be ± 2 pf and ± 0.01 mMho for measurements of capacitance and conductance respectively. Systematic errors could be three times larger than these figures, and will be worse for the earlier sweeps where larger corrections had to be applied for the effects of stray capacitances.

In order to compare the results of these measurements with various theories it is necessary to take into account the effects of the ion sheath. A quantity, C_s, will be calculated which is the capacitance

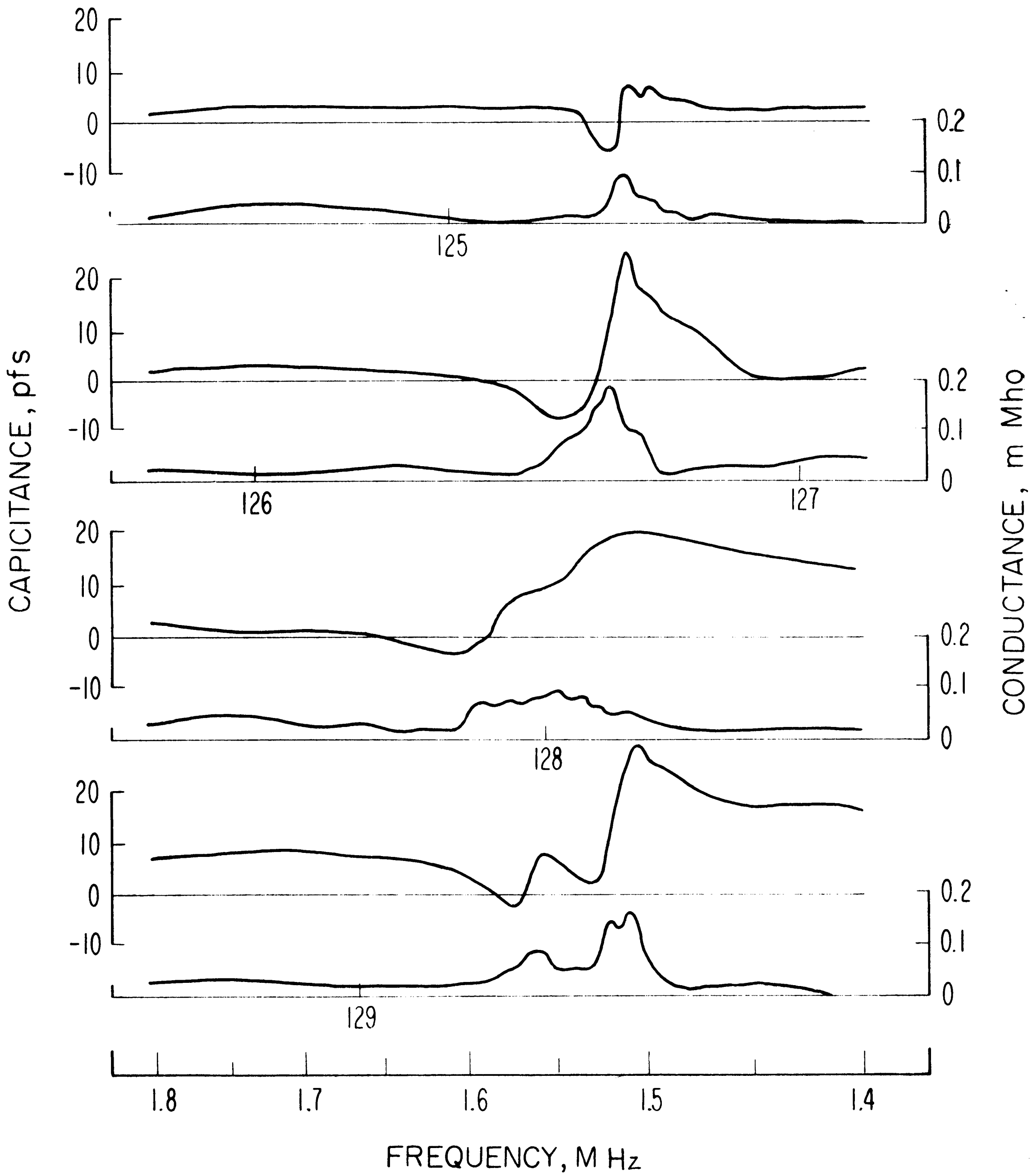

Fig. 1. — Aerial admittance measured near the gyrofrequency. Number against the abscissae are the rocket height in km.

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between each aerial wire and the boundary of the ion sheath. This boundary is a rather vague concept, but the capacitance deduced varies only slowly with r_s, the so-called " sheath radius ". The formula used is that for the capacitance of a cylindrical condenser.

$$(1) \qquad C_s = 2\pi\varepsilon_0\, l/\log_e(r_s/a),$$

where l = the aerial half length in m ;
a = the radius of the wire ;
$\varepsilon_0 = 8.85 \times 10^{-12}$ farad/m.

Whale [1962] has made various estimates of the sheath radius using several different approaches and found that it lay between 2 cm and 5 cm during the flight of the rocket NASA 4.07. A sheath of similar dimensions will be assumed here. Putting $r_s = 3.3$ cm, $a = 0.1$ cm.

$$(2) \qquad C_s = 16 \text{ picofarads per metre}$$

Following Kane *et al.* [1961] we can now calculate the admittance of a fictitious aerial system with the same dimensions as the ion sheath which is immersed in a dielectric consisting entirely of plasma. If the admittance of this aerial system is Y_f, then the measured admittance, Y, is related to Y_f by

$$(3) \qquad \frac{1}{Y} = \frac{1}{Y_f} + \frac{2}{Y_s}$$

Where Y_s is the admittance of the sheath around each wire. For the purpose of discussing the higher frequency results Y_s will be equated to $j\omega C_s$ calculated from equation (2). The values obtained for Y_f are larger than the measured values of Y by a maximum of 30 % for the capacitance component and a factor of two for the conductance component.

Discussion of the Measured Admittance near the Gyrofrequency

The first thing to notice about the measurements of Figure 1 is the small value of the admittance at frequencies away from the gyrofrequency. This is only one third of the calculated free space admittance of 28 pf when the aerial is fully deployed and the discrepancy increases as the length of the aerial is decreased. The whole of this discrepancy cannot be explained as a systematic error. This is probably less than 6 pf. It suggests that the rocket body has a considerable shielding effect ; acting as a screen between the two parts of the aerial system. The dimensions of the Skylark rocket head are approximately 2.5 m × 0.5 m. Bench tests of the effect showed it to be of the right magnitude to explain this result.

The resonance curves themselves are of the general form predicted by Kaiser, but each has its own peculiarity. There are several reasons why the shape of the resonance will be continually changing. The predicted value of the complex ratio of the aerial admittance in the ionosphere to that in free space is given by

$$(4) \quad Y/j\omega C_0 = \varepsilon_{eff} = \alpha_1(\cos^2\zeta + \alpha_3/\alpha_1 \sin^2\zeta)^{\frac{1}{2}}/(1+\log B),$$

where

$$\alpha_1 = 1 - \frac{XU}{U^2 - Y^2}$$

$$\alpha_3 = 1 - \frac{X}{U}$$

Where X, Y, U are the usual ionospheric parameters given by

$$X = \omega_N^2/\omega^2$$
$$Y = \omega_H/\omega$$
$$U = 1 - j\nu/\omega,$$

ζ is the angle between the dipole axis and the earth's magnetic vector. Log B is written for a complicated logarithmic expression involving ζ, α_1, α_3. However the value of this term is of order 0.1 for the aerial on Skylark and it will be neglected in what follows.

It is evident from the ionograms that the value of X over the range covered by the swept frequency device will be small. In this case α_3 is quite close to unity. The shape of the resonance curve is almost entirely determined by the values taken by α_1 and ζ. The angle ζ will vary as the rocket and aerial system rotate unless the axis of rotation is parallel to the earth's field. The rate of rotation of the round varied with the length of wire released, but, during the last ten seconds of deployment it was approximately 120° per second. The time occupied by the sweep past resonance is 0.6 seconds, thus it is possible that a significant variation in ζ can take place in this time. Changes in α_1 can occur if there is a variation of the ambient electron density during the sweep.

The variation of aerial admittance with frequency away from the central part of the resonance curve can be used to make an estimate of the plasma frequency. Such an analysis shows that this is approximately 550 kHz, confirming that X

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is small. In what follows it will be assumed that α_3 is nearly equal to unity.

The Shape of the Resonance Curves

The agreement between the admittance of the fictitious aerial system Y_f and the theory of Kaiser will be examined in more detail near the resonance itself. The complex value of α_1 is given in terms of its real and imaginary parts by

$$(5)\quad R(\alpha_1) = 1 - \frac{\omega_N^2(\omega^2 + \nu^2 - \omega_H^2)}{(\omega^2 - \nu^2 - \omega_H^2)^2 + 4\omega^2\nu^2}$$

$$I(\alpha_1) = -\frac{\nu}{\omega}\frac{\omega_N^2(\omega^2 + \nu^2 + \omega_H^2)}{(\omega^2 - \nu^2 - \omega_H^2)^2 + 4\omega^2\nu^2}.$$

Assume that $\zeta = 0$ for the moment, then ε_{eff} has the same form as α_1, and it can be shown that the half-width $\Delta\omega$ of $I(\alpha_1)$ as a function of ω is 2ν. The halfwidth of the curves showing G as a function of f in Figure 9 is 0.02 MHz giving an approximate value for ν of

$$(6)\qquad 6.3 \times 10^4 \text{ per second.}$$

This value is much higher than those usually quoted for this height. A typical value of ν determined from ground-based experiments is 10^4 per s.

In Figure 2 plots of C_f and G_f/ω are shown in the Argand diagram. Their significance will be clear from equation (4). Also plotted are the two functions $\alpha_1 C_0$ and $\sqrt{\alpha_1}\, C_0$, the two extreme values of $\varepsilon_{eff}C_0$. These curves are defined by the dimensionless parameter $\omega_N^2/\nu\omega_H$ whose values has been placed at 16. The points shown in Figure 2 are for the measurements taken between 126 km and 130 km. The measurement of admittance

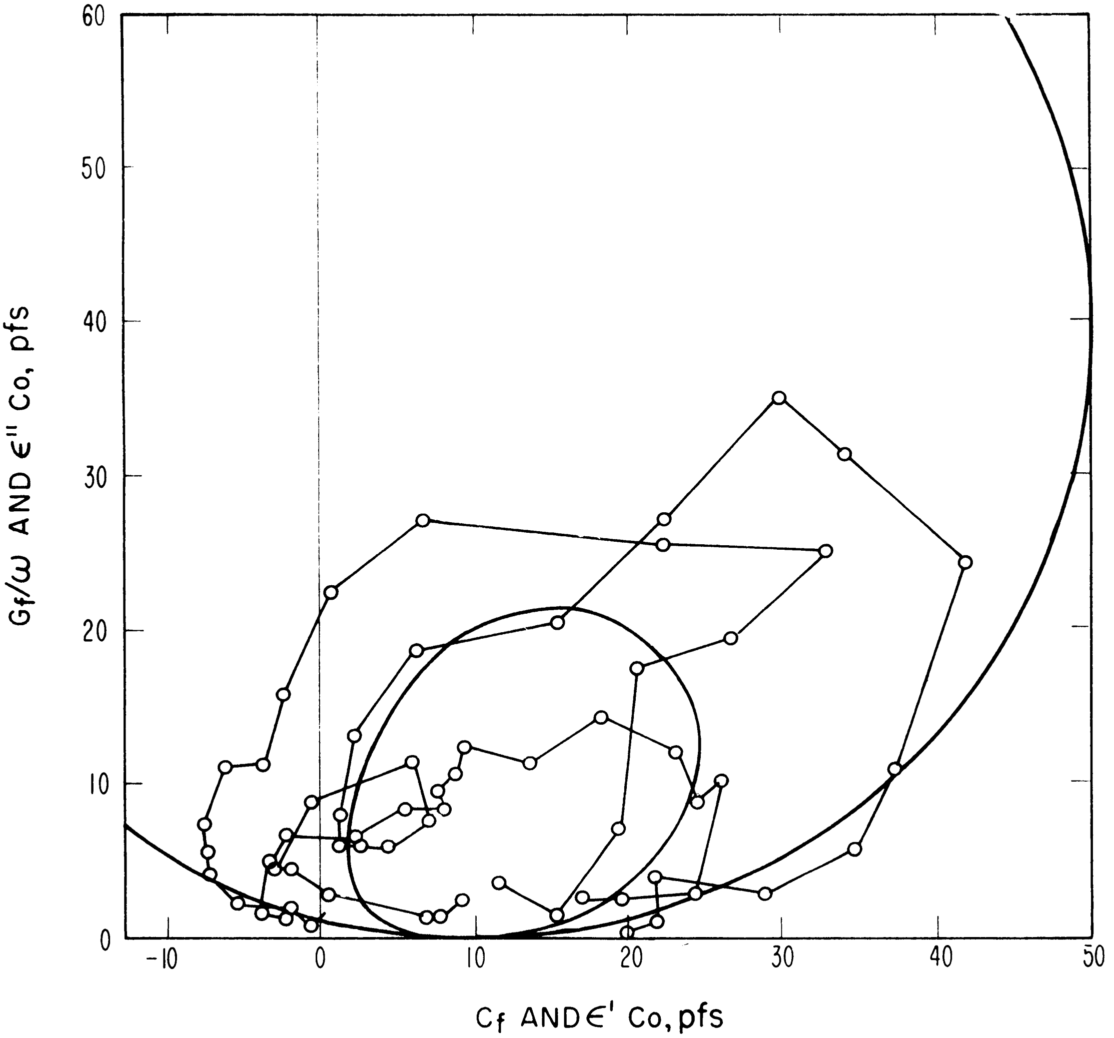

Fig. 2. — Plots in the Argand diagram of the admittance of the fictitious aerial system. The two functions $C_0\alpha_1$ and C_0/α_1 are also shown. C_0 was taken to be 10 pf and α_1 is defined by the dimensionless parameter $\omega_N^2/\nu\omega_H$, whose value was placed at 16.

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at 125 km has a much smaller range than those at greater heights and is not consistent with the measurements of the other three curves.

It is seen that the fit with the theoretical curves is not especially good. This is not surprising in view of the number of approximations that have been made. In particular it was not possible accurately to assess the shielding effect of the rocket body, and the angle between the aerial wires and the magnetic vector was unknown and could not be allowed for in detail. However, it should be noted that the magnitude of the conductance component of aerial admittance near resonance is of the same magnitude as the maximum susceptance component as predicted by the theory of KAISER.

60 kHz MEASUREMENTS

The measurements of admittance at 60 kHz, made for an interval of 3s just before the aerial shorted, are shown in Figure 3. Corrections have been applied for the effect of stray capacitance between the aerial wires inside the rocket body, and between the wires and the body itself, but the effect of the ion sheath has not been corrected for. Indeed, at such a low frequency, one may expect the ion sheath to contribute the largest part of the total impedance. There is a well defined modulation of the observed admittance repeating at twice the spin frequency ; its explanation is considered below.

MLODONSKY and GARRIOTT assume that at such low frequencies the ionospheric plasma acts as an almost perfect conductor, so that it can not support any electric fields. In this case the measured admittances is just that of the ion sheath. In order to account for the spin modulation of the measured admittance it might be supposed that the radius of the sheath varies. The voltage induced along the aerial wire by its rotation in the earth's magnetic field is much too small to account for this effect. It is only 12 mV.

The ion sheath may also be modulated in the following way. Its radius depends on the voltage acquired by the wires and rocket body. The positive ion current to the aerial and rocket body depends on their frontal area projected in the direction of motion. This may vary appreciably as the rocket rotates. In order to balance the positive ion current the electron current will also vary, and so will the sheath radius.

The measured capacitance could be a function of the angle between the aerial wires and the rocket body. If the body has sufficient effect and the angle of precession is large it provides a very simple explanation of the observed modulation. This point can be examined in more detail when the records of the magnetometers and rate gyros have been analysed. The modulation frequency in this case is not quite equal to the spin frequency but depends also on the precession rate of the rocket head.

EXPLANATION OF THE RESULTS BY KAISER'S THEORY

KAISER's theory accounts for the spin modulation in a quite different way. If we take the values of f_N and f_H given by the higher frequency results it follows that, at 60 kHz,

$$X = 84$$
$$Y = 26$$

Under these conditions the appropriate formula for aerial admittance of a thin dipole given by KAISER is

$$Y_f = j\omega C_0(1 - X\sin^2\zeta)^{\frac{1}{2}}, \tag{7}$$

where C_0 is the free space capacitance of the fictitious aerial system. For values of ζ greater than 7° in the present case Y_f is a pure conductance whose value is strongly dependent on ζ.

For comparison with KAISER's theory it is convenient to convert the measured admittance in the equivalent series combination of a capacitance C_s with a resistance R_s. The results are presented in the lower half of Figure 3. Now identify C_s with the sheath capacitance and R_s with the resistance of the fictitious aerial system. The sheath capacitance is seen to be much less variable, although there is still some effect of the rotation. The strong spin modulation exhibited by R_s which is equal to $1/Y_f$ can be explained by variation of the angle ζ, between the aerial wires and the magnetic vector. Detailed comparison with the theory must await the results of analysis of magnetometer data.

CONCLUSION

It is concluded that the variation of the admittance of the simple dipole aerial system used on Skylark 81 A can be adequately explained within the limits of experimental error by KAISER's theory of this variation, although some unexpected effects occurred. In particular the rocket body

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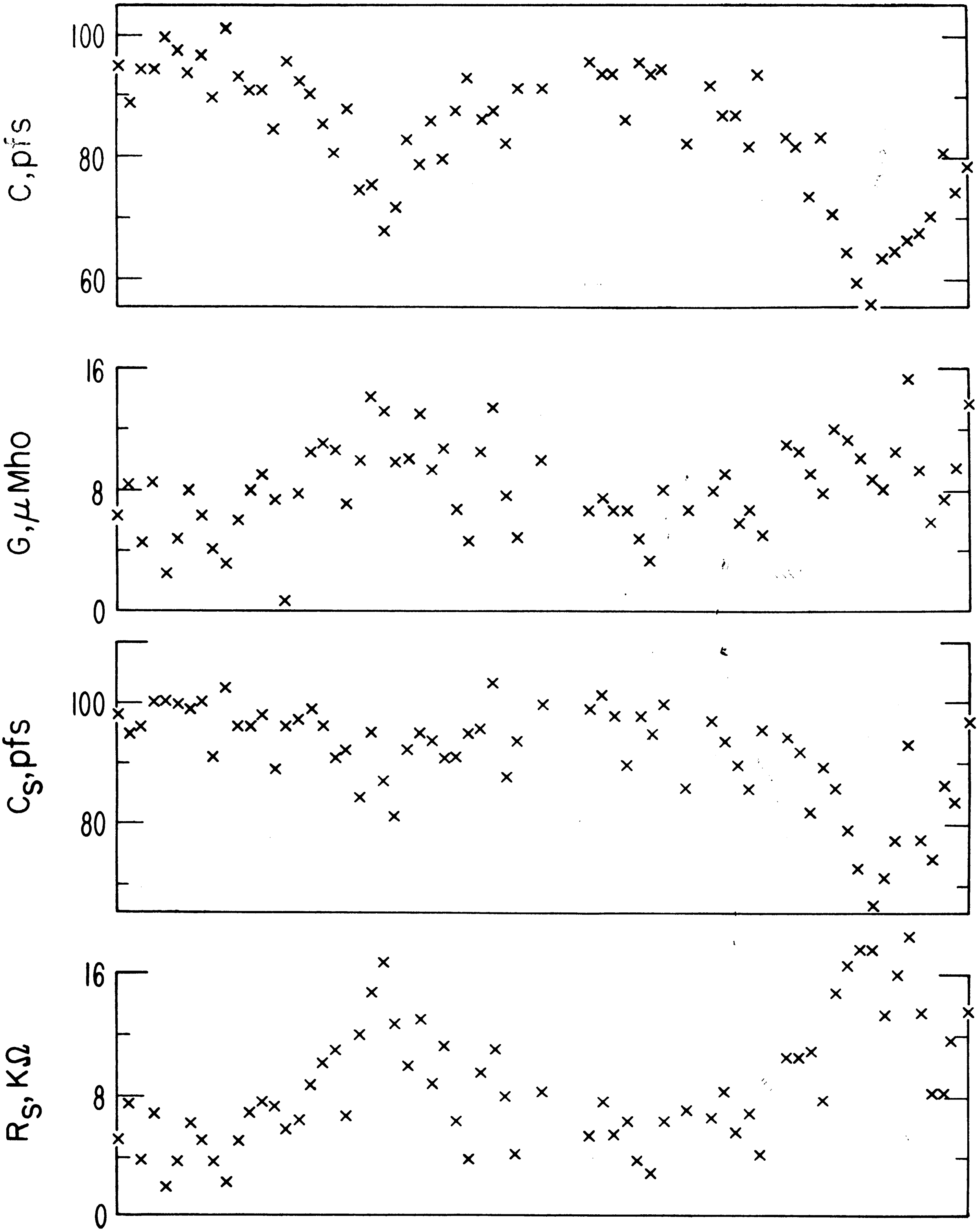

Fig. 3. — Aerial admittance at 60 kHz and the equivalent séries combination, R_s and C_s.

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had an appreciable effect of shielding the two wires of the dipole from each other. It is possible that discrepancies between theory and experiment will become apparent when the orientation between the aerial wires and the earth's magnetic vector can be estimated.

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