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MEASUREMENTS OF ANTENNA IMPEDANCE IN THE IONOSPHERE. II. OBSERVING FREQUENCY GREATER THAN THE ELECTRON GYRO FREQUENCY

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ABSTRACT

23736

The results of measurements of the impedance of a short dipole antenna in the ionosphere at observing frequencies above the electron gyro frequency but near the electron plasma frequency are reported. The reactive component of impedance is found to change from capacitive to inductive at the hybrid resonance frequency, $X = 1 - Y^2$, as predicted by theory. The real component of impedance becomes orders of magnitude larger than the free space radiation resistance in the region bounded by the hybrid frequency, $X = 1 - Y^2$, and the plasma frequency, $X = 1$, in qualitative agreement with theory. For $X > 1$, however, the resistance remains larger than predicted theoretically. Although the large peaks in resistance are accompanied by large enhancements in the apparent radio noise level, it is still not clear what portion of the measured resistance is due to electromagnetic radiation. Other mechanisms such as losses via electrostatic waves may help to account for the difference between the experimental data and simple theory.

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INTRODUCTION

In a previous paper (1), the driving point impedance characteristics of a short dipole as measured in the ionosphere were discussed for magneto-ionic conditions corresponding to the observing frequency less than the electron gyro frequency ($Y < 1$). For observing frequencies near the electron plasma frequency, the resistive component of impedance was found to be many orders of magnitude larger than the free space radiation resistance, whereas the measured reactance, which was capacitive, decreased with increasing plasma frequency. Qualitative agreement was found between these measurements and the existing theories of antenna impedance in a magneto-ionic medium. The possible physical significance of the large resistance was discussed, although from the impedance measurements alone it was not possible to reach a definite conclusion.

In this paper additional results are presented which extend the measurements to observing frequencies higher than the electron gyro frequency. Here again, conditions are found for which, in addition to a reversal of the sign of the reactive part of the impedance, large resistive components of impedance exist. Part of the data to be presented was obtained from a radio astronomy rocket experiment (2) so that the received radio noise data can be compared with the impedance measurements obtained on the same flight. This type of comparison is of considerable value in attempting an interpretation of either the noise data or the impedance measurements. Walsh and Haddock (3) have given a critical review of many aspects of impedance measurements with respect to their effects on radio astronomy measurements in space.

In order to interpret the experimental data to follow, it will be useful to consider both the propagation of radio waves in a magneto-ionic medium and the expected impedance characteristics of an antenna immersed in an anisotropic plasma. This can be conveniently done by considering the various regions shown on the X versus Y^2 diagram in Figure 1. Here $X = \left(f_p/f\right)^2$ and $Y = \left(f_H/f\right)$ where f_p is the electron plasma frequency, f_H is the electron gyro frequency, and f is the observing frequency. Figure 1 also shows the trajectories of observations encountered during the flight experiment.

The wave propagation modes are considered first. In region I ($0 < X < 1 - Y$) both the ordinary and extraordinary waves can propagate in the plasma. In region II $\left(1 - Y < X < 1 - Y^2\right)$ only the ordinary wave can propagate. In region III $\left(1 - Y^2 < X < 1\right)$ the ordinary wave can propagate in any direction

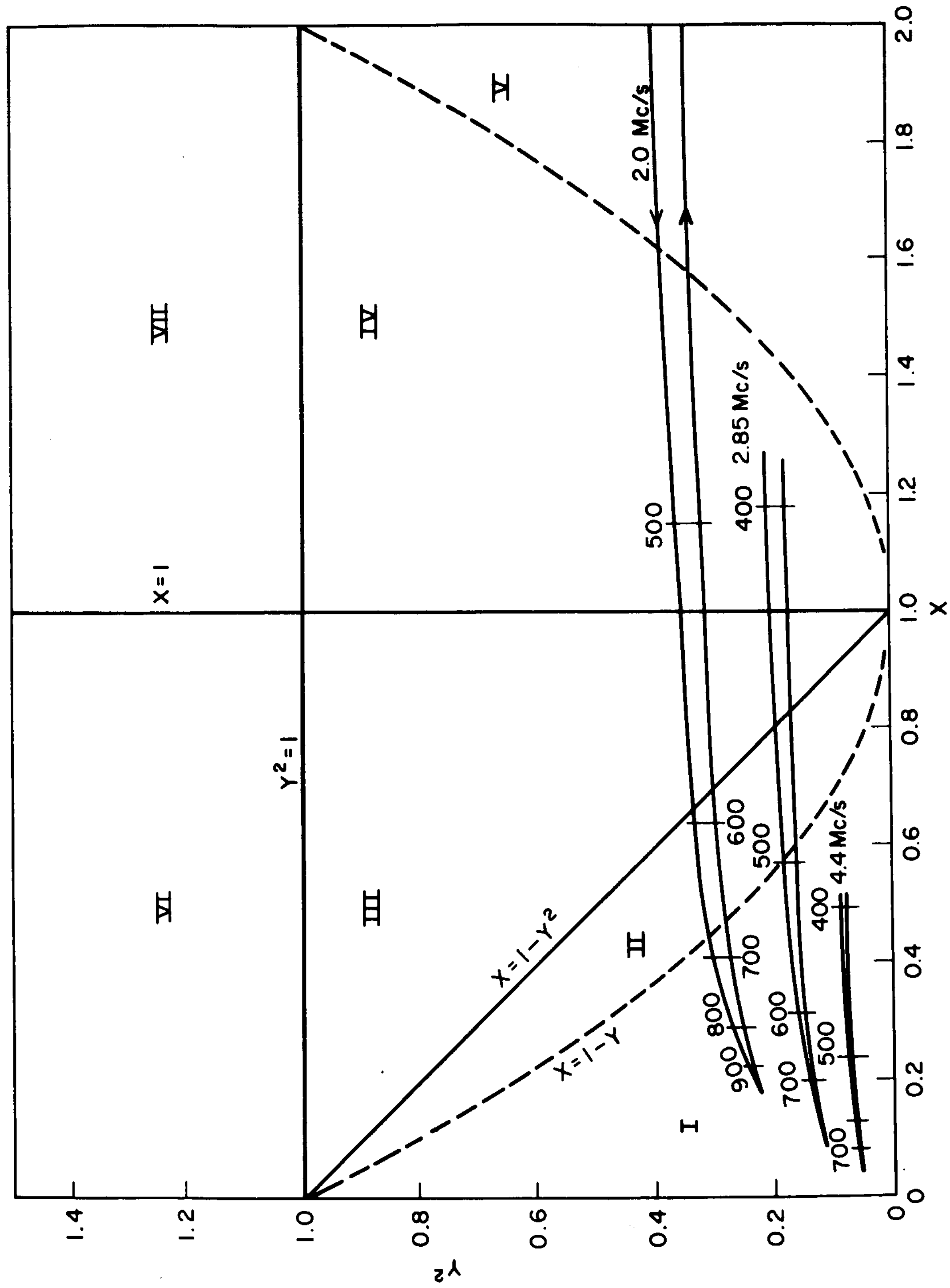

VII
VI
IV
III
II
I
V
X = 1
$Y^2 = 1$
$X = 1 - Y^2$
$X = 1 - Y$
2.0 Mc/s
2.85 Mc/s
4.4 Mc/s
500
400
600
700
800
900
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
X
Y^2

Figure 1

while the extraordinary wave will propagate only at large angles to the magnetic field. In region IV ($1 < X < 1 + Y$) only the extraordinary wave is able to propagate. For region V ($X > 1 + Y$) neither mode should be able to propagate.

If only the modes of propagation needed to be considered, then the received noise would be governed by the above considerations alone. In fact, there are changes in antenna impedance due to changes in the dielectric constant of the magneto-ionic medium which are further complicated by the disturbance of the medium due to the presence of the antenna and rocket. These latter effects are extremely difficult to handle quantitatively in many cases. (In a subsequent paper in this series, the variation of impedance as a function of angle between the antenna and the static magnetic field will be considered in which we will show that the perturbations in the ambient plasma produced by the rocket and antenna can at times "swamp" magneto-ionic impedance effects.)

Many of the theories of the impedance of a short dipole were discussed in connection with the results presented earlier (1). For example, from the principle term of the theory derived by Ament et al. (4),

$$Z = \frac{\ln\left(\frac{L}{\rho}\right)}{j c 2\pi\epsilon_0} \frac{\cot\ (\omega PL/c)}{P} \tag{1}$$

where

$$P^4 = \alpha_1^2\left(\cos^2\theta + \frac{\alpha_3}{\alpha_1}\sin^2\theta\right), \tag{2}$$

we can get an approximate expression which describes the general characteristics of a very short antenna –

$$Z = \left[\frac{\ln\left(\frac{L}{\rho}\right)}{j\omega 2\pi\epsilon_0 L}\right]\left[\alpha_1\left(\cos^2\theta + \frac{\alpha_3}{\alpha_1}\sin^2\theta\right)^{1/2}\right]^{-1} \tag{3}$$

The first bracketed term is the free space reactance of a short monopole of length L, radius ρ, and excitation angular frequency ω. In this short antenna approximation the real component of the driving point impedance is zero. In equation 2 and 3

$$X = (\omega_P/\omega)^2, \qquad Y = (\omega_H/\omega), \qquad Z = (\nu/\omega)$$

$$\alpha_1 = 1 - \frac{XU}{U^2 - Y^2}, \qquad \alpha_3 = 1 - \frac{X}{U}, \qquad U = 1 - jZ$$

where ω_p is 2π times the plasma frequency, ω_H is 2π times the gyro frequency, ν is the collision frequency, and θ is the angle between the antenna and the magnetic field. The second bracketed term in equation 3 then accounts for the interaction of the antenna with the plasma. Similar results are obtainable from the work of Balmain (5) and Kaiser (6). Most of the theoretical work assumes that the antenna does not disturb the ambient plasma, i.e. the effects of ion sheaths, plasma waves, inhomogeneities, etc. are neglected.

Referring again to Figure 1, the following characteristics of the impedance are inferred from equation 1 or 3. In region I, the reactance is capacitive and greater than its free space value. In region II, although the simplified expressions show no unusual behavior, both Ament (4) and Weil and Walsh (7) have shown the occurrence of changes in the resistance. When the upper hybrid resonance, $X = 1 - Y^2$, is crossed, the resistive component of impedance can become very large (particularly for the small collision frequency applicable to the experimental conditions), and the reactance changes sign to become inductive. When the plasma frequency is crossed at $X = 1$, another peak in the resistance and a small increase in reactance is predicted.

EXPERIMENTAL MEASUREMENTS

With one exception, all of the experimental data to be presented were obtained from a Javelin rocket flight using an improved version of the impedance probe described previously (1). To improve the measurement accuracy for the range of small resistance values, an expander readout channel for the phase output in the 80° - 90° range was used. The antenna system was a dipole formed by two (Raymond Engineering) telescoping monopoles of length 4.88 meters and 0.44 cm average diameter. No DC bias was applied to the antenna system. The topside ionospheric electron density distribution was obtained from a pass of the Explorer XX topside sounder satellite over Wallops Island close to the time of rocket launch (1100 EST, 23 Oct. 1964). Good data were obtained for the entire 20 minutes of flight which reached an apogee altitude of 1068 km. Since the rocket was primarily intended for radio noise measurements, impedance measurements were taken at the frequencies of 2.0, 2.85, and 4.4 Mc/s at twenty second intervals. The impedance data at 2.0 Mc/s shown in Figure 4, however, was obtained on the Apache rocket experiment previously reported (1) using a 2.6 meter dipole biased +4.5 v DC with respect to the rocket body. The latter measurements were performed in the lower ionosphere where electron collision effects may not be considered negligible.

The experimental data for 2.0 Mc/s on the high altitude flight are shown in Figure 2. All measurements were obtained in the topside ionosphere, and hence electron density decreases with altitude. The upper plot shows the variation of

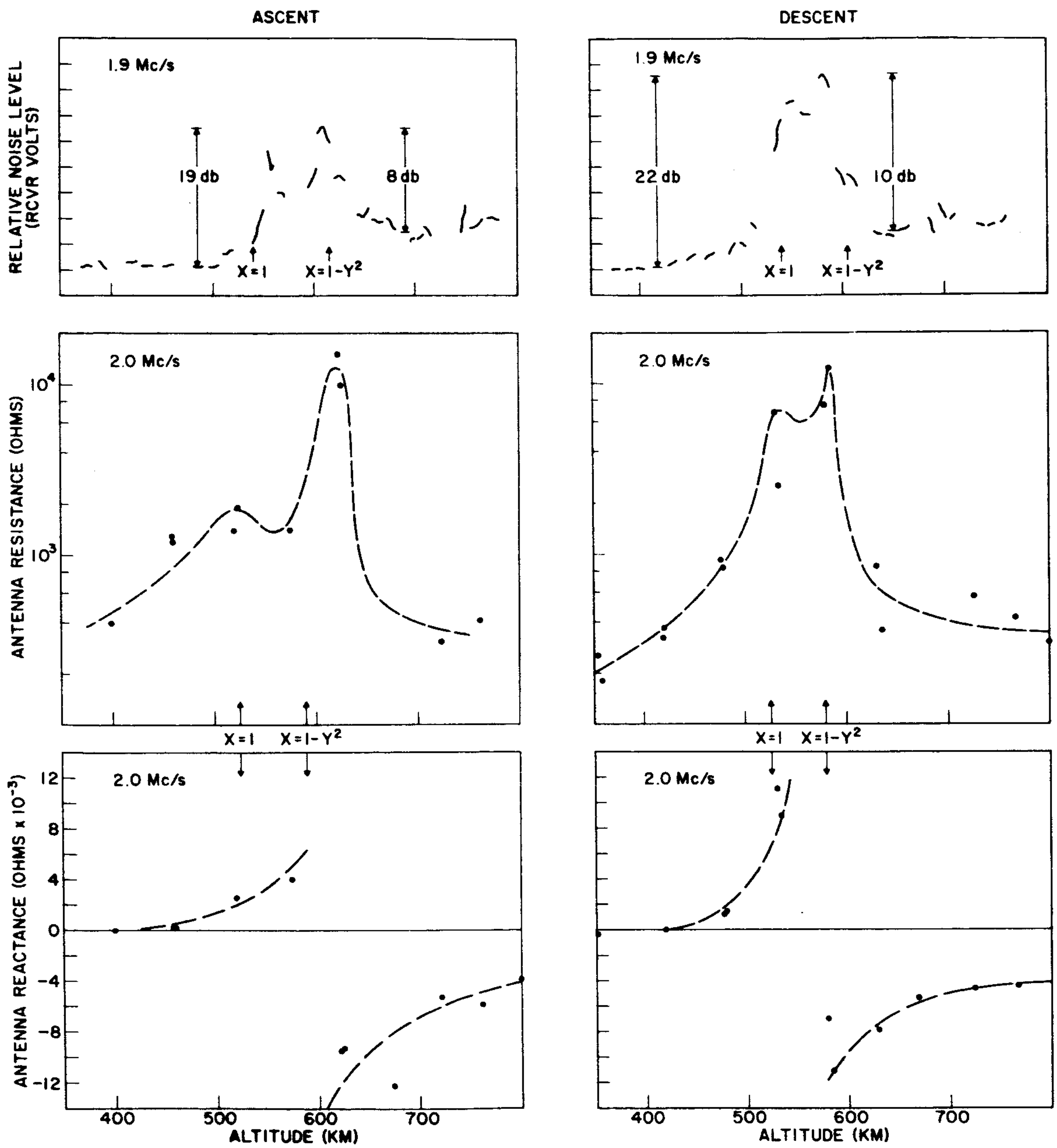


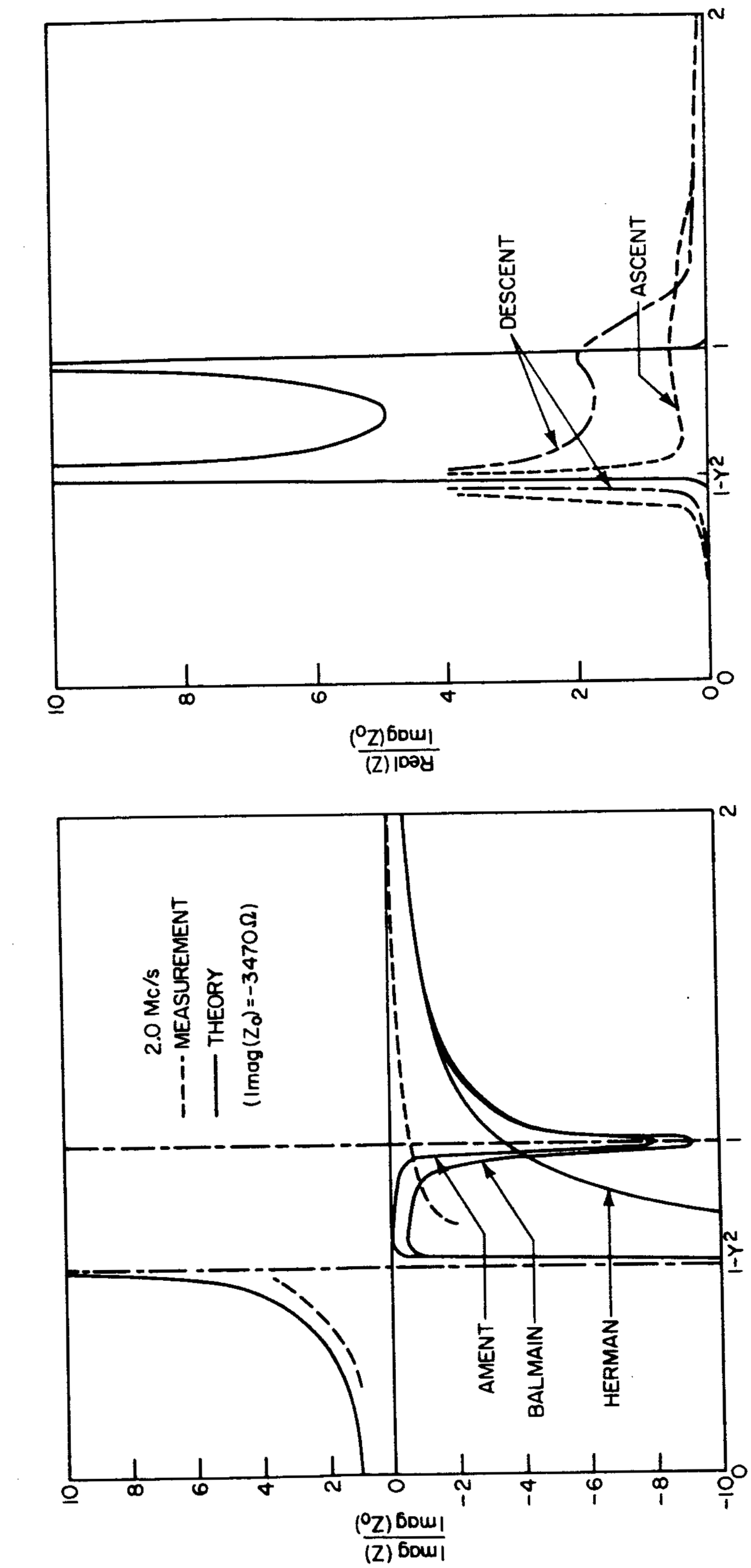
Figure 2

apparent radio noise intensity as a function of altitude. During both ascent and descent, enhanced radio noise was observed in the region bounded approximately by $X = 1$, the plasma frequency, and $X = 1 - Y^2$, the upper hybrid frequency. Similar noise enhancements have been observed on other rocket and satellite experiments (8, 9, 10). Although the noise enhancement appears to be composed of two peaks, part of this effect may be attributed to the change in aspect between the antenna and magnetic field. The data obtained by Harvey (10) for example, does not seem to show a bifurcation. Note, however, the difference in the dip between the ascent and descent results.

The middle set of curves in Figure 2 shows the variation of the driving point series resistance for ascent and descent. The experimental measurements are shown by the individual dots whereas the dashed curves represent our attempt to present the smooth variation of impedance consistent with the data points. Obviously, this is not the only smooth curve which will fit the data. Furthermore, because the long period between sampling was comparable to the spin period of the rocket detailed variations might well have been missed. The most striking features of this data are the peak in resistance at the hybrid frequency and a less pronounced maximum at the plasma frequency. Proceeding from the less dense plasma region, the resistance increases quite rapidly near $X = 1 - Y^2$ and then decreases to a minimum between this frequency and the plasma frequency although the value at the minimum still represents a considerable resistance. Beyond the peak at $X = 1$, the resistance decreases at a rather slow rate. The bottom set of curves in Figure 2 show the corresponding reactance measurements. The most important feature is the rapid change from capacitive to inductive reactance at the hybrid frequency. Although there is no clear evidence for a large change in the reactance at $X = 1$, the data are not sufficient to provide conclusive answers on this point.

In Figure 3 the theories as derived by Ament (4), Balmain (5) and Herman (11) have been compared with the experimental results for 2 Mc/s. The curves have been normalized to the free space reactance value. The curve on the left in this figure shows the behavior of the reactance. For $X < 1 - Y^2$ where the individual theories give nearly identical results, the agreement is very good. At the hybrid frequency, the abrupt change in the sign of the reactance occurs as predicted. Beyond this point the agreement is only qualitative at best. An exact comparison is difficult, however, because of the unknown influence of the measuring system on the ambient plasma as well as unknown collision effects. There is no indication of a dip at the plasma frequency although as stated earlier the sampling rate was too slow to definitely establish this point. For large values of X, the agreement between theory and experiment improves. Considering the uncertainties regarding the perturbations on the plasma by the measuring system as well as the limitations of the theory the overall agreement is good.

The curve on the right of Figure 3, shows the comparison for the resistance. The theories of Balmain and Ament do predict a large value of resistance at the plasma frequency and hybrid frequency as is found. The measured values are generally below the theoretical predictions although still considerably above the



2.0 Mc/s
MEASUREMENT
THEORY
(Imag(Z₀)=-3470Ω)
AMENT
BALMAIN
HERMAN
DESCENT
ASCENT
Imag (Z) / Imag (Z₀)
Real (Z) / Imag (Z₀)
1-Y2

Figure 3

free space radiation resistance. The measurements also show a substantial component of resistance beyond $X = 1$ which decays slowly with increasing plasma frequency. For values of X less than $1 - Y^2$, the increase in resistance is quite abrupt as the hybrid frequency is approached. It would appear then, that the theory as presented here is able to account only for the general characteristics of the observed impedance properties. The broadening of the resistance curves and the decrease in their amplitude compared to the predicted values seems to be indicative of a damping mechanism in addition to the collisions which have been already incorporated in the calculations. We shall consider this question later.

Preliminary results of the low altitude measurements of antenna resistance at 2.0 Mc/s are shown in Figure 4. The conditions of this experiment differ from

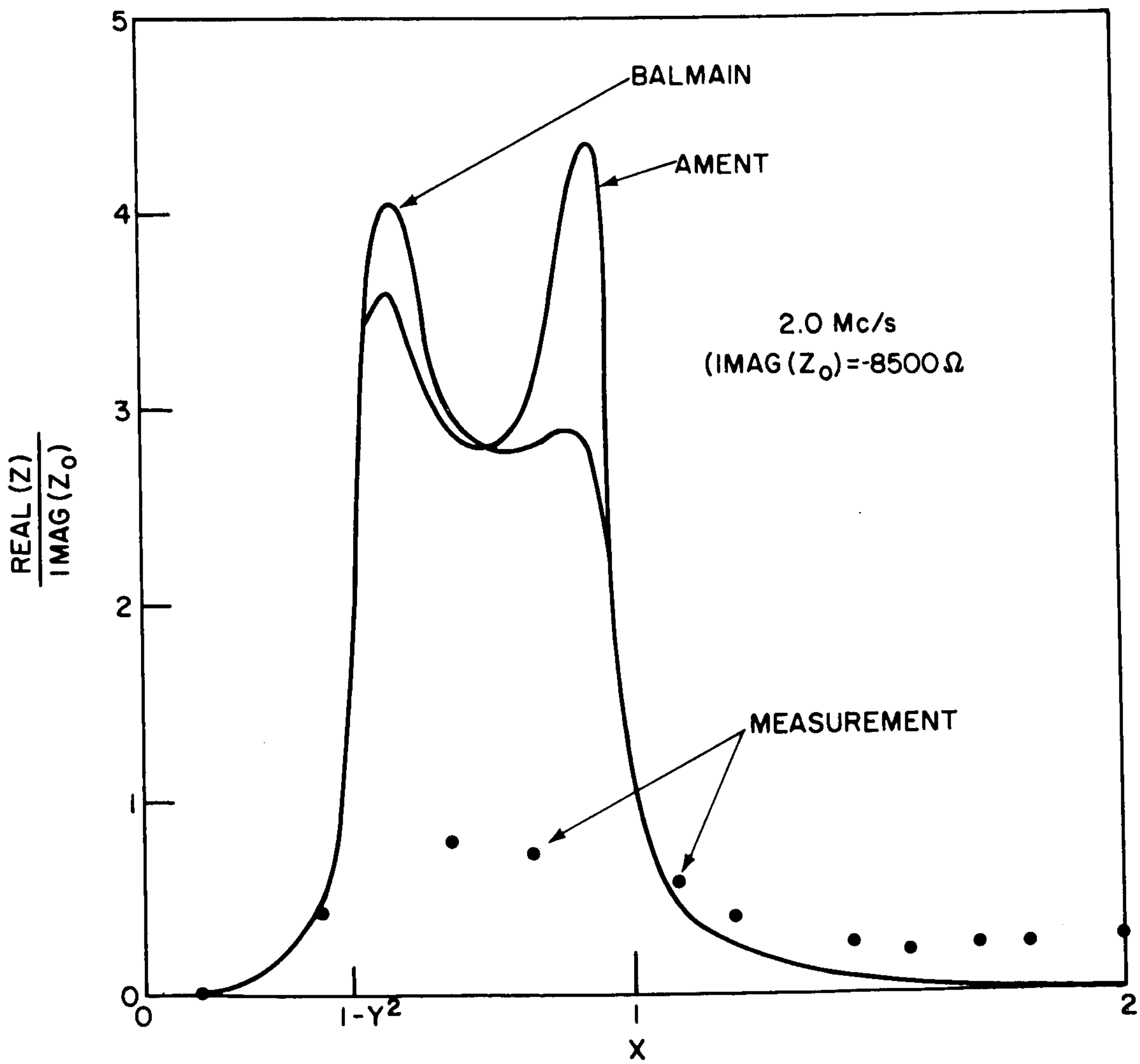


Figure 4

those of the measurements described above in that the antenna was only 1/4 as long as in the high altitude experiment, a DC bias of about +4.5 v was applied to the antenna, and the electron collision frequency was roughly 10^3 times greater for the measurements in the lower ionosphere. Although the resolution in altitude, or X, is still hampered due to the time-sharing manner in which the measurements were made, one can see the same general behavior of the resistance . The measurements show a large increase in the neighborhood of $1 - Y^2 < X < 1$ which only partially decays beyond $X = 1$. The data confirm the results of Figure 3 showing only qualitative agreement with the theory.

Smoothed plots of the measured antenna impedance at 2.85 Mc/s from the high altitude experiment are shown in Figure 5. The reactance is essentially identical to that predicted by theory for $X < 1 - Y^2$, although after becoming inductive at the hybrid resonance the agreement is no better than in the case of the 2 Mc/s data shown in Figure 3. The resistance shows a sharp peak at $X = 1 - Y^2$. Radio noise measurements at 2.85 Mc/s confirm the data at 2.0 Mc/s and show a strong enhancement between $X = 1 - Y^2$ and $X = 1$ which accompanies the increase in resistance in this region.

The measurements at 4.4 Mc/s, which cover a much smaller range in X, are shown in Figure 6. The results are characterized by close agreement between theory and experiment for the reactance and an appreciable value of the resistive component even for small X. When collisions are negligibly small, the theory does not predict an increase in resistance until $X = 1 - Y^2$.

DISCUSSION

The physical significance of the resistive component of the driving point impedance has been considered by a number of investigators, although as yet a completely satisfactory theory does not exist. When the antenna is excited during the impedance measurements, it is not clear just how the power supplied to the antenna is partitioned between electromagnetic radiation and other loss mechanisms such as electrostatic waves. The separation into purely transverse and longitudinal waves may not always be possible in the presence of a static magnetic field, although for the present discussion we shall assume that the separation is possible so that the contributions to the resistance from radiation and plasma waves may simply be added. In the previous paper (1) a number of the theoretical results which explain the large resistance observed for a short antenna in a magneto-ionic medium in terms of a real radiation resistance have been discussed. Several investigators suggest that along a cone of half angle

$$\theta = \arc \sin \left[\left(Y^2 - 1 + X \right) / (XY) \right] \qquad (4)$$

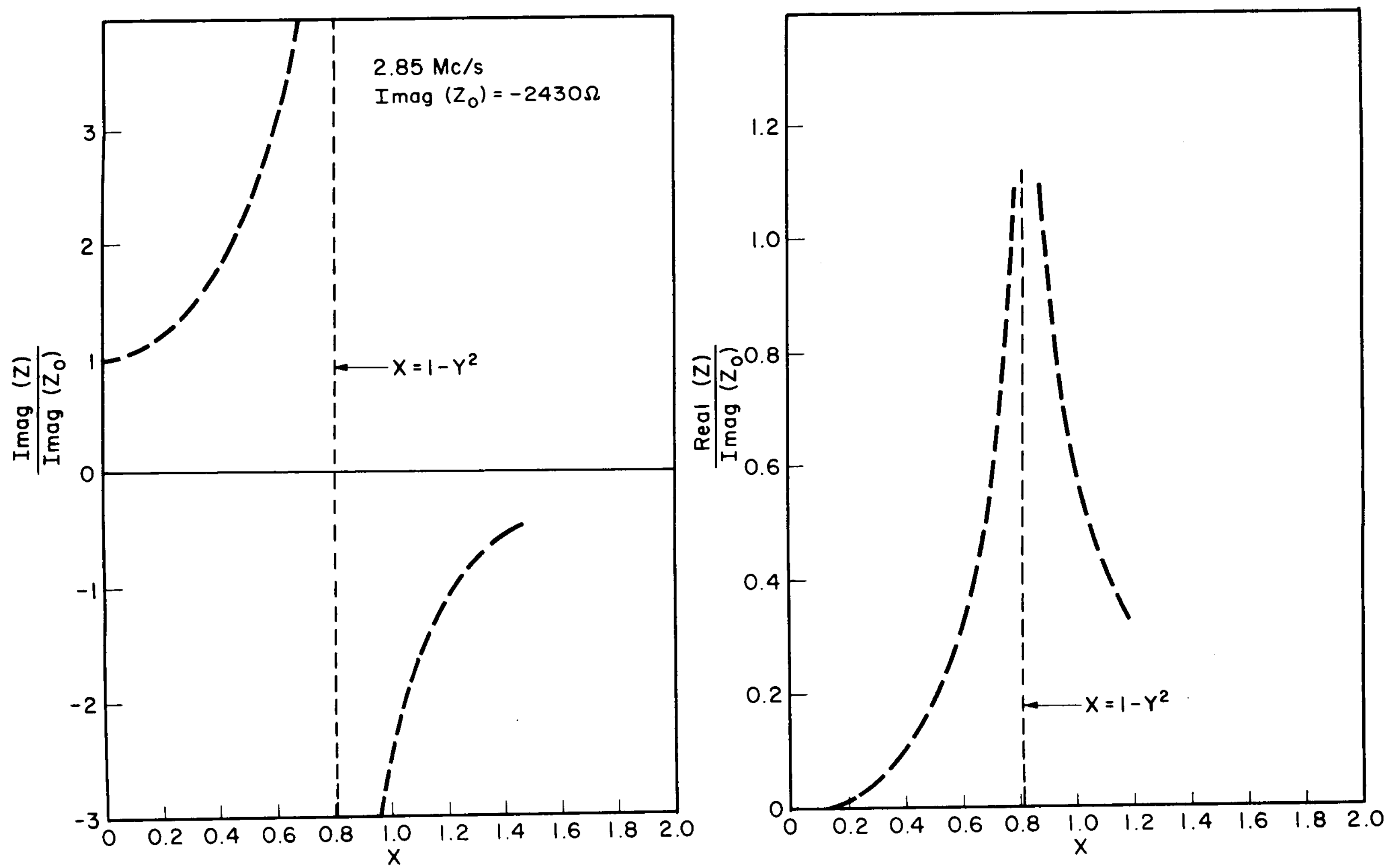
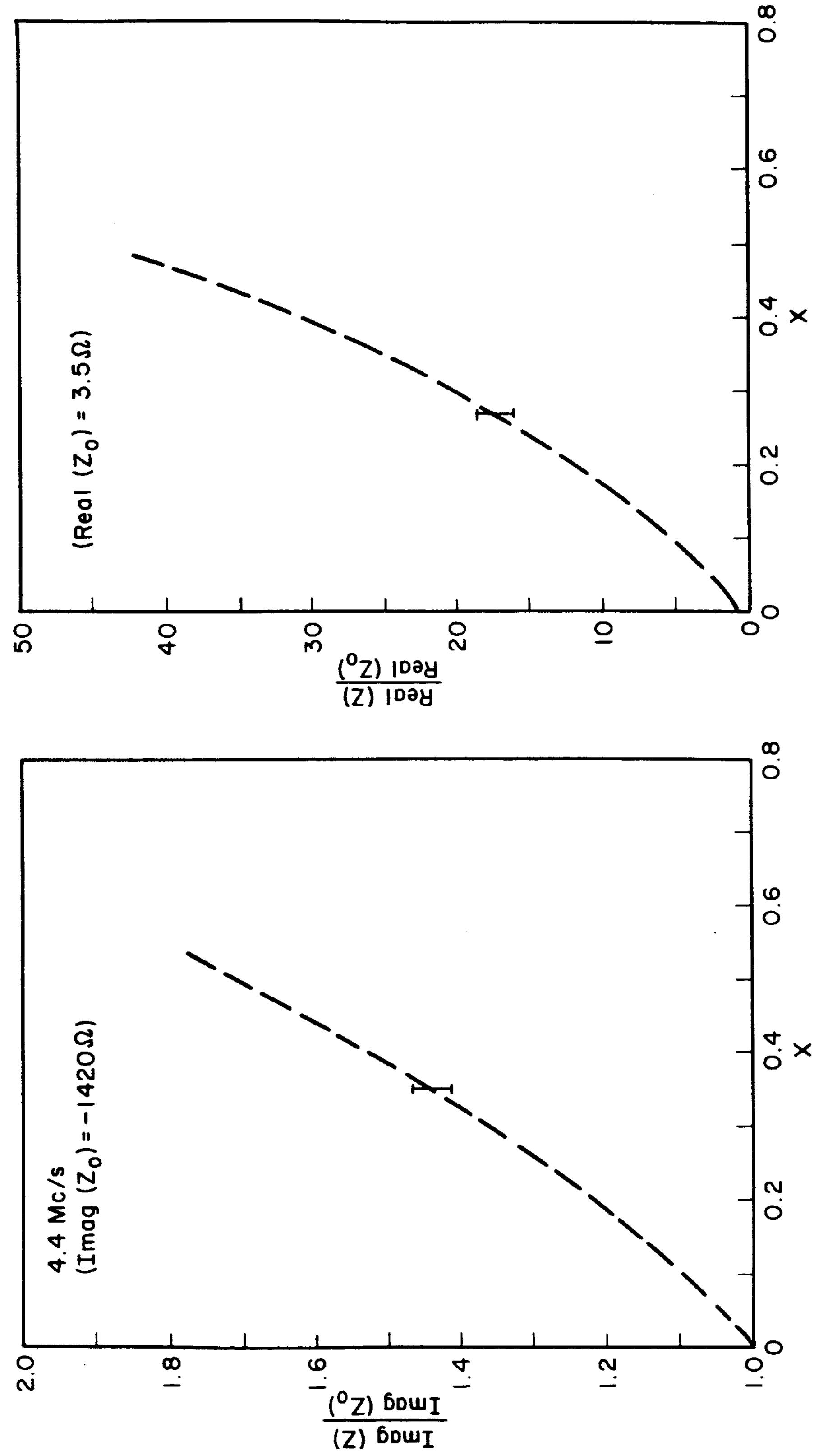

2.85 Mc/s
Imag (Zo) = -2430Ω
X = 1-Y²
Imag (Z) / Imag (Zo)
Real (Z) / Imag (Zo)
X
3
2
1
0
-1
-2
-3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Figure 5



4.4 Mc/s
(Imag (Z_o) = −1420Ω)
(Real (Z_o) = 3.5Ω)
Imag (Z) / Imag (Z_o)
Real (Z) / Real (Z_o)
2.0
1.8
1.6
1.4
1.2
1.0
50
40
30
20
10
0
0.2
0.4
0.6
0.8
X

Figure 6

about the antenna the electric field, and consequently the radiated power, may become very large (12, 13). Far field measurements would go a long way towards determining what part of the resistance is due to electromagnetic radiation losses.

A considerable amount of work is available on the generation of electrostatic waves in a current-carrying plasma. The problem as it relates to the antenna has been investigated by Cohen (14), Whale (15), Walsh and Haddock (3), and Balmain (5). Walsh and Haddock utilize Cohen's work and a triangular current distribution to show that the electrostatic waves contribute to the resistance an amount given by

$$R_p = 60 \frac{\lambda_0}{L} \left(\frac{X}{1 - X} \right) \qquad (5)$$

where L is the length of a filamentary dipole and λ_0 is the free space wavelength. Equation 5 applies to the field-free case and is applicable for $L \gg \lambda_p$. λ_p, the wavelength in the plasma, is given by $v_0 \, (f \, (1 - X)^{1/2})^{-1}$ where v_0 is the electron thermal velocity. This result illustrates that plasma waves can contribute significantly to the resistance particularly as the plasma resonance is approached. Balmain's calculations of the effects of plasma waves take into account the finite diameter of the antenna. It seems likely that a treatment of this problem including the static magnetic field will give a resistance which includes a dependence on the hybrid resonance since this is also an electrostatic mode. It is interesting to note that on the Alouette satellite resonance effects due to longitudinal waves have been observed to occur at the plasma frequency, multiples of the gyro frequency and the hybrid frequency (16).

A loss mechanism which results from electrons being absorbed at the metallic boundary of the antenna has been suggested by Bramley (17). Balmain (18) has analyzed the impedance of a parallel plate capacitor with an absorptive surface for the case where the ion sheath is collapsed. His results show a resistive component of impedance even in the collisionless plasma case. For very large X, the impedance is predominently resistive, very much as is indicated in our data at large X.

Figure 2 shows the presence of an increased noise level which extends over the band of frequencies from the plasma resonance to the hybrid resonance. Similar bands of increased noise has been reported by Walsh, et al. (8), Huguenin, et al. (9) and Harvey (10). Although these observations have frequently been interpreted as evidence of real noise fields in the ionosphere, one cannot neglect the possibility that the apparent noise enhancements are only the result of an enhancement of the antenna radiation resistance. Our limited data would seem to indicate that the noise enhancement extends to the hybrid frequency; whereas Harvey's more extensive data suggests that the noise has dropped off to its undisturbed value at the hybrid resonance. If this is in fact the case, then the large resistance which we observe at the hybrid frequency would seem not to be mainly radiation resistance.

The nature of the noise enhancements is an extremely important question. If the noise is a real property of the ionosphere, its origin is not clear. On the other hand it may be generated by the presence of the antenna and rocket which disturb the ambient plasma distribution. For example, the noise may be generated in the near field of the antenna by a conversion of electrostatic waves into radiation field energy. If electrostatic waves can be generated by the antenna, there are a number of mechanisms, such as density gradients, which could convert this electrostatic field into the radiation field. Even in the absence of such density gradients or inhomogeneities, there may still be a flow of energy from the longitudinal to the transverse mode. The generation of radio waves from the longitudinal wave conversion at a gradient is considered for example by Field (19) and Tidman (20). The production of radio noise even in the absence of gradients has been analyzed for large amplitude plasma oscillations by Tidman and Weiss (21) and Dawson and Oberman (22), for example. We note that along the cone defined by equation 4, the large electric fields predicted would be especially conducive to production of plasma oscillations.

CONCLUSIONS

Comparison of measurements of the impedance of a short dipole in the ionosphere has shown only qualitative agreement with theory. How much of the difference between theory and experiment is due to basic assumptions which make the theory weak in certain regions or to processes for which the theory does not account remains to be seen. In the magneto-ionic region bounded by the plasma resonance and the upper hybrid resonance, large increases in the real part of the antenna impedance are accompanied by enhancements in the apparent radio noise level. From our data it has not been possible, so far, to determine whether the noise bands are ionospheric noise fields or just the effects of an increased "radiation" resistance. The measurements do suggest, however, that the impedance of the antenna is affected, in part, by other loss mechanisms such as electrostatic waves, collision effects and absorption of electrons on the surface of the antenna.

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