Antenna Laboratory Report No. 70-3

IMPEDANCE OF CYLINDRICAL ANTENNAS IN PLASMA -- A REVIEW

by

S. W. Lee and M. J. Al-Hakkak

Scientific Report No. 13

January 1970

Sponsored by

National Aeronautics and Space Administration

NGR-14-005-009

Antenna Laboratory
Department of Electrical Engineering
Engineering Experiment Station
University of Illinois
Urbana, Illinois 61801

Antenna Laboratory Report No. 70-3

IMPEDANCE OF CYLINDRICAL ANTENNAS IN PLASMA -- A REVIEW

by

S. W. Lee and M. J. Al-Hakkak

Scientific Report No. 13

January 1970

Sponsored by

National Aeronautics and Space Administration

NGR-14-005-009

Antenna Laboratory
Department of Electrical Engineering
Engineering Experiment Station
University of Illinois
Urbana, Illinois 61801

ACKNOWLEDGMENT

The authors wish to acknowledge the support of the National Aeronautics and Space Administration through Grant No. NGR-14-005-009. Also, appreciation is expressed to Prof. G. A. Deschamps for many fruitful discussions.

TABLE OF CONTENTS

Page

PART I: THEORY

Page

PART II: MEASUREMENTS

LIST OF FIGURES

Figures Page

PART I

THEORY

by

S. W. Lee

M. J. Al-Hakkak

1. INTRODUCTION

A plasma is an ionized gas composed of electrons and ions with an effectively zero net charge density, and is sometimes called the fourth state of matter. An interest in the problems of antennas in plasma stems from the use of antennas aboard rockets and satellites that travel through the ionosphere. Generally, the antenna is employed (i) as a probe to determine certain properties (usually the electron density) of the surrounding medium, (ii) as a communication link with the ground base, and for (iii) as a detector of the noise field from the sun and other radio stars. In all these applications, the most important characteristic of the antenna is its impedance, defined as the ratio of the terminal voltage and input current at the antenna feed. The determination of the antenna impedance is generally a very difficult problem even when the antenna is in free space. Rigorously, one has to solve a diffraction problem between the transmission lines (or the waveguide feed) and the antenna. However, the problem is commonly simplified by considering separately the feed and the antenna. In discussing the feed, the antenna is replaced by its terminal impedance, while in solving the antenna problem, the feed is considered as an idealized voltage or current generator. Such an approach is well justified by experiments for many antenna problems in free space. However, the validity of this approach for antennas in plasma has not been seriously studied. Fortunately, in many applications such as aperture antennas in space vehicles, or a monopole mounted on the anode in a laboratory plasma tube, the feed of the antenna is actually not in plasma but in free space. Therefore, idealizing the feed for antenna problems in plasma does not seem to constitute a serious limitation.

The first step in solving the antenna problem in plasma is to choose a suitable mathematical model for the plasma itself. Commonly, the dynamics of the plasma may be described either by kinetic theory or fluid models.* In general, the former is expected to be very complicated since it contains the information about the entire system. The latter have their limited validity, but are simpler mathematically and, furthermore, their solution yields directly macroscopic quantities of physical interest. Therefore, in the study of antenna problems, the fluid models are commonly employed. There are two serious limitations associated with the fluid models, however. First, one cannot account for the nonlinear effect. To a first approximation, this effect may be neglected if the signal electric field is very small compared to the plasma field.[556] When an antenna in plasma is used as a transmitter, the near field is relatively strong even for a moderate amount of power and the nonlinearity in the surrounding plasma is inevitable. Second, the particle aspect of the plasma is ignored; consequently, the treatment of the plasma as a continuous medium in the fluid models may fail in the description of phenomena involving a very small scale of distance, such as the radiation of a very short dipole in plasma.

Once the medium is described, another difficulty arises when the antenna is brought into the plasma. The presence of the antenna disturbs the homogeneity of the plasma, and there exists a region of highly nonuniform electron density around the antenna's surface, known as "ion sheath." The form of the ion sheath may be explained as follows: The rapidly moving electrons in the plasma are more easily captured by the conductors than the heavy ions. Consequently, the antenna surface is at a negative potential

---

*Two most common types of fluid models are the cold and warm plasma models.

with respect to the plasma potential[*] and attracts an excess of ions in a region measured a few Debye wavelengths away from the surface. The details of the sheath structure are quite complicated and may play a decisive role in the determination of the antenna impedance. Thus, in working with the sheath problems, one should be very cautious because some over-simplified models for the sheath may lead to some dubious results for the impedance In certain laboratory plasma experiments, however, one may remove the sheath by applying a positive D.C. bias to the antenna so as to bring its potential back to the plasma potenital, a situation known as "sheath collapse." Under a sheath collapse condition, the plasma is reasonably uniform up to the surface of the antenna.

In addition to the potential difference between the antenna and plasma, as described above, there are other causes which can render the plasma inhomogeneous in the neighborhood of the antenna, such as the motion of space vehicles, the influence of the earth's magnetic field, etc.

The physical problem of antennas in plasma, as described above, is extremely complicated and, needless to say, is very difficult to solve. In the past ten years, numerous papers and reports have been published on this subject, and some basic understanding has been gained. It has become evident that there exists a great need for carrying out a comprehensive survey of the literature with a view to sorting out the pertinent information in a systematic manner and making it readily available to future workers in this area. This is the motivation for this review.

The report consists of three parts. The first one deals with the theoretical aspects of the antenna impedance in plasma, while in the second part, the important experimental results and their comparisons with theory are summarized.

---

[*] Also known as space potential.

Finally, an extensive and classified bibliography is included in the third part.

As far as the theoretical analysis is concerned, a variety of different antennas has been treated in the literature. They include cylindrical antennas, biconical antennas, strip antennas, aperture antennas, open-ended waveguides and horns. In the present report, we will discuss the cylindrical antennas only. The reason for such a choice is two-fold. First, the cylindrical antenna is one of the most frequently used antennas in experiment and practice, and also, is the subject of most extensive discussion in the literature. Second, the behavior of the cylindrical antenna in free space is well understood, and various techniques for handling the mathematical problem have been successfully developed. Therefore, in the treatment of the cylindrical antenna in plasma, it should perhaps be easy to separate the effect of the plasma from that of a specific antenna configuration.

The geometry of the cylindrical antenna to be considered is shown in Figure 1.1. Some explanations with regard to its parameters are in order.

(i) Length: We will treat both the extreme cases (i.e., infinitely long and infinitesimally small) and the finite case. For the finite antennas, we will give, whenever available, results for both relatively long and relatively short ones.

(ii) Radius: The radius is always assumed to be small as compared with a certain characteristic wave length[*] in the plasma. Thus, we do not treat the thick antenna problem.

(iii) Feed: In the rigorous boundary value approach, the model of slice generator (i.e., δ-source excitation) is always used. However, in the computation of the admittance, a small gap at the feed is allowed in order to avoid the infinite value of the admittance.

---

[*] This will be specified explicitly in each case.

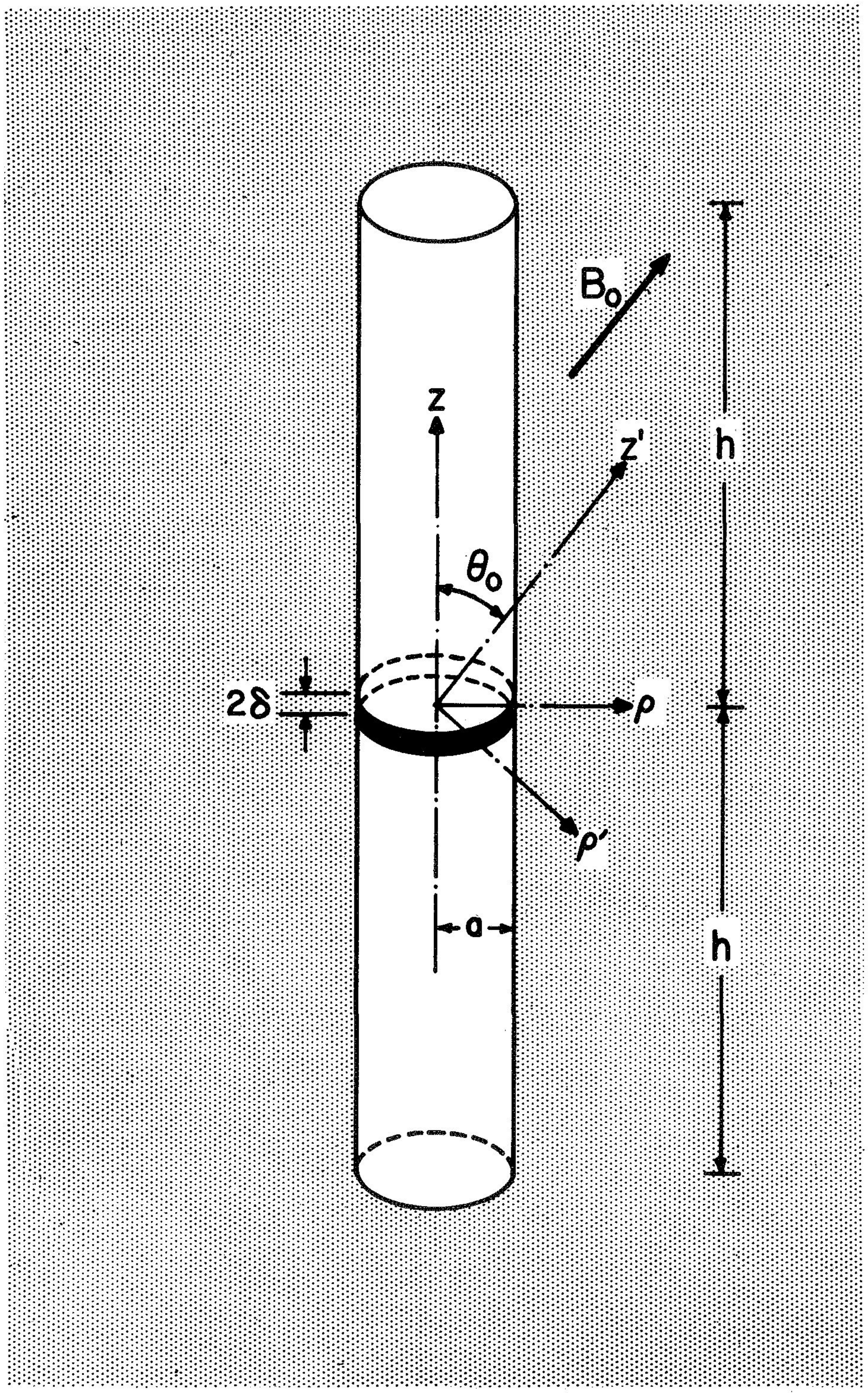


Figure 1.1 Cylindrical antenna in plasma

(iv) Orientation (of the antenna axis with respect to the applied static magnetic field): Except for some special cases, practically all theoretical results obtained for the cylindrical antenna in an anisotropic plasma have been for the case of parallel orientation. Therefore, unless specified otherwise, parallel orientation ($\theta_0 = 0$) is implied throughout this first part of the report.

To describe the plasma, we will use the linearized fluid models, namely, (i) isotropic cold plasma, (ii) uniaxial (cold) plasma, (iii) anisotropic cold plasma, (iv) isotropic warm plasma, and (v) anisotropic warm plasma. When available, results will be given for each of the above five cases. The plasma medium is always assumed of infinite extent and homogeneous. Therefore, problems where reflections from boundaries and discontinuities cannot be ignored are not considered here. Also, the sheath problem will not be discussed in the first part because no completely satisfactory theory is available.

The organization of this part of the report is as follows: Section 2 is a brief description of the cold and warm plasma models. It is intended to serve as a reminder of the basic equations and notations. The next two sections consider the two extreme cases, namely, the Hertz dipole and the infinitely long antenna. The finite problem is treated in Section 5 as a boundary value problem, and in Section 6, by the induced e.m.f. method with a triangular current. In the main contents of this report emphasis is placed on the final results, their comparison and physical implications, but not on mathematical manipulation. The reader is referred to the original papers for the derivation of the formula and the procedures of computations.

It should also be remarked that a few formulas which appeared in this report have been rearranged from their original form, and many graphs were recomputed by using different parameters. Therefore, any error in this process is the responsibility of the present authors.

2. PLASMA MODELS AND RADIATION CONDITION

The basic equations of the fluid models for describing plasma may be derived by taking the moments of the Boltzmann equation in addition to the usual Maxwell's equations. However, a closed set of equations can not be obtained in this manner. Therefore, some "reasonable" assumptions must be introduced in order to close the set of moment equations. These assumptions are the basis of various fluid models. For the purpose of the present report, it is sufficient to mention briefly only the cold and warm plasma models. In both these two models, the plasma is commonly regarded as a gas of free electrons, which is imbedded in an electrically neutralizing background of immobile ions. A static (D.C.) magnetic field $\vec{B}_o = \hat{z}\, B_o$ is applied to the plasma, and consequently the plasma is anisotropic. At each point in the plasma, the state of the electron gas is described by a velocity vector[*] $\vec{v}$, and a perturbed pressure scalar p (pressure deviation from its mean), in addition to the usual $(\vec{E},\vec{H})$ fields. The basic assumptions and equations in the cold and warm plasma models are given below.

(A) Cold Plasma Model:[557] The first two linearized (valid for small signal) moment equations are used, and the pressure term is discarded due to the assumption of low thermal energy of the electrons. If the effect of the convection current in the plasma is included in the flux term, the Maxwell's equations for the time-harmonic field [with exp(jωt) time variation] become

$$\nabla \times \vec{E} = -j\omega\mu_o \vec{H} \qquad (2.1a)$$

$$\nabla \times \vec{H} = j\omega\varepsilon_o \overline{\overline{K}}\cdot\vec{E} + \vec{J} \qquad (2.1b)$$

---

[*] We do not consider the drifting plasma, therefore $\vec{v}$ is of the same order as p.

where $\overline{\overline{K}}$ is the relative dielectric tensor

$$\overline{\overline{K}} = \begin{bmatrix} K_{\perp} & jK_x & 0 \\ -jK_x & K_{\perp} & 0 \\ 0 & 0 & K_{\parallel} \end{bmatrix} \tag{2.1c}$$

$$K_{\parallel} = 1 - \frac{X}{U}$$

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

$$K_x = \frac{-XY}{U^2-Y^2}$$

$$X = \left(\frac{\omega_p}{\omega}\right)^2, \quad Y = \left(\frac{\omega_c}{\omega}\right)^2, \quad U = 1-jZ = 1-j\frac{\nu}{\omega}$$

$\omega_p = \left(\frac{N_o e^2}{m\epsilon_o}\right)^{1/2}$ = plasma frequency, $\omega_c = \frac{eB_o}{m}$ = cyclotron frequency

ν = collision frequency

N_o = average electron density

e = magnitude of the charge of an electron

m = mass of an electron

Furthermore, the perturbed velocity vector $\vec{v}$ is related to the field by

$$j\omega m\vec{v} = -e(\vec{E} + \vec{v} \times \vec{B}_o) - m\nu\vec{v} \tag{2.1d}$$

which is the linearized second moment equation (or the linearized equation of motion).

To obtain the dispersion relation for the modal plane wave

$$(\vec{E},\vec{H}) = (\vec{E}_o,\vec{H}_o)e^{j\vec{k}\cdot\vec{r}} \tag{2.2}$$

we may set $\vec{J} = 0$ and eliminate $\vec{H}$ from (2.1). The result is

$$[\vec{k}x\vec{k}x + k_o^2 \overline{\overline{K}}]\vec{E}_o(\vec{r}) = 0 \qquad (2.3)$$

For non-trivial solution, it requires

$$\det [\vec{k}x\vec{k}x + k_o^2 \overline{\overline{K}}] = 0 \qquad (2.4)$$

which is the well-known dispersion relation in an anisotropic cold plasma. The computation of (2.4) by a simple graphical method was described by Deschamps[565] and its use in the radiation problem was reviewed by Deschamps[564] and Felsen.[133] Typical dispersion surfaces[*] as functions of X and Y^2 are sketched in Figure 1.2. This type of display has been used extensively in the literature, and will be referred to as a CMA diagram (after Clemmow, Mullaly and Allis). For a given plasma (i.e, given ω_p and ω_c), the variation of the frequency ω corresponds to a locus of a straight line passing the origin on CMA diagram. In this report, and wherever possible, we will present our data based on the parameters specified on the three straight lines shown in Figure 1.2 corresponding to the cases $(\omega_c/\omega_p) = 1.5, 1, 0.5$, and the arrows indicate the directions of increasing ω. The critical frequencies which separate the various regions are

$$\begin{array}{llll} \text{plasma frequency:} & \omega_p, & (X = 1) & \\ \text{cyclotron frequency:} & \omega_c, & (Y = 1) & \\ \text{upper hybrid frequency:} & \omega_u = \sqrt{\omega_p^2 + \omega_c^2}, & (X = 1-Y^2) & (2.5) \\ & \omega_+ = +\omega_c/2 + \sqrt{\omega_p^2+(\omega_c/2)^2}, & (X = 1+Y) & \\ & \omega_- = -\omega_c/2 + \sqrt{\omega_p^2+(\omega_c/2)^2}, & (X = 1-Y) & \end{array}$$

---

[*] A plot of $|\vec{k}|$ as a function of θ, the angle between $\vec{k}$ and the static magnetic field.

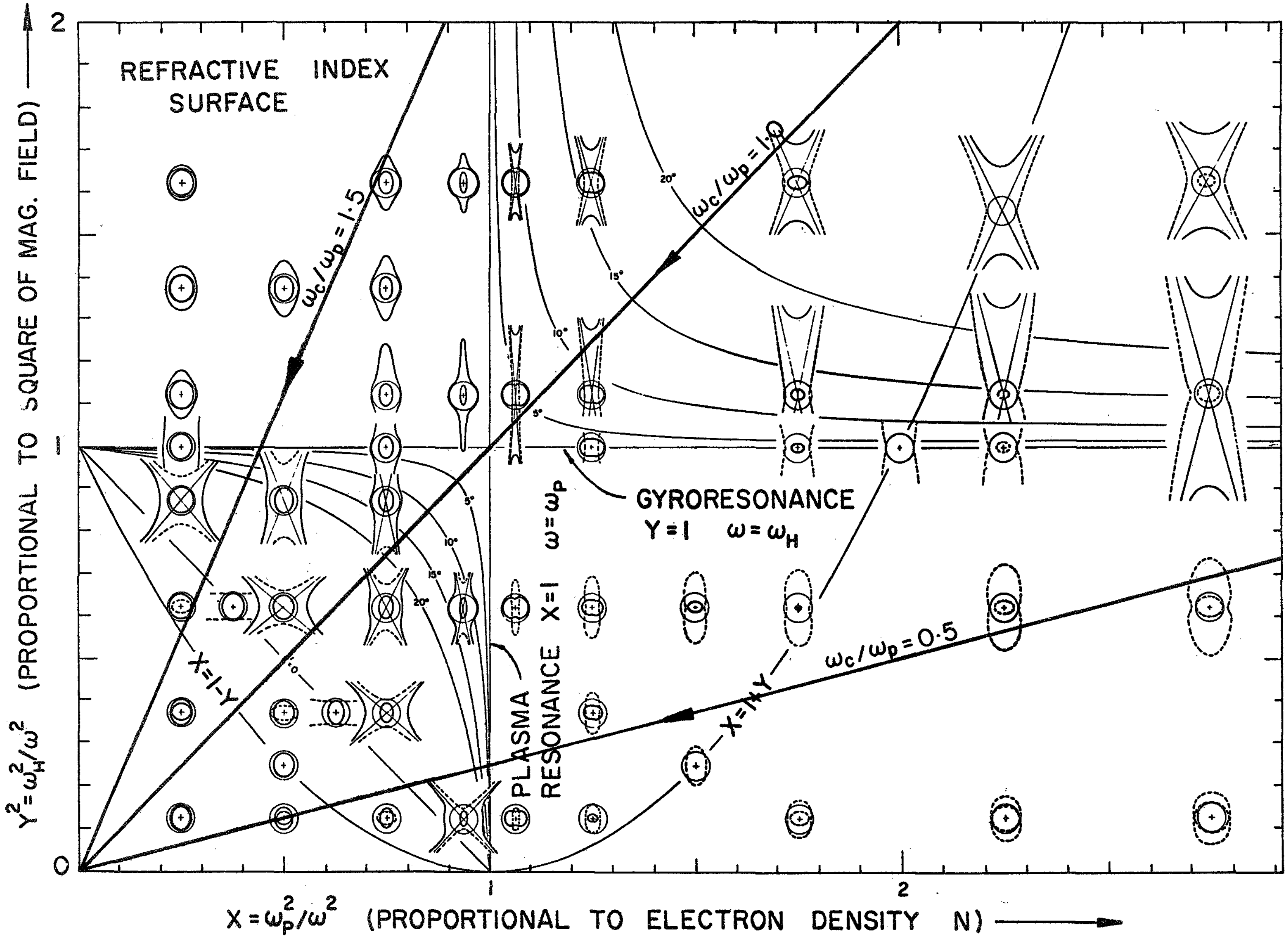


Figure 1.2 CMA diagram for a cold plasma (after Deschamps[564]) with three frequency paths corresponding to the ratios $\omega_c/\omega_p = 0.5, 1.0, 1.5$

Generally, at the above five critical frequencies the antenna impedance as a function of ω blows up or displays discontinuity in its slope, and therefore deserves special attention.

There are two special cases of the cold plasma model which have been frequently employed in the analysis of antenna problems. The first, when the static magnetic field is null ($B_o = 0$), is the isotropic plasma. The relative dielectric tensor is reduced to

$$\overline{\overline{K}} = (K_{\parallel})\,\overline{\overline{I}} \tag{2.6}$$

where $\overline{\overline{I}}$ is an identity tensor. The second special case arises when B_o, and hence Y, is very large. Then one may set K_x approximately equal to zero, and $\overline{\overline{K}}$ in (2.1c) becomes

$$\overline{\overline{K}} = \begin{bmatrix} K_{\perp} & 0 & 0 \\ 0 & K_{\perp} & 0 \\ 0 & 0 & K_{\parallel} \end{bmatrix} \tag{2.7}$$

In the limit $B_o \to \infty$, a further simplification may be obtained with the result

$$\overline{\overline{K}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & K_{\parallel} \end{bmatrix} \tag{2.8}$$

Both cases described in (2.7) and (2.8) are known as uniaxial plasmas. In the present report, we will always use (2.7). The uniaxial plasma may be further classified as elliptical uniaxial plasma for $K_{\parallel} > 0$, and hyperbolic for $K_{\parallel} < 0$.

(B) Warm Plasma Model:[89] The first two moment equations are again used; however, the compressibility of plasma (inversely proportional to the electron temperature T) is taken into consideration by allowing a scalar p in the linearized equation of motion, namely

$$j\omega m\vec{v} = -e(\vec{E} + \vec{v} \times \vec{B}_o) - m\nu\vec{v} - \frac{1}{N_o} \nabla p \qquad (2.9)$$

To compensate the additional unknown p in (2.9), an equation of state is assumed such that

$$j\omega p = -u^2 m N_o \nabla \cdot \vec{v} \qquad (2.10)$$

where u is the speed of sound in the electron gas, and is related to the temperature T by $u = (3KT/m)^{1/2}$ where κ is the Boltzman constant. In addition to (2.9) and (2.10), one has the usual Maxwell's equations

$$\nabla \times \vec{E} = -j\omega\mu_o \vec{H} \qquad (2.11a)$$

$$\nabla \times \vec{H} = j\omega\epsilon_o \vec{E} - N_o e\vec{v} + \vec{J} \qquad (2.11b)$$

which completes the set of basic equations for the warm plasma model. It may be noted that due to the additional pressure term in (2.9), $\vec{v}$ is no longer directly proportional to $\vec{E}$, and consequently it is not convenient to eliminate the convection current term in (2.11b) by introducing a relative dielectric tensor as in the cold plasma model.

For problems of radiation from a time-harmonic current source in an unbounded, lossless plasma described by either cold or warm plasma models, the solutions to the basic equations described above are not unique. The uniqueness of solution may be assured only if one imposes on the solution a further constraint, known as radiation condition. In the isotropic medium the radiation condition is that provided by Sommerfeld, which requires that the phase of the radiated field be progressing outwardly from the source. However, in an anisotropic medium the directions of phase progress and energy transmitted are generally different, and consequently, it is no longer physically plausible to use the Sommerfeld's "phase" criterion. In past years, at least three different radiation conditions were proposed for problems of radiation in anisotropic media. They are briefly summarized below:

(i) Introduction of loss: In a slightly lossy medium the radiated field must be evanescent far away from the source, and the lossless medium is regarded as a limiting case when the loss approaches zero. The introduction of loss in a medium can be achieved by either of the following two ways: (a) considering a physical loss mechanism in the medium, such as introducing the collision in plasma; (b) introducing a growing factor in the source frequency,[558] i.e. let $\omega \rightarrow \omega - j\delta$, where $\delta > 0$ [for $\exp(+j\omega t)$ time convention].

(ii) Energy criterion: It is required that each constituent of the radiated field should have a power flow outwardly directed from the source.[133]

(iii) Causality: Consider the steady-state radiation as a limiting case of transient radiation as an infinitely long time has elapsed after the switch-on of the source. Then the causality requires that there is no radiated field before the source is switched on.[559]

3. RADIATION RESISTANCE OF A HERTZ DIPOLE

The Hertz dipole is not physically realistic ; nevertheless, it was considered most extensively in the literature. The main reasons are: (i) mathematical simplicity, (ii) an arbitrary electric source can always be considered as a superposition of Hertz dipoles, and (iii) the behavior of a Hertz dipole is usually a good indication of that of a very short dipole.

The current density on a Hertz dipole oriented parallel to $\vec{B}_o$ may be specified by

$$\vec{J}(\vec{r}) = \hat{z}\, I(2h)\delta(\vec{r}) \tag{3.1}$$

It should be noted that (3.1) is sometimes used as an approximation to describe a very short dipole having a current moment $I(2h)$. In that case, I may be interpreted as the current and (2h) as the length of the dipole. To find the radiation resistance, we need to compute the radiated power and then divide it by I^2.

For a given current distribution $\vec{J}(\vec{r})$, Deschamps and Kesler[115] have shown that the radiated power in plasma (isotropic or anisotropic, cold or warm) may be expressed as

$$P = \sum_i \iint_{\sigma_\omega^{(i)}} \left| \frac{\vec{\Phi}^{(i)}(\vec{k})\cdot\vec{\mathcal{J}}(\vec{k})}{4\pi} \right|^2 dk^2 \tag{3.2}$$

where $\sigma_\omega^{(i)}$ is the i^{th} sheet of the (real) dispersion surface of the medium and $\vec{\Phi}^{(i)}(\vec{k})$ is the elective field vector in the normalized modal wave with wave vector $\vec{k}$; $\vec{\mathcal{J}}(\vec{k})$ is the Fourier transform (with transform variable $\vec{k}$) of the current. For the special case of a Hertz dipole, described by (3.1), the radiation resistance is given by

$$R_{rad} = \sum_i \iint_{\mathfrak{S}_\omega^{(i)}} \left| \frac{\vec{\Phi}^{(i)}(\vec{k})\cdot\hat{z}}{(2\pi/h)} \right|^2 dk^2 \tag{3.3}$$

The values of R_{rad} for various plasma models are summarized below.

(A) Isotropic Cold Plasma

The plasma behaves the same as a dielectric with relative dielectric constant (1-X), and the radiation resistance is then given by

$$R_{rad} = \begin{cases} \frac{\eta_o}{6\pi}(k_o h)^2\sqrt{1-X}, & X < 1 \\ \\ 0 & , \quad X > 1 \end{cases} \tag{3.4}$$

where $\eta_o = \sqrt{\mu_o/\varepsilon_o}$ is the free space impedance, and $k_o = \omega\sqrt{\mu_o\varepsilon_o}$ is the free space wave number. For $X > 1$ (i.e., $\omega<\omega_p$) there is no (real) dispersion surface $\mathfrak{S}_\omega^{(i)}$, and consequently no radiation is possible from a Hertz dipole.

(B) Uniaxial Plasma

For the elliptical case, the resistance can be obtained by a simple scaling procedure to the corresponding value in free space. The result is

$$R_{rad} = \frac{\eta_o}{6\pi}(k_o h)^2 \sqrt{K_\perp}, \quad X < 1 \text{ (elliptical)} \tag{3.5}$$

In the limit $Y \to \infty$ (3.5) becomes exactly the same as the R_{rad} in free space and is independent of the plasma parameter X. For the hyperbolic case, the radiation resistance computed from (3.2) is infinitely large. In order to see how R_{rad} approaches infinity, Seshadri[401] examined a short dipole with an assumed triangular current distribution. As the dipole length (2h) approaches zero, his result is*

---

*This or very similar results have also been obtained by Balmain,[23] Blair,[42] Galejs[151] and Wang and Bell.[506]

$$R_{rad} = \lim_{h \to o} \left[\frac{\eta_o}{2k_o hK_{\perp}}\right], \quad X > 1 \text{ (hyperbolic)} \qquad (3.6)$$

which goes to infinity as $(1/k_oh)$. The infinite radiation resistance is not physically realistic. This indicates that the hyperbolic uniaxial plasma model fails to describe the radiation from a Hertz dipole. However, many attempts have been made, while staying within the uniaxial model, to explain this anomalous behavior and further suggest methods for removing it. Some of these methods are briefly mentioned below:

(i) Sufficiently smooth current distribution:[9,434 and others] In the hyperbolic medium one sheet (extraordinary sheet) of the dispersion surface resembles a hyperboloid and is infinitely extended [see Figure 1.2]. From (3.3) it is seen that R_{rad} becomes infinite since the integration is to be carried out over the entire dispersion surface. One way to obtain a finite radiated power is to allow a finite dimension of the antenna with a sufficiently smooth current distribution so that $\vec{\mathcal{J}}(\vec{k})$ in (3.1) decreases fast enough for large $\vec{k}$. In particular for a linear antenna, Deschamps[560] has shown that the condition for obtaining a finite radiation resistance is that the derivative of $\vec{J}(z)$ be square integrable.

(ii) Introduction of loss: In any realistic plasma, the collision loss inevitably exists. Therefore, it is interesting to examine to what extent the paradox[*] described above exists in a slightly lossy hyperbolic plasma. Waineo and Mittra[472] have computed the radiation power $P(r=r_o)$ due to a short dipole through a sphere of radius r_o centered at the dipole. They found that $P(r=r_o)$ is indeed proportional to h^{-1} for small r_o, as predicated in (3.6); however, $P(r=r_o)$ becomes proportional to h^{-2} for large r_o. Therefore as far as the communication ability is concerned, a longer antenna with a given

---

[*] Note from (3.4) that the shorter the antenna, the larger is the radiation resistance.

current at its terminal does transmit more power at a large distance in a slightly lossy hyperbolic plasma.

(iii) Transient View: The field radiated by a point source in a hyperbolic uniaxial plasma is known to be infinite over the surface of a symmetrical bicone C_∞ defined by the cone angle (referred to the dipole axis)

$$\theta = \sin^{-1} \left(\frac{1}{\sqrt{X}}\right) \tag{3.7}$$

The infinite resistance may be associated with the infinite field intensity on C_∞. In order to examine how this infinite field builds up, Lee and Mittra[272] have considered the radiation problem by a transient dipole. It was found that the cone C_∞ is always in the dark region, i.e., the main signal reaches there only after an infinite lapse of time after the switch-on of the source. With a finite loss, however small, the field cannot grow to extremely large values, since the collision time will always be smaller than the time required for the signal to reach the cone C_∞. Consequently, the infinite R_{rad} computed based on steady state analysis is not realizable (even when staying in the uniaxial model).

(C) Anisotropic Cold Plasma

The expression for the radiation resistance of a Hertz dipole with an arbitrary orientation with respect to $\vec{B}_o$ in an anisotropic cold plasma was first given by Kogelnick[245,246] in an integral form. Extensive results have been computed by Weil and Walsh[510] based on numerical integrations. In Figures 1.3-1.5, we present some typical values of the radiation resistance [normalized with respect to its free space value $R_o = 20(k_o h)^2$] as a function of ω. Take Figure 1.3 as an example. For (source) frequency lower than ω_c, R_{rad} is infinite due to the infinitely extended dispersion surface

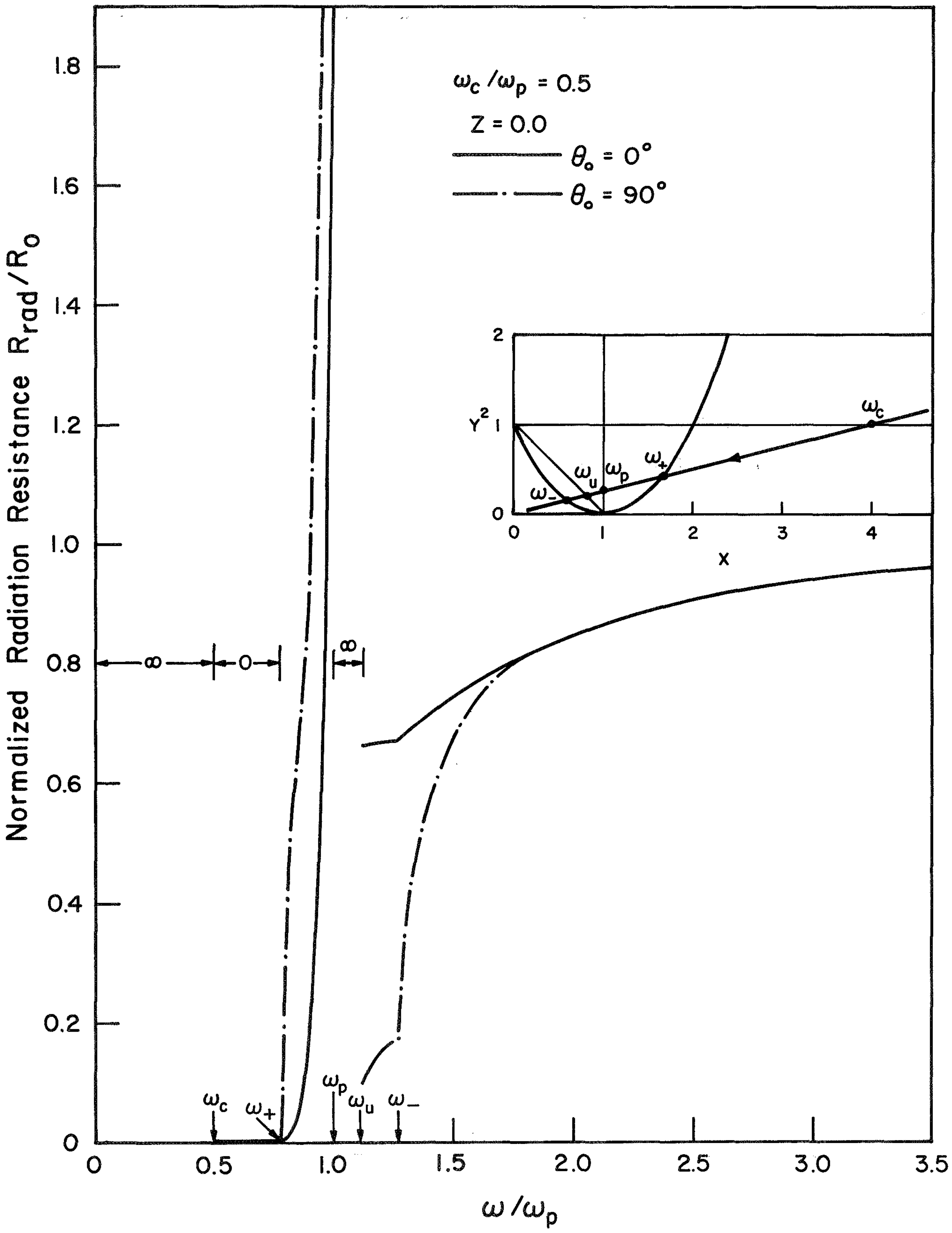


Figure 1.3 Normalized radiation resistance of a Hertz dipole as a function of frequency with $\omega_c/\omega_p = 0.5$

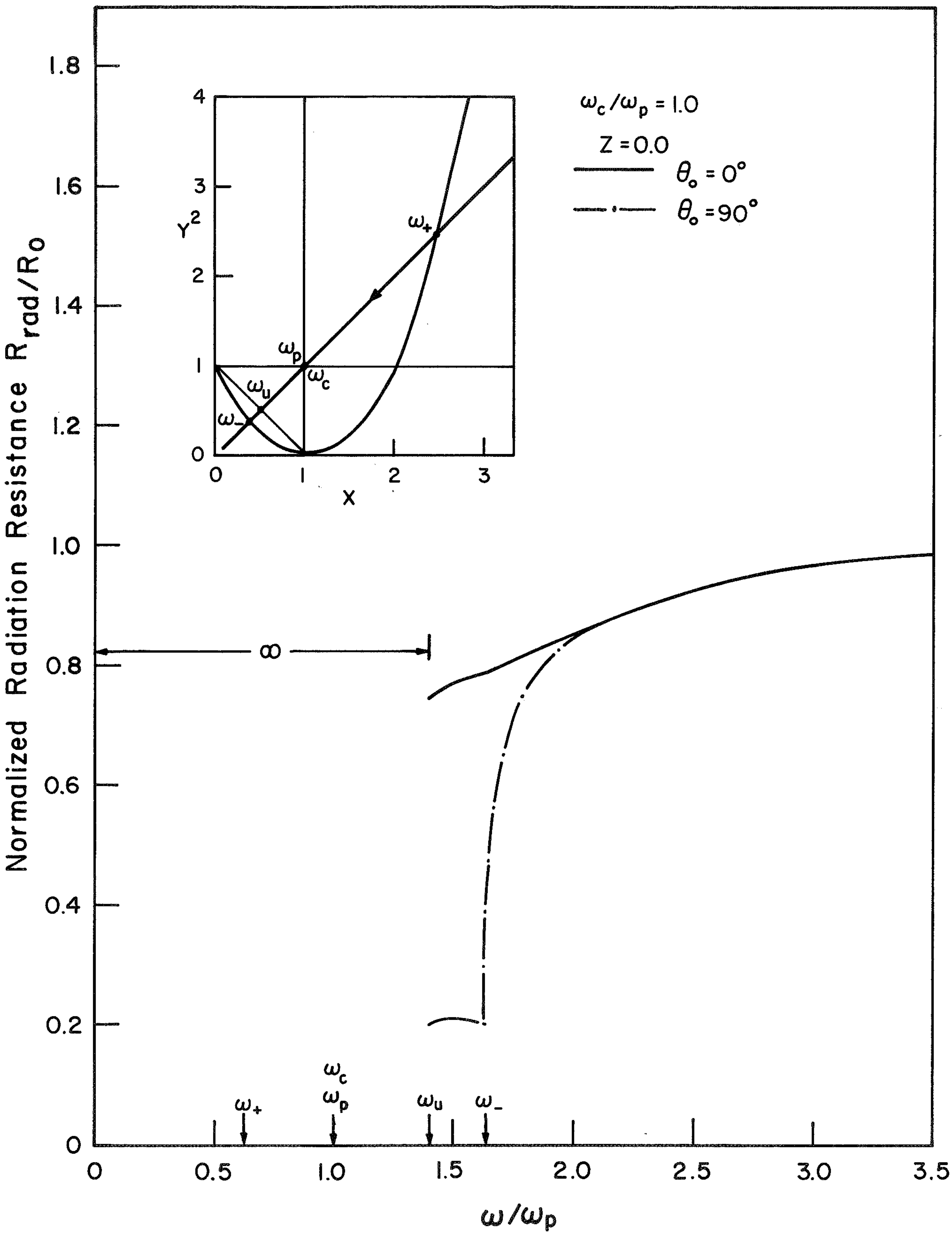


Figure 1.4 Normalized radiation resistance of a Hertz dipole as a function of frequency with $\omega_c / \omega_p = 1.0$

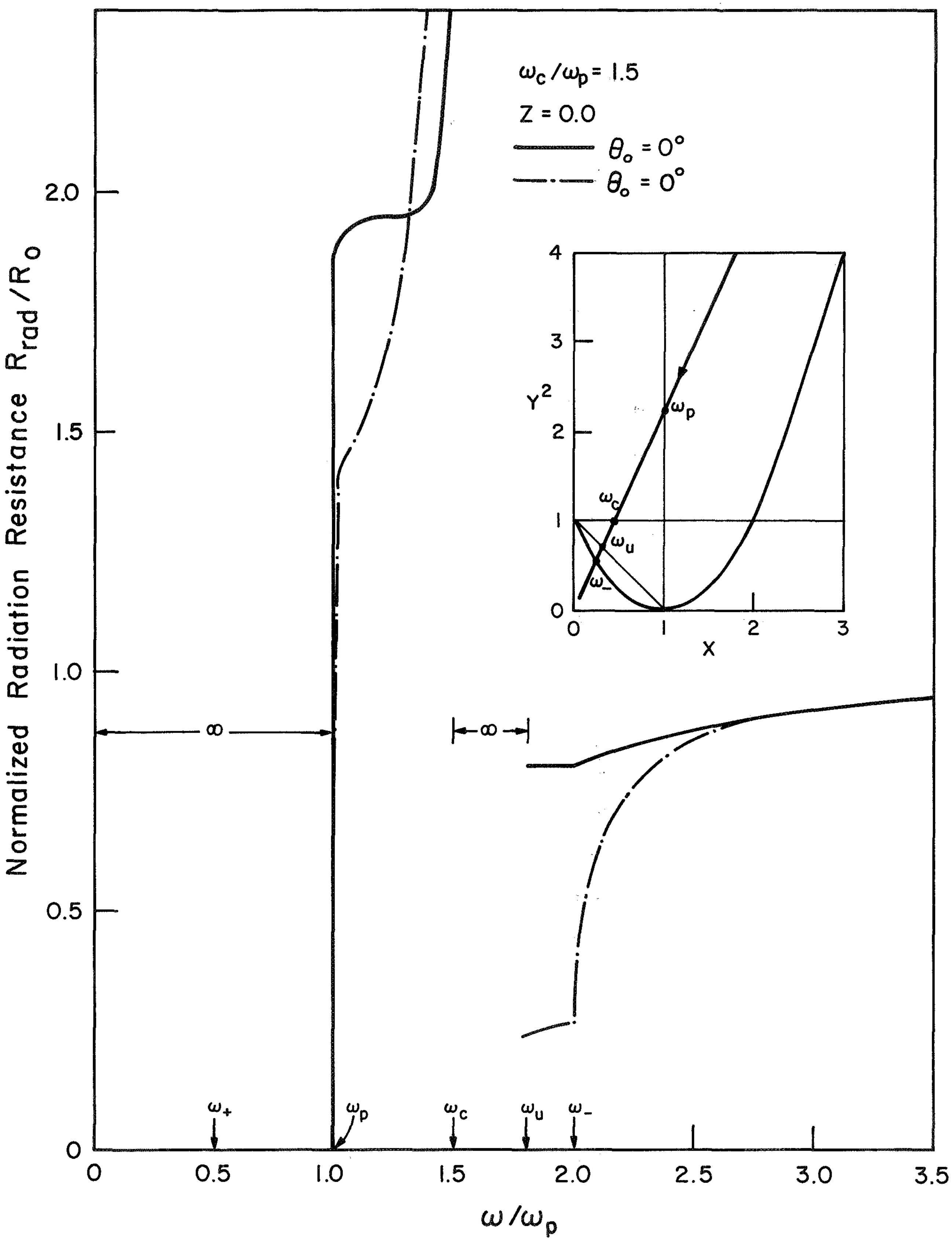


Figure 1.5 Normalized radiation resistance of a Hertz dipole as a function of frequency with $\omega_c / \omega_p = 1.5$

(hyperbolic region). As ω increases, R_{rad} becomes identically zero for $\omega_c<\omega<\omega_+$ since in this range no propagating wave can exist in plasma. For $\omega_+<\omega<\omega_p$, R_{rad} increases very rapidly as the plasma frequency is approached. It becomes infinite again for ω in the range $\omega_p<\omega<\omega_u$. As ω further increases, the plasma becomes "transparent" and R_{rad} tends to its free space value. Similar interpretations can be applied to Figures 1.4 and 1.5.

In Figures 1.3-1.5, we have also plotted the values of R_{rad} when the inclination angle of the dipole (with respect to $\vec{B}_o$) $\theta_o = \pi/2$. For an arbitrarily oriented dipole the radiation resistance is

$$R_{rad}(\theta_o) = \cos^2\theta_o R_{rad}(0) + \sin^2\theta_o R_{rad}(\pi/2) \tag{3.8}$$

Note from Figures 1.3-1.5 that for a frequency slightly higher than ω_- the orientation effect is almost not observable, since the plasma becomes almost isotropic.

(D) Isotropic Warm Plasma

For a given current source radiating in an isotropic warm plasma, the fields $(\vec{E},\vec{H},\vec{v},p)$ may be decomposed into completely uncoupled electromagnetic and acoustic modes, each satisfying a conventional wave equation with wave numbers $k_o\sqrt{1-X}$, and $(c/u)k_o\sqrt{1-X}$, respectively. The radiation resistance of a point source is found to be[76,188,483]

$$R_{rad} = \begin{cases} R_e + R_a, & X < 1 \\ 0 \quad , & X > 1 \end{cases} \tag{3.9a}$$

where

$$R_e = \frac{\eta_o}{6\pi}(k_oh)^2\sqrt{1-X} \tag{3.9b}$$

$$R_a = \frac{1}{2}\left(\frac{c}{u}\right)^3 X\, R_e \tag{3.9c}$$

Observe that R_e, the component due to the electromagnetic mode, is precisely the same as (3.4); while R_a is the additional contribution due to the excitation of an acoustic wave in the warm plasma. From (3.9c), it is noted that R_a increases as u (proportional to $\sqrt{T}$) decreases, indicating that the lower the temperature of the plasma, the more power is radiated in the acoustic mode. This paradoxical conclusion is again due to the unrealistic assumption of point source and the fact that the dispersion surface of the acoustic sheet is extremely large compared to that of the electromagnetic sheet, [cf. Eq. (3.2)]. In fact, if a finite source is considered with a sufficiently smooth current the above conclusion may be completely reversed.

4. IMPEDANCE OF AN INFINITELY LONG ANTENNA

The other extreme of a cylindrical antenna is the infinitely long one, which has also been treated extensively in the literature. The excitation of the antenna is generally regarded as a unit voltage source applied across a very small gap $|z| < \delta$ on the <u>outside</u> surface of the antenna [Figure 1.1 with $h \to \infty$]. The applied electric field may then be approximated by

$$E_z^{(\text{applied})}(\rho,z) = \delta(z), \text{ at } \rho = a+ \tag{4.1}$$

where $\delta(z)$ is a delta function and $(a+)$ means $\lim_{\varepsilon\to 0}(a+\varepsilon)$ and $\varepsilon>0$. The induced current on the antenna can be expressed as a superposition of modal waves guided along the infinite cylinder, and therefore is in the form of an inverse Fourier integral. The (input) admittance of the antenna is defined by

$$Y_{in}^{\infty} = I(\delta) \tag{4.2}$$

since the input voltage is of unit amplitude.

(A) Isotropic Cold Plasma

For $X < 1$, a proper scaling of the well-known result for Y_{in}^{∞} in free space[566-570] gives the approximate expression

$$Y_{in}^{\infty} \simeq \left\{\frac{(-\pi)}{\eta \ell n(1.26A)}\right\} + j\left\{\frac{2A}{\eta}\,\ell n\,\Delta + \frac{(-0.9)}{\eta \ell n(1.26A)}\right\}, \qquad \Delta \ll A \ll 1. \tag{4.3}$$

In the above formula, we have used the following notation

$$\eta = \eta_o/\sqrt{K_{\parallel}}\ ,\ A = \sqrt{K_{\parallel}}\, k_o a,\ \Delta = \sqrt{K_{\parallel}}\, k_o \delta \tag{4.4}$$

This result is also valid[112] when a small collision is included, i.e., when $K_{\parallel} = 1-(X/U)$. In that case, the square root $\sqrt{K_{\parallel}}$ should be taken such that $\operatorname{Im}\sqrt{K_{\parallel}} < 0$.

For $X > 1$, it may be shown that Y_{in}^{∞} is given by the expression

$$Y_{in}^{\infty} = \frac{-2jk_o a(X-1)}{Z_o} \int_o^{\infty} \frac{K_1(\gamma a)\cos\alpha\delta}{\gamma K_o(\gamma a)}\, d\alpha \tag{4.5}$$

where $\gamma = [\alpha^2+k_o^2(X-1)]^{1/2}$, and K_o and K_1 are the modified Bessel functions of the second kind. Note that Y_{in}^{∞} is purely inductive for a lossless plasma.

Some typical values of Y_{in}^{∞} as a function of ω computed by numerical integration are presented in Figure 1.6.[301] The antenna radius is 1 cm when the plasma frequency is 1 MHz. The plasma is slightly lossy so that there is a very small but non-zero conductance when $X > 1$. When the frequency is about the plasma frequency, Y_{in}^{∞} approaches its free space value rapidly.

(B) <u>Uniaxial Plasma</u>

For an elliptical uniaxial plasma, it may be shown that the input admittance of an antenna of length $(2h)$, radius a and feed gap (2δ), may be obtained from the following scaling formula

$$Y_{plasma}(k_o h, k_o a, k_o \delta) = \sqrt{K_\perp}\, Y_{free\ space}(\sqrt{K_\perp}\, k_o h,\ \sqrt{K_\parallel}\, k_o a,\ \sqrt{K_\perp}\, k_o \delta) \tag{4.6}$$

where $Y_{free\ space}$ is the admittance in the free space. Thus, the admittance of an infinitely long antenna in elliptical uniaxial plasma is again given by (4.3) with the parameters redefined as follows[*]

$$\begin{aligned} \eta &= \eta_o/\sqrt{K_\perp} \\ A &= \sqrt{K_\parallel}\, k_o a \\ \Delta &= \sqrt{K_\perp}\, k_o \delta \\ H &= \sqrt{K_\perp}\, k_o h \end{aligned} \tag{4.7}$$

---

[*] The notation H will be used later in Section 5.

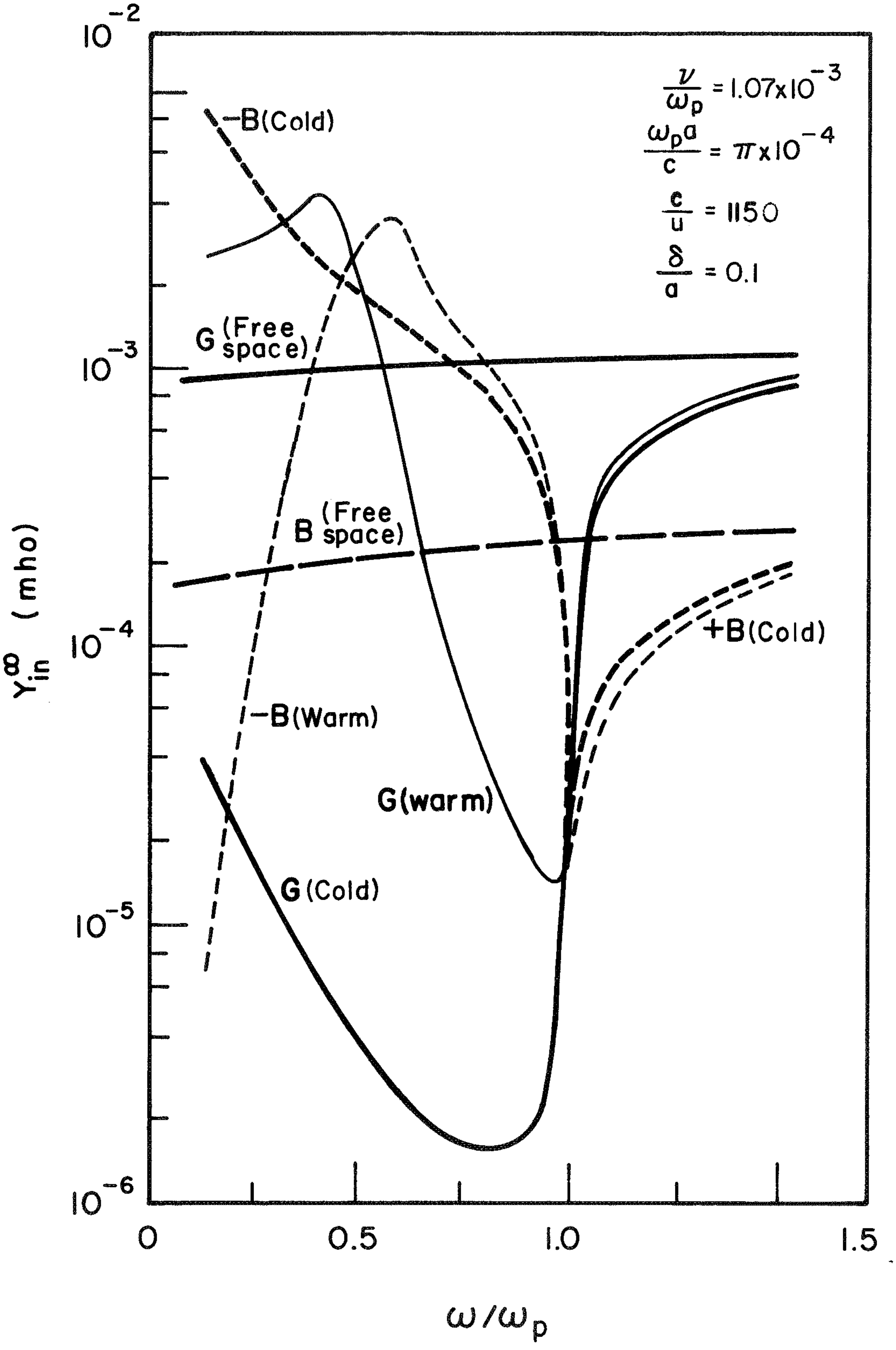


Figure 1.6 Admittance of an infinitely long antenna in free space, isotropic cold plasma and isotropic warm plasma vs. frequency (after Miller[300])

Some typical values are shown in Figure 1.7a. As will be shown later, the simple expressions in (4.7) also yield very good approximate results for an infinitely long antenna in an anisotropic cold plasma (including the off-diagonal term, in $\overline{\overline{K}}$) for certain parameter ranges.

In the hyperbolic uniaxial plasma, we cannot apply a scaling procedure to (4.3) to obtain the input admittance. This is because the modal wave in the hyperbolic plasma is a <u>backward</u> wave along ρ-direction, and the Hankel functions of the first kind instead of the second kind have to be used in the formulation of the current.* The approximate expression for the admittance of an infinitely long antenna is found to be[268]

$$Y_{in}^{\infty} \simeq \{\frac{-2A}{\eta} \ln \frac{\Delta}{A} + \frac{0.95}{\eta} \frac{(-1)}{\ln 1.26A}\} + j\{-\frac{\pi A}{\eta}\}, \quad 1 >> A >> \Delta \tag{4.8}$$

where

$$\begin{aligned} \eta &= \eta_o/\sqrt{K_\perp}\ , \quad K_\perp > 0 \\ A &= \sqrt{-K_\parallel}\ k_o a, \quad K_\parallel < 0 \\ \Delta &= \sqrt{K_\perp}\ \ k_o \delta \\ H &= \sqrt{K_\parallel}\ \ k_o h \end{aligned} \tag{4.9}$$

It is interesting to note that the conductance in (4.8) is practically** the same as the expression which one would obtain from (4.3) and (4.6) by analytic continuation. However, the susceptance in (4.8) is not simply related to the susceptance in elliptical plasma. Some typical values of Y_{in}^{∞} computed from (4.8) and (4.9) are shown in Figure 1.8a.

---

*All the radiation conditions described in Section 2 lead to the same result.

**Note the approximation

$$\ln\sqrt{K_\parallel}\ k_o a = \ln\sqrt{-K_\parallel}\ e^{j\pi/2}\ k_o a \simeq \ln\sqrt{-K_\parallel}\ k_o a$$

since $\sqrt{-K_\parallel}\ k_o a << 1$.

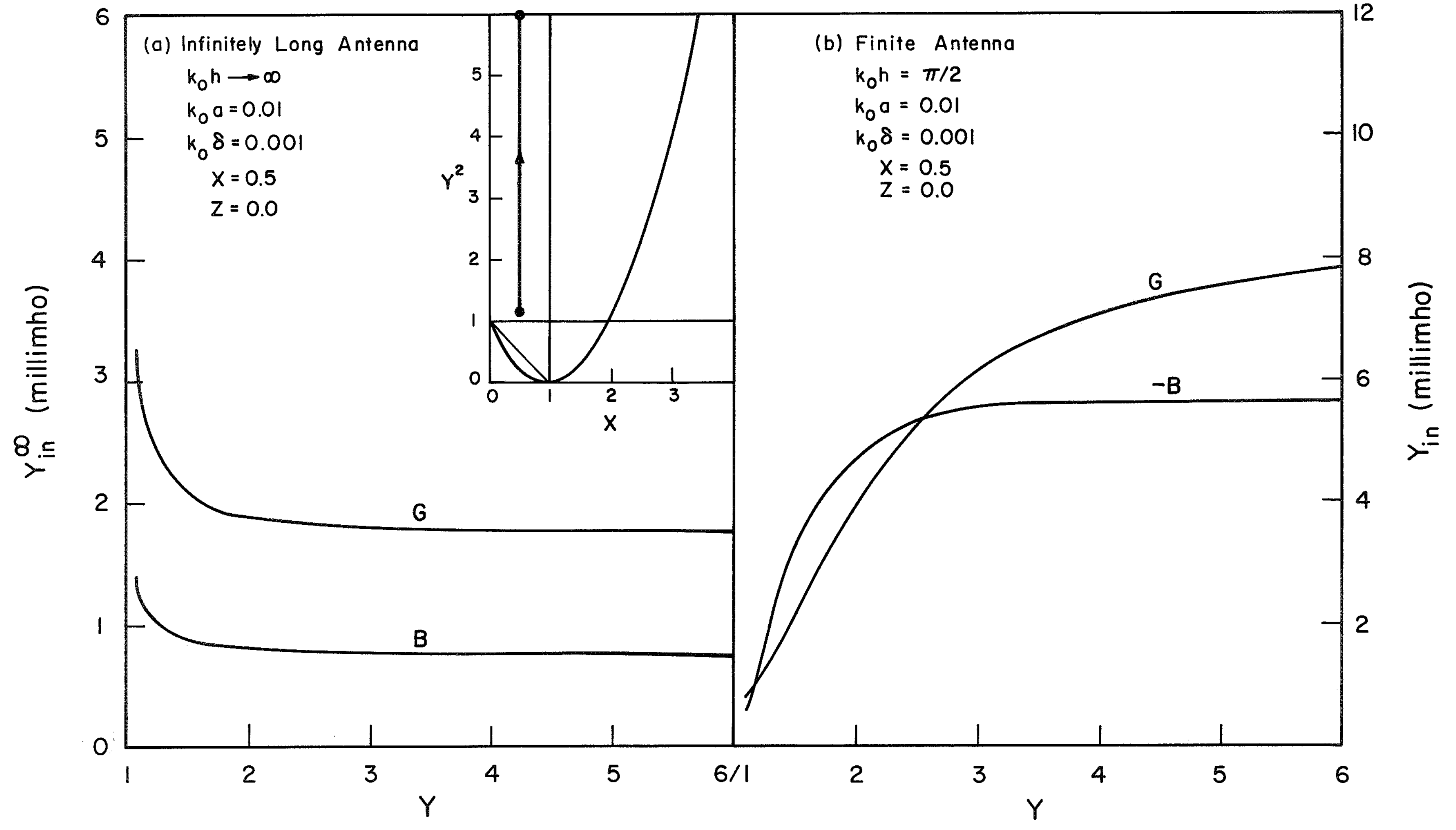


Figure 1.7 Input admittance $Y_{in} = G + jB$ of a cylindrical antenna in an elliptical uniaxial plasma vs. the static magnetic field

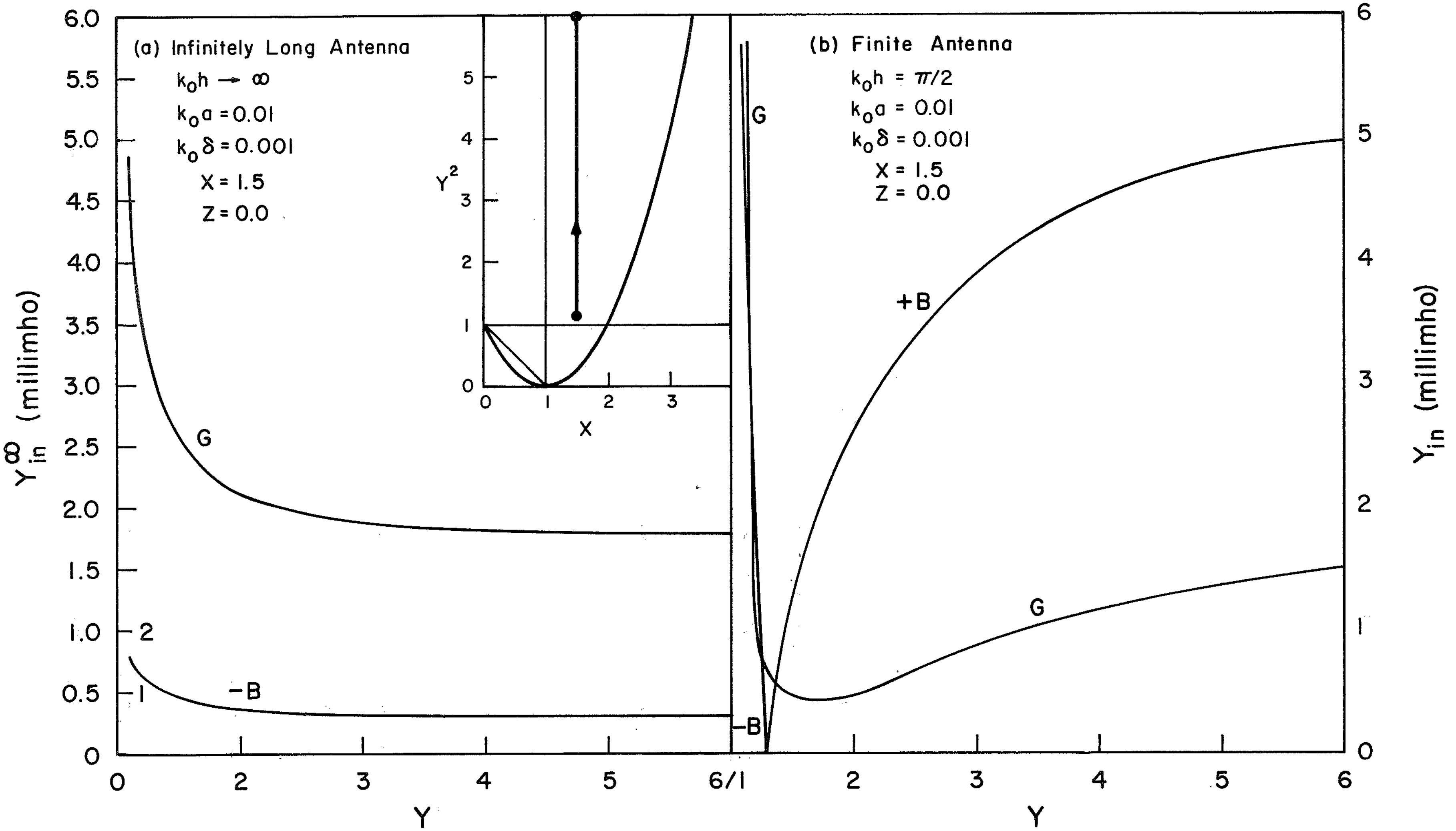


Figure 1.8 Input admittance $Y_{in} = G + jB$ of a cylindrical antenna in a hyperbolic uniaxial plasma vs. the static magnetic field

It may be noted that the input conductance approaches infinity as the feedgap $\delta \to 0$ due to the logarithmic term in (4.8). This difficulty is traced to the unrealistic assumption of a delta source in (4.1), and thus can be circumvented by allowing a not-too-small value of δ. Chen and Seshadri[71] have indicated that the input conductance remains finite in the limit $\delta \to 0$ if a thin sheath (free space) is included in the analysis.

The effect of truncating an infinite antenna on the input admittance is shown in Figures 1.7b and 1.8b. Details are reserved for Section 5 where the effect of reflections from the terminals will be discussed. Furthermore, as Y increases to a large value all the curves in Figures 1.7 and 1.8 approach constant values. This behavior is obvious from (4.6)-(4.9) since $K_\perp$ approaches unity for large Y.

(C) Anisotropic Cold Plasma

When an infinite cylindrical antenna is immersed in an isotropic or uniaxial plasma, the tangential magnetic field component on its surface is H_ϕ, and therefore produces only a longitudinal current. However, if the plasma is described by the model of anisotropic cold plasma, both H_ϕ and H_z exist, and therefore produce not only longitudinal but also circumferential current components. Unfortunately there is no detailed study of the circumferential current; hence, the importance of this current component to the radiation characteristics of the antenna is unknown.

The longitudinal current wave excited by the source in (4.1) was computed numerically for certain cases.[271] When $K_\perp > 0$, the magnitude of the current decays slowly with distance from the source (due to radiation loss), and its phase is nearly linear in the distance from the source with a wave number slightly greater than $\sqrt{K_\perp}\, k_o$ for thin antennas. When $K_\perp < 0$, there is no propagating wave. Consequently, the magnitude of the current decays rapidly from the source; however, its rate of decay does not seem to be simply related to K . For clarity, the lines of constant $K_{\perp}$ in the CMA diagram are sketched in Figure 1.9.

The admittance of an infinitely long antenna has been computed by Miller.[299] Two typical results are presented in Figures 1.10 and 1.11, where the frequency is again the variable. The radius of the antenna is 1 cm when plasma frequency is 1.5 MHz in Figure 1.10 and 1 MHz in Figure 1.11. Consider Figure 1.10 as an example. At the low frequency end below ω_c, the values of Y_{in}^{∞} should be the continuation of those in the uniaxial model and will be examined in more detail later. In the range $\omega_c < \omega < \omega_u$ which corresponds to the shaded region in Figure 1.9, the conductance G is very small. This may be attributed to the rapidly decaying current. For $\omega > \omega_-$, the admittance approaches its free space value rapidly.

In connection with the results in Figures 1.10 and 1.11, it is very interesting to compare them with the results based on a uniaxial model. In the low frequency end $\omega < \omega_c$ in Figure 1.10, the results computed from (4.8) and (4.9) by using a hyperbolic uniaxial model are also plotted as (x—x) and (x x x). The conductance checks with Miller's numerical results very well. The susceptance, however, starts to deviate from Miller's result as frequency decreases. Miller has indicated that at low frequencies the value of the susceptance is very small and his numerical method may not have an accuracy better than 10%.[299]

In Figure 1.11, we use (4.8) and (4.9) [of the hyperbolic uniaxial plasma] in the frequency range $\omega < \omega_p$. Deviation of the susceptance from Miller's results is less pronounced for frequencies above ω_+. For frequencies higher than ω_p, we use (4.3) and (4.7) of the elliptical uniaxial plasma all the way. The agreement with Miller's results is so remarkably well that we do not need to repeat them in Figure 1.11.

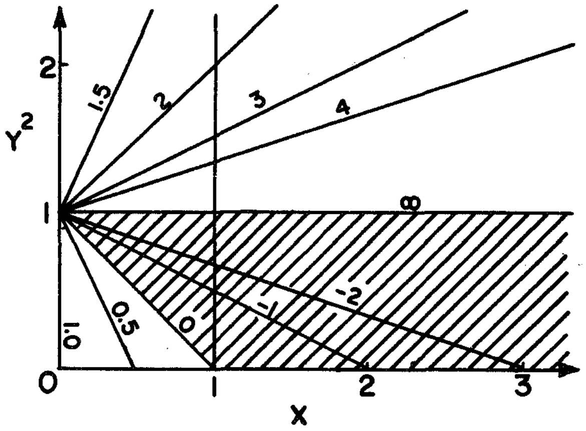


Figure 1.9 Lines of constant $K_\perp$. In the shaded region $K_\perp$ is negative (after Deschamps[113])

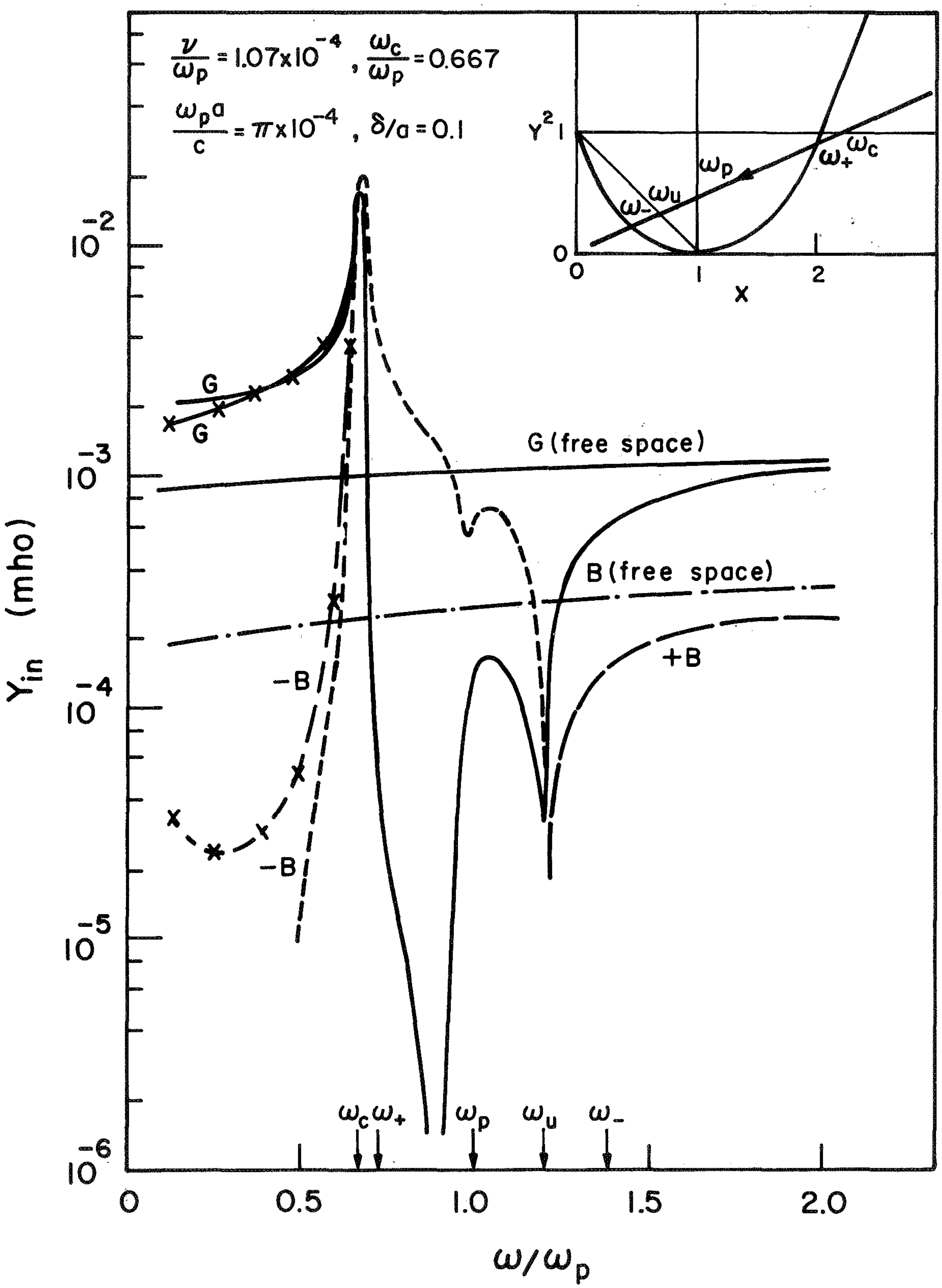


Figure 1.10 Admittance of an infinitely long antenna in an anisotropic plasma vs. frequency with $\omega_c/\omega_p = 0.5$ (after Miller[299]). The curves with crosses are computed from (4.8) and (4.9) using a hyperbolic uniaxial plasma model.

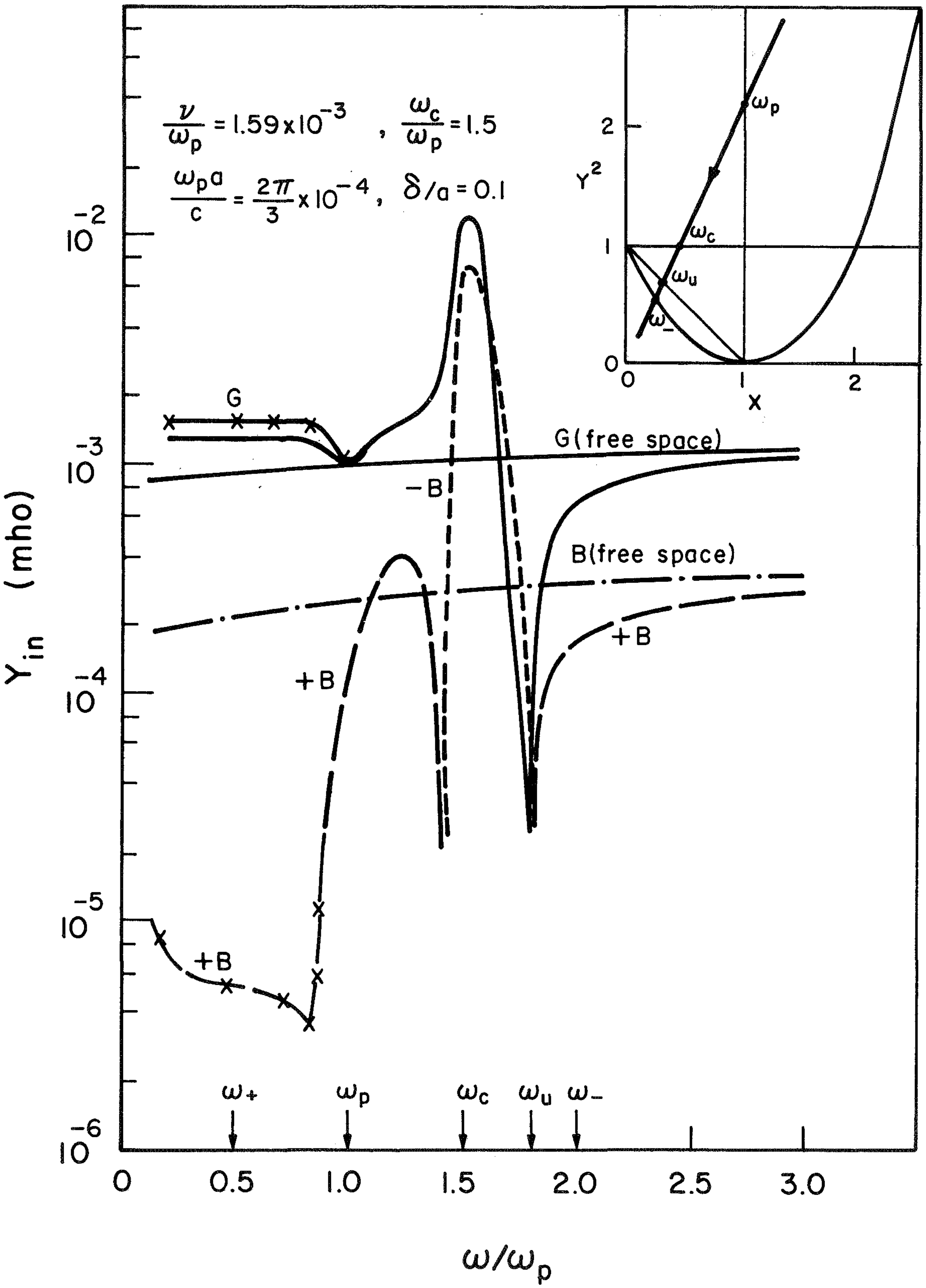


Figure 1.11 Admittance of an infinitely long antenna in an anisotropic plasma vs. frequency with $\omega_c/\omega_p = 1.5$ (after Miller[299]). The curves with crosses are computed from (4.8) and (4.9) using a hyperbolic uniaxial plasma model

It is especially interesting to note that in the range $\omega_c < \omega < \omega_u$ the dispersion surface in the anisotropic cold plasma model is of hyperbolic type* [see Figure 1.2]. Nevertheless we continue to use the formula (4.3) and (4.7) and the result seems to justify such an analytical continuation procedure.

The above discussion leads to the conclusion that the admittance of an infinitely long antenna in an anisotropic cold plasma is roughly independent of the off-diagonal term K_x in the dielectric tensor for parameters in the non-shaded regions of Figure 1.9 (i.e., when $K > 0$). In these regions, one may use (4.3) and (4.7), or (4.8) and (4.9) to obtain an approximated evaluation of the admittance.

(D) Isotropic Warm Plasma

When a boundary value problem is treated by using a warm plasma model, an additional boundary condition at the plasma-conductor (or vacuum) interface is needed for a unique solution. Many authors used the so-called rigid boundary condition which requires the elastic reflection of the electrons at the interface, viz.

$$v_\perp = 0 \tag{4.10}$$

where v is the normal component of the velocity vector $\vec{v}$. The limited physical significance of (4.10) is well-known, and has been discussed by many authors.[90] Here we would like to further point out[561] that the rigid boundary condition also makes it difficult to recover completely cold plasma solution in the limit of zero temperature (or equivalently as the acoustic velocity u → 0). This is because (4.10) is relaxed in the cold plasma model. In the cold plasma model, v is directly proportional to E , and therefore is generally not zero at the interface.

---

*Note that the dispersion surfaces in this region roughly resemble a two-sheeted hyperboloids, and are different from those in the region $X > 1$ and $Y > 1$. See reference 268.

A new feature of the warm plasma model is the excitation of a surface wave along the exterior of the infinite antenna, in addition to the usual space wave. For $X < 1$, the propagation constant k_s of the surface wave is found to be close to the wave number of the acoustic mode in an unbounded plasma, viz,[396]

$$k_s \simeq \frac{\omega}{u} \sqrt{1-X} \tag{4.11}$$

provided that X is not close to unity. In Figure 1.12, we plot the phase velocity of this surface wave as computed from the exact dispersion relation.[525] Note that k_s is not zero at plasma frequency. For $X > 1$, k_s decreases with frequency. In the limit when the radius $a \rightarrow \infty$ and $X \rightarrow \infty$,

$$k_s = \frac{\omega}{\sqrt{cu}} \tag{4.12}$$

The introduction of a vacuum sheath modifies slightly the propagation constant k_s given in (4.11) for $X < 1$. However, in the range $X > 1$, k_s varies considerably with the thickness of the sheath.

The input admittance of an infinite antenna in an isotropic warm plasma is presented in Figure 1.6.[300] For $X < 1$, its value is almost identical to that computed based on an isotropic cold plasma model. This result is somewhat surprising in view of the following fact. Seshadri[400] has computed the radiated power from an infinite antenna in an isotropic warm plasma. He found that the contribution from the electromagnetic mode is practically the same as that in a cold plasma, while there is an additional contribution from the longitudinal acoustic mode in a warm plasma. For $\omega \simeq \omega_p$, the radiated power in acoustic modes is even greater than that in electromagnetic modes. Except for $\omega \gg \omega_p$, the contribution from the acoustic mode is generally comparable to that from the electromagnetic mode. Therefore,

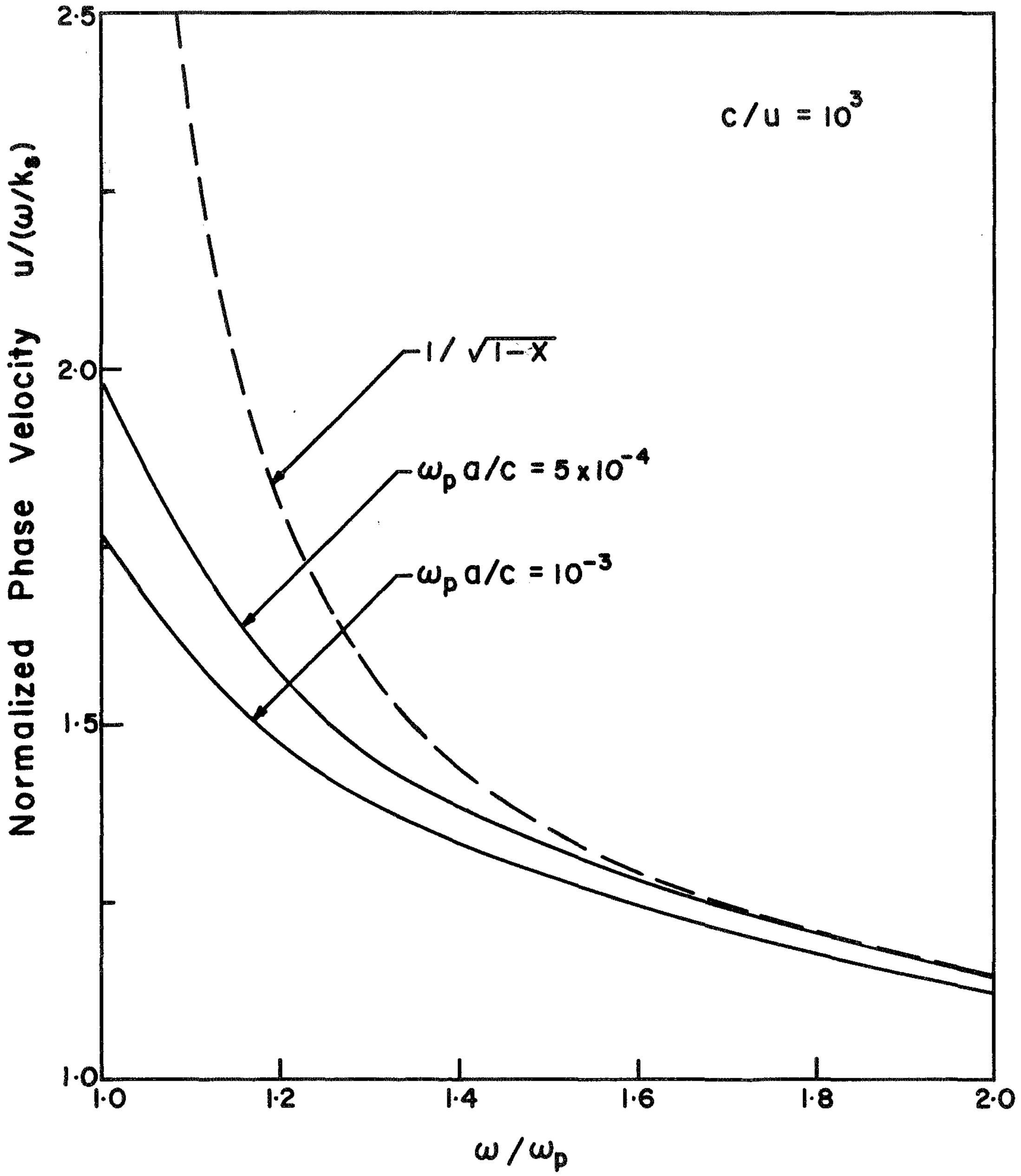


Figure 1.12 Normalized phase velocity of the surface waves along the outside of an infinite antenna immersed in a warm plasma (after Wunsch[525])

from Seshadri's result, one expects a more significant modification in the admittance due to the presence of acoustic waves than those computed by Miller.[300]

For X > 1, the value of Y_{in}^{∞} computed on the basis of the warm plasma model differs appreciably from that based on the cold plasma mode [Figure 1.6]. The value of G in the latter model is very small and is entirely due to the collision loss. In the warm plasma model, however, G is considerably larger and is perhaps due to the excitation of the surface wave discussed earlier.

If a vacuum sheath is included in the analysis, the input admittances computed from warm and cold plasma models agree closely for all X.[302]

5. IMPEDANCE OF A FINITE ANTENNA I: BOUNDARY VALUE PROBLEM

For a cylindrical antenna in an isotropic medium, there are usually two methods to attack the impedance problem, namely, the integral equation and the multiple reflection approaches. In the former, an integral equation for the unknown current distribution is set up from the Green's function of the medium and the source condition [i.e., Equation (4.1)], then the current is solved for by iterations or other numerical methods.[562] This approach is suitable for short antennas. In the multiple reflection approach,[563] the finite antenna is regarded as a truncated version of an infinitely long one, and the terminations at the ends of the antenna cause multiple reflections of the current wave. Since asymptotic techniques are used in calculating the multiple reflections, this approach gives accurate results only for relatively long antennas (say, $k_o h > 1$).

Neither one of the above two approaches can be applied to antennas in a general anisotropic plasma without considerable difficulties. This is briefly explained below.

In the integral equation approach, the first difficulty arises from the fact that the Green's function in a general anisotropic plasma can not be found in a closed form. Furthermore, in a hyperbolic plasma, the Green's function is singular not only at the source point but also at other places. Therefore, how to regularize those singular points in the kernel of the integral equation is another difficult task. Thirdly, the current in general has two components, longitudinal and azimuthal, and therefore, one may have to solve two coupled integral equations. The last but not the least difficulty for a tubular antenna is that the integral equation approach includes both inside and outside currents on the antenna.

In hyperbolic plasma or in warm plasma, the inside current may play an important role to the solution from the integral equations, even for a thin antenna. More detailed explanation about this point will be given later.

If the multiple reflection approach is used for an antenna problem in an anisotropic plasma, the major difficulty lies in the calculation of the reflection from the terminals. Furthermore, a key fact which contributes to the success of the multiple reflection approach in the isotropic medium is that the reflected and the incident current waves vary along the longitudinal direction according to the same universal function.[*] It is because of this that the multiple reflections can be summed up in a closed form (Neumann series).[†] Whether the current waves in an anisotropic plasma also have such a property remains a crucial question.

Due to these difficulties, the finite rigorous solutions for antenna problems in plasma have been obtained only for several special cases, as presented below.

(A) Isotropic Cold Plasma

For $X < 1$, we give here two well-known formulas, one is suitable for a short dipole and the other for a relatively long antenna. For $\sqrt{K_{\parallel}}\, k_o h \ll 1$, an approximate expression for the input admittance derived from the integral equation[237] is given by

$$Y_{in} \simeq \frac{2\pi H}{\eta[2\ell n(\frac{H}{A})-2]} \left\{ \frac{H^3}{6\ell n\frac{2H}{A} - 9} + j\left[1 + \frac{H^2}{3}\left(1 + \frac{1.08}{2\ell n\frac{2H}{A} - 3}\right)\right]\right\}, \qquad (5.1)$$

$$A \ll H \ll 1$$

---

[*] The leading term is $(\ell n\ kz)^{-1} e^{\pm jkz}$

[†] See, for example, reference 571.

In the above formula we have used the notations defined in (4.4). For a relatively long antenna, one approximate expression is obtained by considering the multiple reflections between the two ends of the antenna; the result is[563, 571]

$$Y_{in} \simeq Y_{in}^{\infty} + \frac{2RU^2(H)}{1-RU(2H)}, \qquad H > 1 >> A \tag{5.2}$$

where

$$R = \frac{-\eta\Omega_o}{2\pi}\left(1 + \frac{\pi^2}{12}\Omega_o^{-2} + 2.404\,\Omega_o^{-3}\right)^{-2}$$

$$\begin{aligned} \Omega_o &= -2\,\ell n\,A - 1.15 - j\pi \\ U(H) &= \frac{2\pi}{\eta}e^{-jH}\left[\frac{1}{P(H)} - \frac{0.5772}{P^2(H)} - \frac{1.3118}{P^3(H)} + \frac{0.252}{P^4(H)} + \frac{3.9969}{P^5(H)}\right] \\ P(H) &= \ell n\,[-2jH/(1.78A)^2] \end{aligned} \tag{5.3}$$

In (5.2), Y_{in}^{∞} is the admittance of an infinitely long antenna in the same medium, as given in (4.3). The notations H and A are again defined as in (4.4).

For X < 1, no convenient analytical formula is available. However, since the current wave on an infinitely long antenna decays exponentially away from the feed, the termination effect at the two ends of the antenna is relatively unimportant. Hence, provided the antenna is not too short, its input admittance should be very close to that given in (4.5).

(B) Uniaxial Plasma

For elliptical plasma, the scaling procedure leads to (5.1) for a short antenna, and (5.2) for long ones with Y_{in}^{∞} as given In (4.3) and η, A, Δ, and H as defined in (4.7). The formula in (5.1) is practically the same as the one derivable from the quasi-static approximation and will be detailed in the next section. For relatively long antenna, some typical results of Y_{in} computed from (5.2) as a function of Y are presented in Figure 1.7b.

The finite antenna in hyperbolic uniaxial plasma was recently considered by Lee.[268] He indicated that the classical Hallén type integral equation approach is not suitable since it does not describe the actual physical situation closely. The current $I^{(t)}(z)$ used in the integral equation formulation generally consists of two components

$$I^{(t)}(z) = I^{(in)}(z) + I(z) \tag{5.4}$$

where $I^{(in)}(z)$, and I(z) are the currents on the inner and outer surfaces, respectively. If the antenna is situated in the free space or the elliptical plasma, the antenna radius is generally small enough so that all the waveguide modes inside the antenna tube are far below cutoff, and therefore $I^{(in)}(z)$ does not contribute significantly to the total current $I^{(t)}(z)$. However, the situation is completely reversed for an antenna in a hyperbolic plasma where the waveguide modes do not suffer any cutoff due to the infinitely extended dispersion surface. Consequently, the wave propagating inside the cylindrical antenna may play an important role for the solution of $I^{(t)}(z)$ from the classical integral equation. In the actual physical situation, however, this is not quite so. Either the antenna is made of a solid rod, or a tube whose radius is so thin that the plasma practically cannot penetrate into the interior of the tube freely. In the latter case, to be precise we need to solve the problem of an antenna in an inhomogeneous medium, which of course is quite difficult. The solid antenna in a hyperbolic plasma was recently treated by considering the multiple reflections between the two terminals of the antenna. This result for the input admittance is given by (5.2) with the following notations:[268]

$$R = \frac{+\ \eta\Omega}{2\pi}\left(1 + \frac{\pi^2}{12}\Omega^{-2}\right)^{-2}\left[1 - \frac{A}{12}\right] \tag{5.5}$$

Ω, U(H), and P(H) are given in (5.3)

η, A, Δ, and H are defined in (4.9).

It is interesting to note that except for a minus sign the reflection coefficient R at the solid end of the antenna is practically (since $A \ll 1$) the same as that in (5.3) for a hollow-tube antenna in an elliptical plasma, as far as the current on the outer surface of the antenna is concerned. Some typical values for the admittance of a finite antenna in a hyperbolic uniaxial plasma are presented in Figure 1.8a.

(C) Isotropic Warm Plasma

The problem of a finite tubular antenna in an isotropic warm plasma can be formulated in terms of two coupled integral equations and has been solved by Wunsch[525] through numerical techniques for the case when the source frequency is greater than the plasma frequency, i.e., $X < 1$.

If X is not close to unity, the current distribution along an (acoustically) thin antenna is slowly varying, similar to that in a cold plasma. Therefore, for an (acoustically) short antenna,* the current is well-approximated by a triangular distribution. However, for X close to unity, the current is oscillating. The oscillating period of the current wave is of the same order as that of the surface wave guided along an infinite cylinder as discussed in Section 4D.

---

*In the examples computed by Wunsch,[525] $h \simeq (1/4)\lambda_p$ where $\lambda_p = (2\pi)/(\omega/u)$.

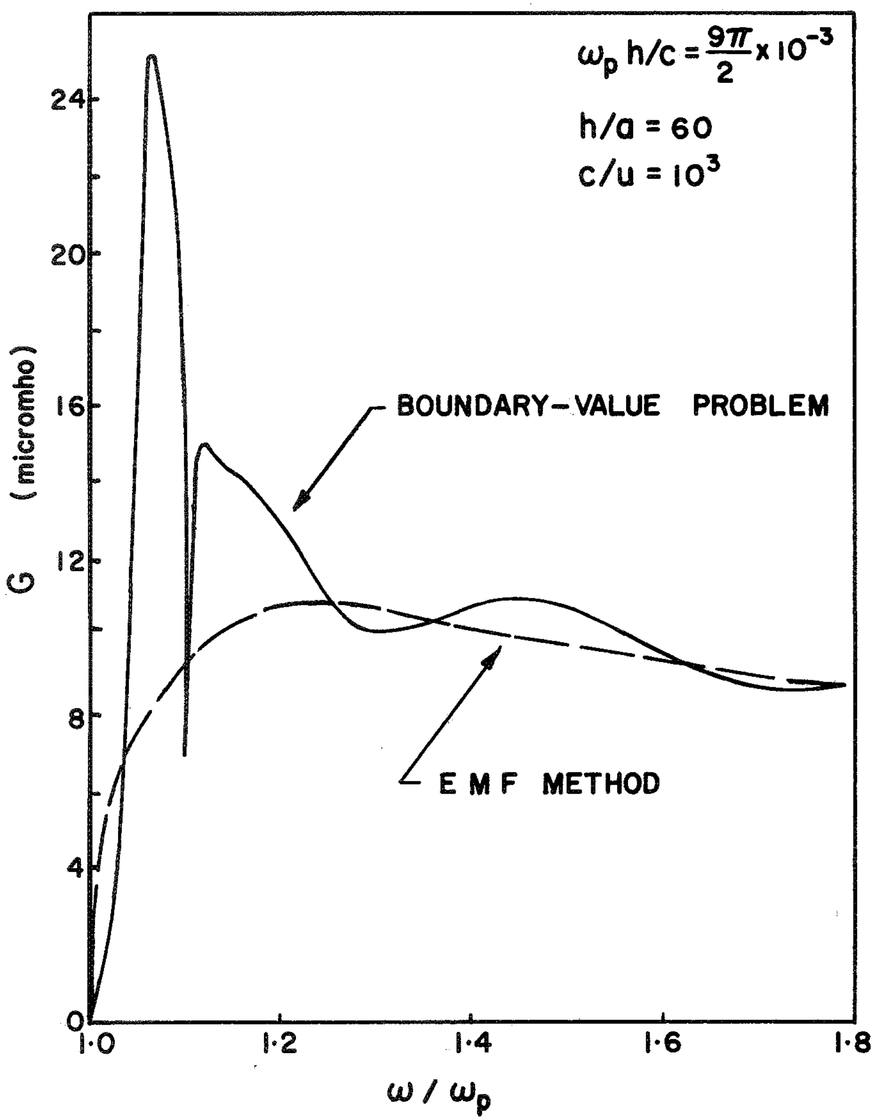


Figure 1.13 Conductance of a cylindrical antenna in an isotropic warm plasma vs. frequency (after Wunsch[525])

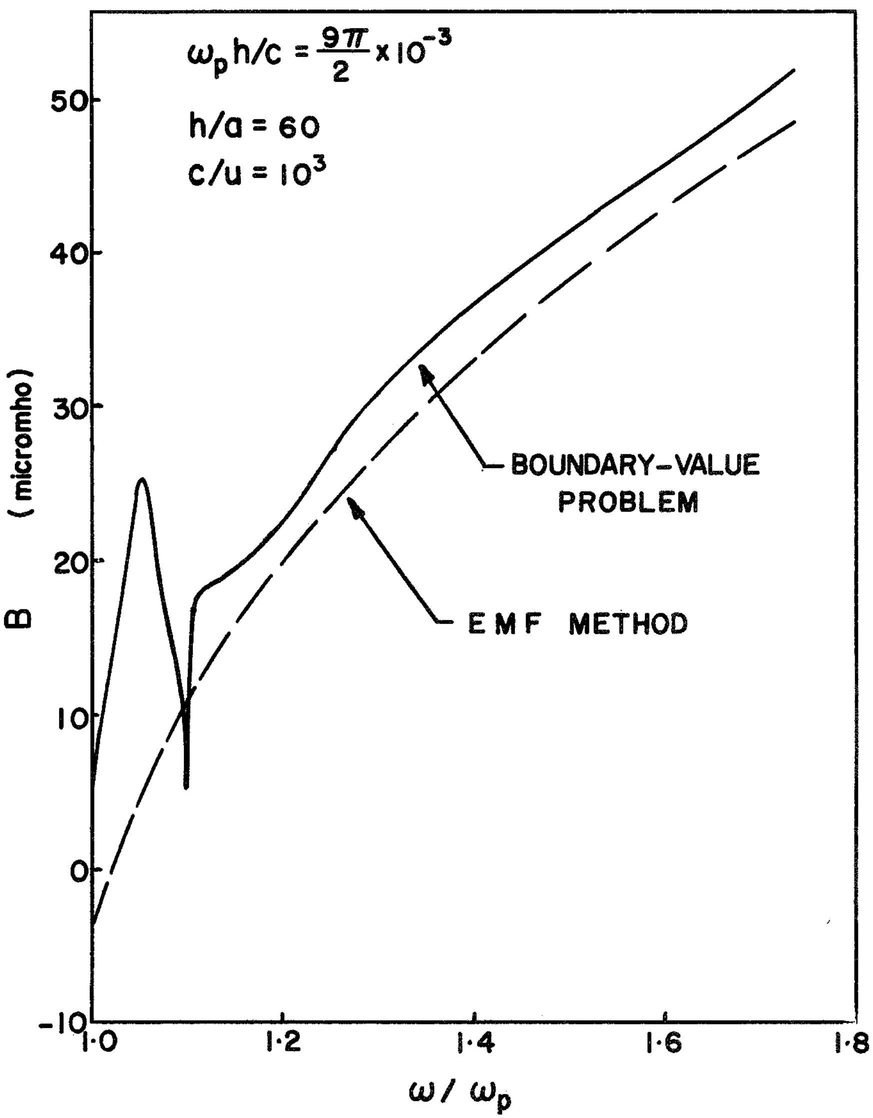


Figure 1.14 Susceptance of a cylindrical antenna in an isotropic warm plasma vs. frequency (after Wunsch[525])

The input admittance of an antenna with parameters[*] $\frac{\omega_p h}{c} = \frac{9\pi}{2} \times 10^{-3}$, $\frac{a}{h} = \frac{1}{60}$ in a warm plasma with $(c/u) = 10^3$, is presented in Figure 1.13 and Figure 1.14. Note that, provided X is not close to unity, results obtained by Wunsch are approximately the same as those resulting from the induced e.m.f. method with assumed triangular distribution for the current. As will be discussed in the next section, these results bear a limited physical meaning due to the inherent difficulty in the warm plasma model.

It should also be mentioned that the solution obtained by Wunsch[525] is that of integral equations similar to Hállen's integral equation in free space. Therefore its current includes both the inner and outer components on the tubular antenna. It is known that there is always a propagating mode[**] inside a tube filled with warm plasma no matter how small the tube radius is. Therefore the inner current should contribute more than a negligible part to the total current, and therefore Wunsch's solution is perhaps not a good approximation for a solid antenna.

---

[*] For $\omega_p = 2\pi \times 10^6$, h is about 0.7 meter. Also $h = (2.25/\sqrt{X})\lambda_p$

[**] Also known as Trivalpiece mode.

6. IMPEDANCE OF A FINITE ANTENNA II: TRIANGULAR CURRENT DISTRIBUTION

The rigorous solution of antenna impedance in plasma as described in the previous section is very difficult, and useful results have been obtained only for a few special cases, by using approximations. Among the various approximate methods for calculating the impedance of a linear cylindrical antenna in plasma, the most commonly used is the induced e.m.f. method; namely, the input impedance is computed from

$$Z_{in} = -\frac{1}{I_o^2}\int E_z J \, ds \tag{6.1}$$

where J is the <u>assumed</u> longitudinal current density, and I_o is the current at a reference point on the antenna. The key to the success of this method lies in the guessing of the "right" current J(z). Unfortunately, very little information, either from experiments or theory, is available for helping us in this guessing.

For an electrically short and thin antenna in free space, the choice of a simple triangular distribution for the current, i.e.,

$$J(z) = I_o\left(1 - \frac{|z|}{h}\right)\frac{\delta(\rho-a)}{2\pi\rho} \quad , \ |z| < h \tag{6.2}$$

is generally considered a good one. Many authors continue to use (6.1) for "short" antennas in plasma, and have obtained some qualitatively good results when compared with experiments. However, there are several difficulties and questions in connection with the use of (6.1) and (6.2) for antennas in plasmas:

(i) Sometimes it is difficult to determine how "short" physically an antenna is to be an electrically short antenna in plasma. In warm plasma, for example, there are two wavelengths, that associate with the electromagnetic wave and that with the acoustic wave. An antenna which is very short in terms of the electromagnetic wavelength may appear extremely long to the acoustic wave. As another example, consider the isotropic plasma with $\omega < \omega_p$. Since there is no wave propagation there is no wavelength to compare to the antenna length.

(ii) In the case of warm plasma, the induced source on the conducting surface of the antenna consists of both current and force. How the force on the antenna affects the validity of the induced e.m.f. method is an important, yet unanswered question.

(iii) In an anisotropic plasma, the current in general has not only longitudinal but also azimuthal components. The effect of the azimuthal current is not included in (6.1).

Despite the above drawbacks, the impedance computations from (6.1) and (6.2) have been carried out in various plasma models and have been cited most extensively in the literature for discussions and comparisons with experiments. In the following, we present results for anisotropic cold plasma and isotropic warm plasma models.

(A) Anisotropic Cold Plasma

The radiation resistance R_{rad} of an infinitesimally thin and short dipole with assumed triangular distribution has been computed by Seshadri[402] and his results are plotted in Figures 1.15 and 1.16. These two figures may be compared with Figures 1.3 and 1.5, where a Hertz dipole was considered. The major difference between the two sets of figures is that R_{rad} of a Hertz dipole is always infinite in the hyperbolic region, while that of a finite short dipole is finite. As pointed out in Section 3, the finite R_{rad} of a dipole in the hyperbolic region is due to the fact that the assumed triangular distribution in (6.1) is sufficiently smooth. However, it is

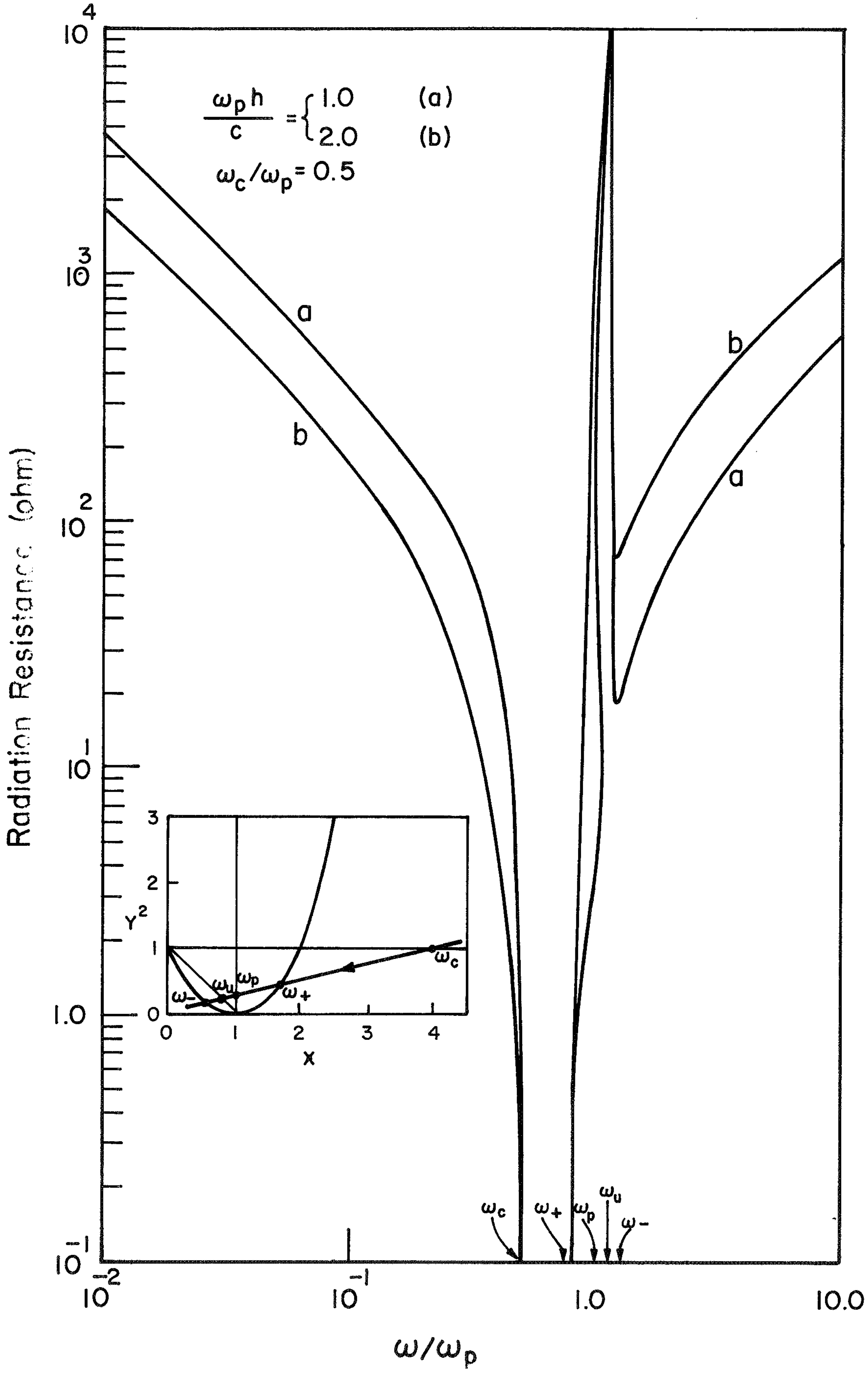


Figure 1.15 Radiation resistance of a short linear current filament vs. frequency with $\omega_c / \omega_p = 0.5$ (after Seshadri[402])

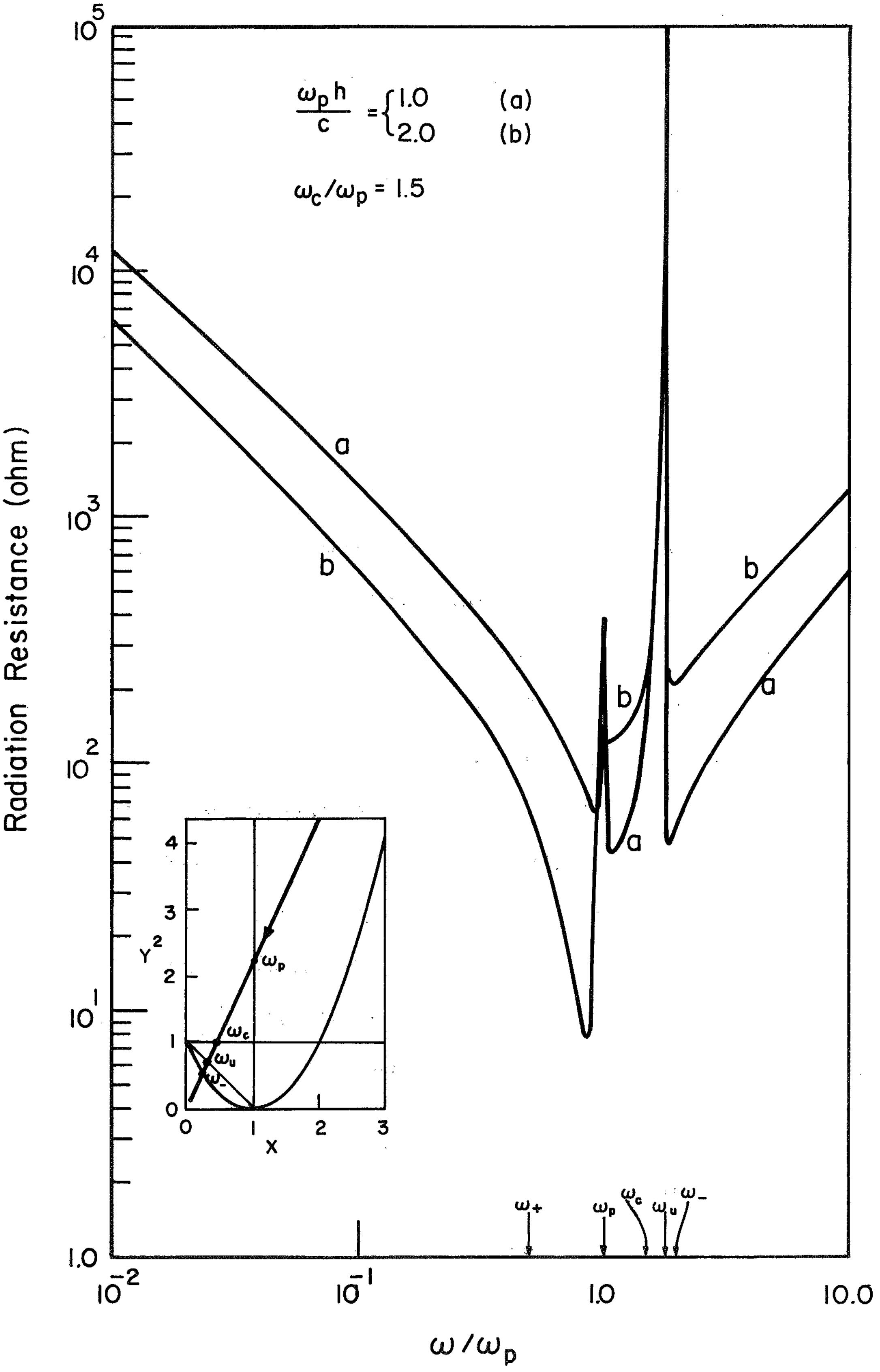


Figure 1.16 Radiation resistance of a short linear current filament vs. frequency with $\omega_c/\omega_p = 1.5$ (after Seshadri[402])

where the upper row for $X > 1$ and the lower one for $X < 1$. It is not surprising that the second term in (6.4) is identical to (6.3). The absence of the small resistive term $(\eta_o/6\pi)(\sqrt{K_\perp}\, k_o h)^2$ in (6.3) is due to the approximation $k_o \rightarrow 0$ involved in the quasi-static method.

Furthermore, we observe that (6.3) agrees with the dominant term of the imaginary part in (5.1), which was obtained for a short dipole in elliptical uniaxial plasma using rigorous approach.

Numerical computations of (6.3) for some typical parameters are presented in Figures 1.17, 1.18 and 1.19 where both lossless and lossy plasmas are considered. In the lossless case, the resistance is zero whenever the dispersion surfaces are bounded. The finite resistance elsewhere results from a negative argument in the logarithmic term. The reactance blows up at ω_u and has two zeros, one at ω_c and the other at a frequency low enough to make $\mathrm{Re}\, \ell n(\sqrt{K_\perp} h/\sqrt{K_\parallel}\, a) = 1$. As ω approaches 0, both the resistance and reactance become infinite, while at very high frequencies they retain their free space values, as expected. The introduction of collision loss tends to smooth the impedance curves, and sometime modify them significantly.

Under quasi-static approximations, Balmain has also computed Z_{in} from (6.1) and (6.2) when the dipole is inclined by an angle θ_o with respect to the z-axis, the direction of the static magnetic field. His result is[23]

$$Z_{in} = \frac{\eta_o}{j\pi(K_t k_o h)} [\ell n \frac{K_t h}{K_\ell a} - 1] \tag{6.5}$$

$$K_t = \sqrt{K_\perp(K_\parallel \sin^2\theta_o + K_\perp \cos^2\theta_o)}$$

$$K_\ell = \frac{1}{2} [\frac{K_\perp\sqrt{K_\parallel}}{\sqrt{K_\parallel \sin^2\theta_o + K_\perp \cos^2\theta_o}} + \sqrt{K_\perp K_\parallel}] \tag{6.6}$$

also interesting to note that the infinite value of R_{rad} at the upper hybrid frequency $\omega_u = \sqrt{\omega_c^2+\omega_p^2}$ can not be gotten rid of even with a triangular current.

The real part of the input impedance Z_{in} computed from (6.1) and (6.2) is believed to be the same as R_{rad} computed by Seshadri[402] [Figure 1.15 and Figure 1.16]. Information about the imaginary part of Z_{in}, however, is not available.

A simple and useful expression for Z_{in} can be obtained from (6.1) and (6.2) if the quasi-static approximation is used. In the quasi-static approximation, the frequency ω (or k_o) is allowed to approach zero but the elements of the dielectric tensor $\overline{\overline{K}}$ are kept fixed. In such a limiting case, Balmain[23] and others[62,151,506] have obtained

$$Z_{in} = \frac{(\eta_o/\sqrt{K_\perp})}{j\pi(\sqrt{K_\perp}\, k_o h)}\left[\ln \frac{\sqrt{K_\perp}\, h}{\sqrt{K_\parallel}\, a} - 1\right], \qquad h \gg a \tag{6.3}$$

which is independent of the off-diagonal term K_x in the dielectric tensor. By considering the radiation of a point source in anisotropic cold plasma, Mittra and Deschamps[311] have shown that the very near field is independent of K_x. This finding seems to support that the absence of K_x in (6.3) is not a serious limitation of the quasi-static method.

An interesting point to be mentioned is that if one uses a uniaxial plasma model (elliptical or hyperbolic), the computation of the impedance from (6.1) and (6.2) gives

$$Z_{in} = \left\{\begin{matrix} \dfrac{(\eta_o/\sqrt{K_\perp})}{6\pi}\,(\sqrt{K_\perp}\, k_o h)^2 \\[2ex] 0 \end{matrix}\right\} - j\left\{\frac{(\eta_o/\sqrt{K_\perp})}{\pi(\sqrt{K_\perp}\, k_o h)}\,\ln \frac{\sqrt{K_\perp}\, h}{\sqrt{K_\parallel}\, a}\right\} \tag{6.4}$$

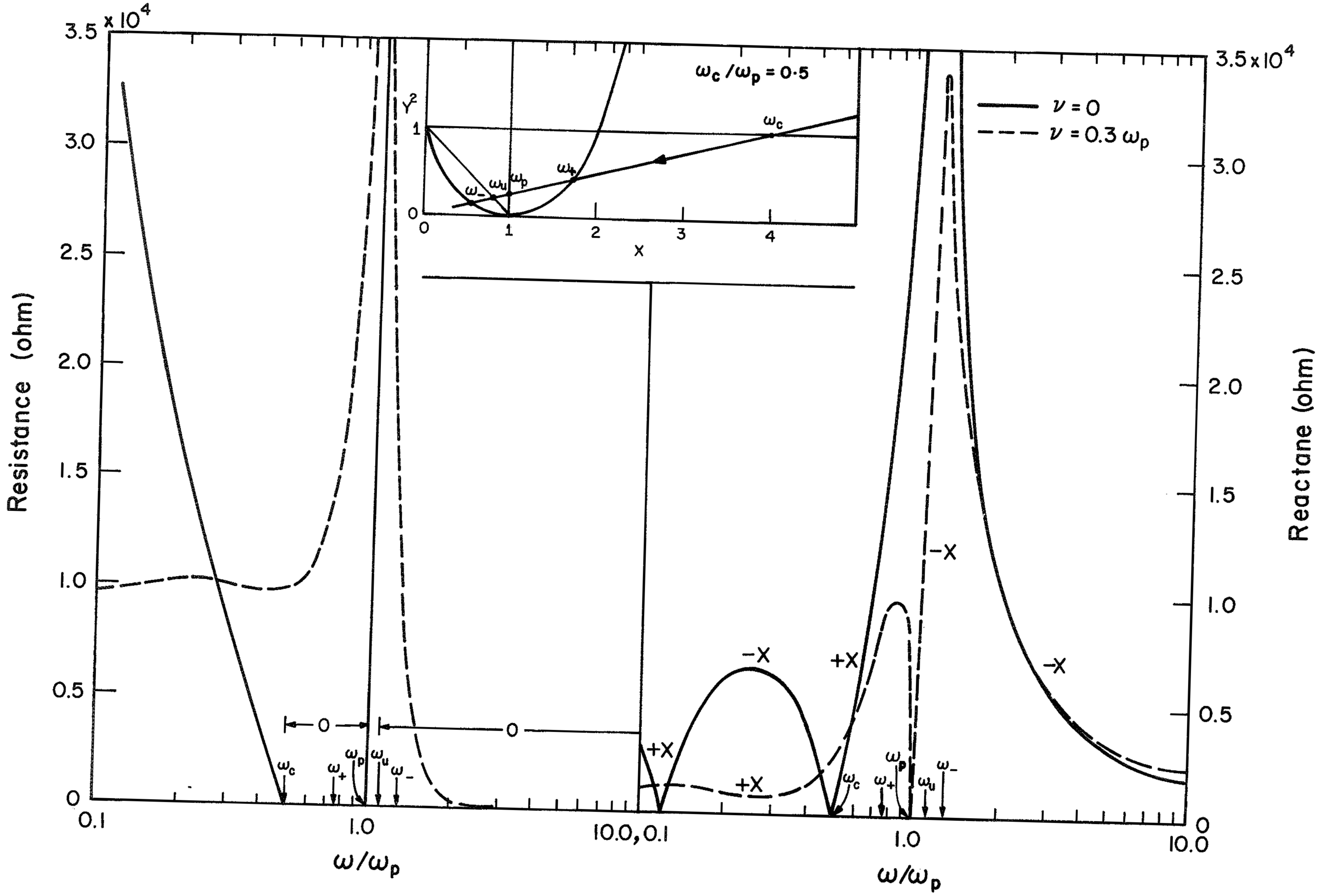


Figure 1.17 Impedance of a short cylindrical antenna in anisotropic cold plasma vs. frequency with $\omega_c / \omega_p = 0.5$

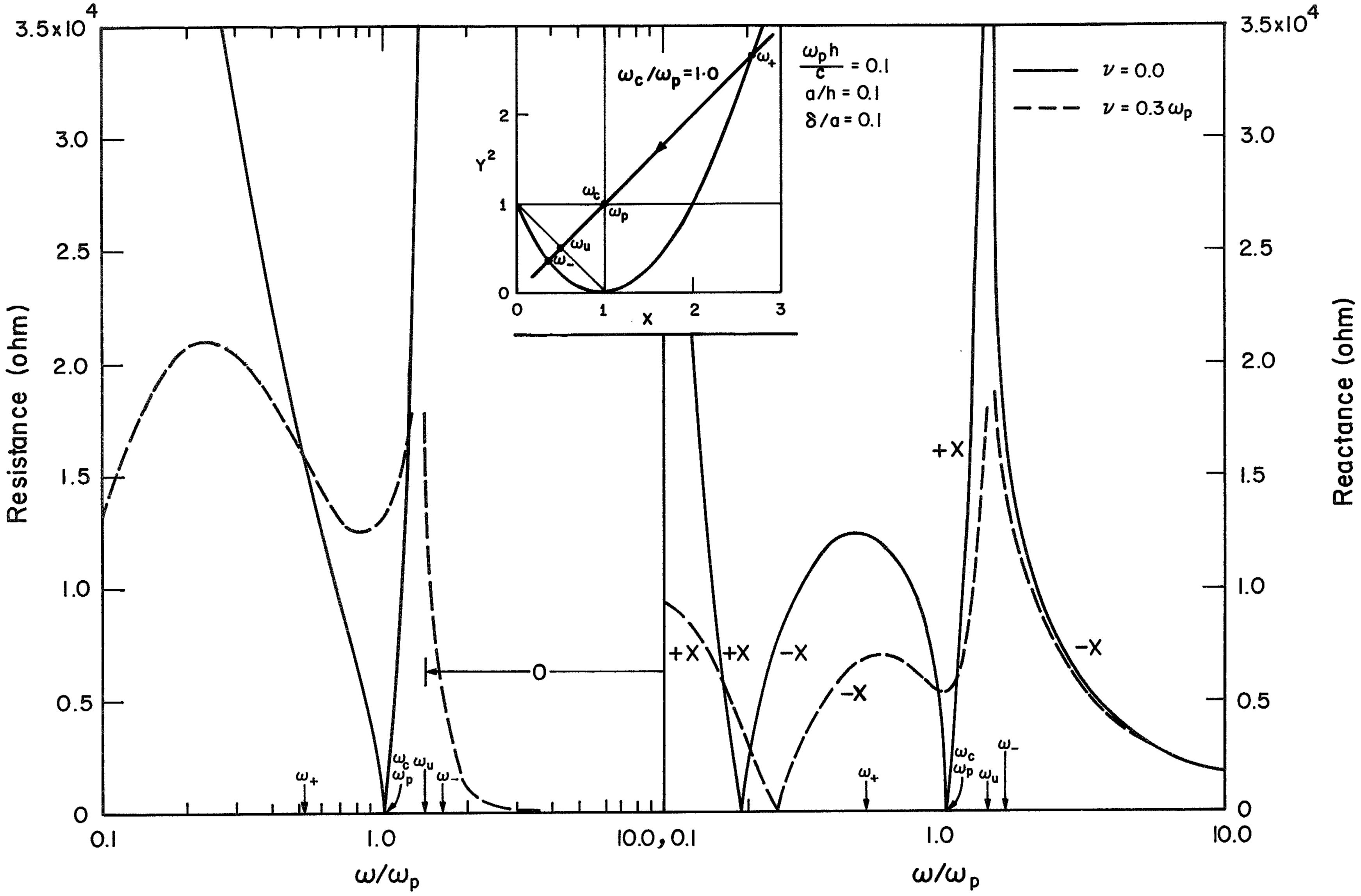


Figure 1.18 Impedance of a short cylindrical antenna in anisotropic cold plasma vs. frequency with $\omega_c/\omega_p = 1.0$

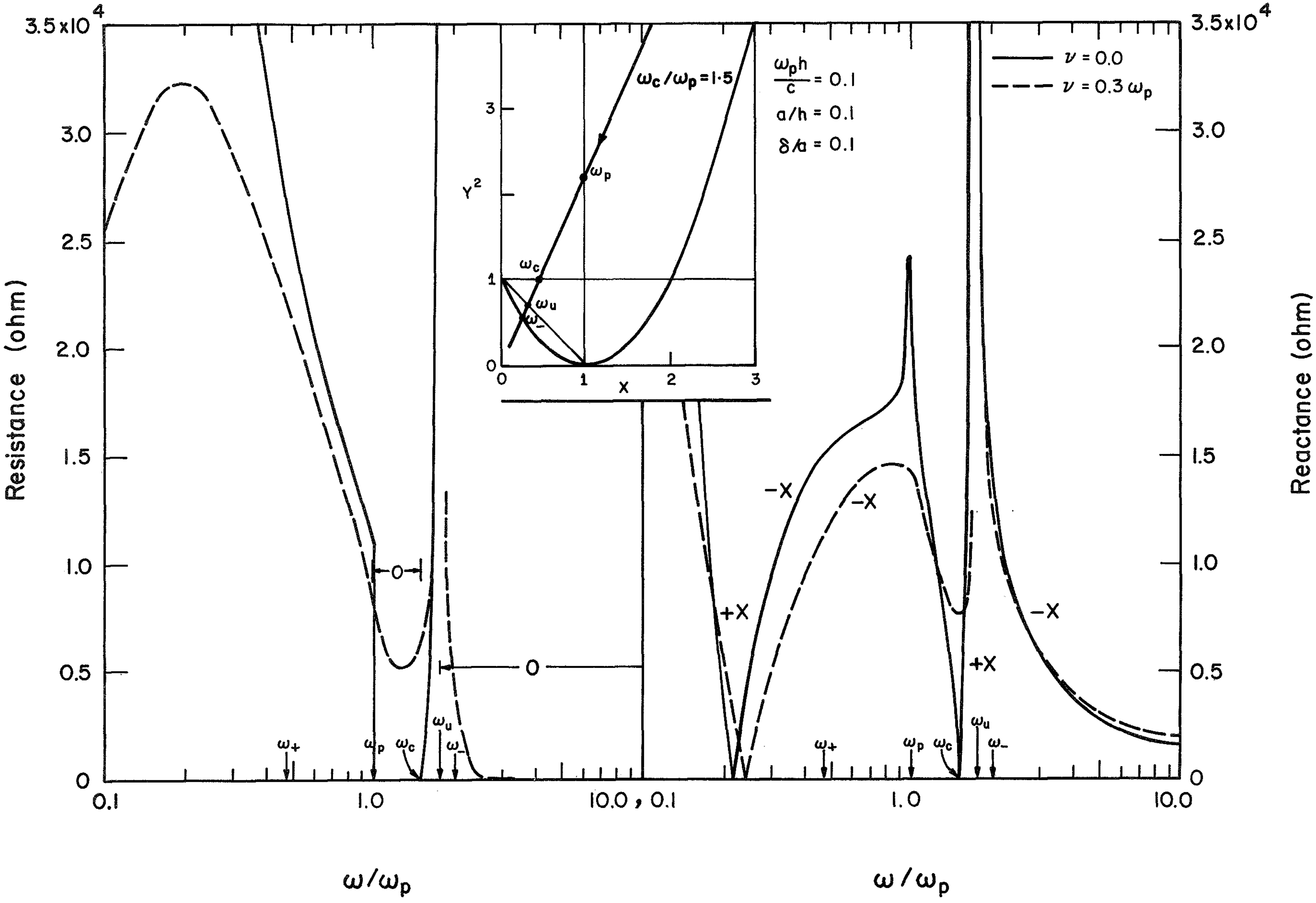


Figure 1.19 Impedance of a short cylindrical antenna in anisotropic cold plasma vs. frequency with $\omega_c/\omega_p = 1.5$

where K_t and K_ℓ may be regarded as the tranverse and the longitudinal scaling factors, respectively. It should be pointed out that (6.5) cannot be obtained by using a uniaxial model. Thus, even though the quasi-static and uniaxial approximations give practically the same results for a short dipole with parallel orientation, they do not agree in general.

(B) Isotropic Warm Plasma

As mentioned earlier, in a warm plasma the computation of Z_{in} from (6.1) does not include the pressure term on the antenna surface, and therefore the validity of the induced e.m.f. method is questionable. In this section, we will furthermore demonstrate that the result obtained from (6.1) and (6.2) is not a stable one, and therefore has limited physical meaning.

For a given current such as that in (6.2) radiating in warm plasma, the contributions from the electromagnetic wave and the acoustic wave can be completely separated. Thus, the impedance of a thin antenna (h>>a) computed from (6.1) and (6.2) is found to be

$$Z_{in} = Z_e + Z_p \tag{6.7}$$

where Z_e is the contribution from the electromagnetic wave and is precisely the same as that given in (6.3); while Z_p is that from the acoustic wave and is given by[24]

$$Z_p = \begin{cases} \dfrac{\eta_o X}{2(k_o h)(1-X)} \; J_o^2(k_p a) + J_o(k_p a) Y_o(k_p a) \quad , & X < 1 \\ \\ -j \dfrac{\eta_o X}{\pi(k_o h)(1-X)} \; I_o(jk_p a) K_o(jk_p a) \quad , & X > 1, \end{cases} \tag{6.8}$$

$$h >> a$$

where $k_p = (\omega/u)\sqrt{1-X} = (c/u)\sqrt{K_{\parallel} k_o}$, the acoustic wave number. J_o, Y_o, I_o and K_o are Bessel functions.

In order to study the influence of the acoustic wave on antenna radiation, let us consider

$$\frac{\mathrm{Re}(Z_e+Z_p)}{\mathrm{Re}Z_e} = 1 + \left[\frac{3\pi X}{(1-X)^{3/2}}\right]\left[\frac{1}{k_o h}\right]^3 \quad J_o^2(k_p a) \tag{6.9}$$

which is a ratio of the resistance of a short antenna in warm and cold plasmas. Concentrate on the second term of the right-hand side of (6.9). The first factor indicates that the radiation is greatly enhanced by the presence of the acoustic wave when $X \simeq 1$. The second factor gives the anomalous behavior that the shorter the antenna the larger the radiation resistance in a warm plasma. This is due to the extremely large dispersion surface of the acoustic wave, as has been explained in Section 3D in association with (3.9). The third factor is the most interesting one. Since in many situations, except perhaps $X \simeq 1$, we may approximate the Bessel function by

$$J_o^2(k_p a) \simeq \frac{2}{\pi k_p a} \cos^2(k_p a - \frac{\pi}{4}), \quad X \not\simeq 1, \; k_p a \gg 1 \tag{6.10}$$

which is a rapidly oscillating function, then if the radius of the antenna a is changed by a small fraction

$$\Delta a = \frac{\pi}{2k_p} = \frac{1}{4}\left(\frac{u}{c}\right) \frac{1}{\sqrt{1-X}} \lambda_o, \quad X \not\simeq 1 \tag{6.11}$$

the ratio given in (6.9) varies from unity to an extremely large number. In other words, the acoustic wave can contribute from zero to nearly 100% of the total radiation just by a variation of $10^{-4}\lambda_o$ or $10^{-5}\lambda_o$ in radius!

Similar conclusions can also be reached due to the variation of a fraction of a degree in temperature of a plasma of several thousand degrees. This, of course, is not physically plausible and is due to the inherent difficulty in the warm plasma model.

7. CONCLUSIONS

Rigorous solutions for the impedance of cylindrical antennas in linear cold or warm plasma have been obtained with either of the following assumptions: First, that certain plasma parameters approach their limiting values, i.e., when the plasma becomes isotropic or uniaxially anisotropic, second, when the antenna becomes infinitesimally small or infinitely long. Even though the applicability of these solutions to practical situations is limited, they do shed some light on the influence of anisotropy of the medium on the impedance of the antenna.

Because rigorous solutions are, in general, difficult to obtain, resort is made to approximations. Oftentimes, these approximations are based on our knowledge about antennas in freespace, but their applicability to the problems of antennas in plasma has not always been fully established. For a " short " dipole, the induced emf method with an assumed triangular current distribution is generally accepted as a reasonable one and has yielded results that compare favorably with experiments for certain ranges of cold plasma parameters. Nevertheless, it is difficult to state precisely what the range of applicability is, for example, to tell how small an antenna must be to be regarded as a " short dipole " in a plasma.

The role played by acoustic waves in the antenna impedance has not been satisfactorily elucidated. Because the acoustic wavelength is extremely small compared to the electromagnetic wavelength, the results obtained so far for the impedance of short dipoles are inconclusive in the sense that the contribution predicted for the acoustic wave to radiation may vary from very small to very large values when very small changes in the antenna dimensions

(10^{-4} λ) or in the plasma temperature (a few degrees) are assumed.

Conceivably, the impedance of an antenna in plasma should be quite sensitive to its immediate surrounding. Thus, the effect of the sheath enclosing the antenna is a vital problem that needs to be solved. Moreover, for transmitting antennas nonlinearities have to be taken into account and very little work has been done in this area.

As a concluding remark, we would like to point out that in the past ten years great attention has been given to the problems of antennas in plasma and almost all the idealized problems which are reasonably manageable from a mathematical point of view have been worked out. Some basic understanding has been gained, but the complete physical problem is far from being completely solved. Future research should be directed towards more realistic modeling of problems and the use of computers to solve the resulting complicated equations numerically, rather than introducing too many idealized assumptions in order to carry out elegant mathematical exercises.

PART II

MEASUREMENTS

by

M. J. Al-Hakkak

1. INTRODUCTION

As in the early stage of the study of any physical problem the importance of the experimental work cannot be overemphasized, there has been relatively very little experimental work on the antenna properties in plasma as compared with the enormous theoretical counterpart. This is because good experimental work, whether in the ionosphere or in laboratory plasma, is even more difficult than theoretical analysis and is also quite expensive. Insofar as the available experimental data are concerned, they have, at best, only shown qualitative agreement with theoretical predictions. This is not surprising, however, if one considers the following reasons: First, the plasma models used in theoretical analyses (unbounded, homogeneous, etc.) do not exactly represent the physical situation. Second, there is not yet a complete set of reliable theories which can be used for the interpretation of the measurements. Third, accurate and complete diagnosis of the plasma parameters is extremely difficult. Despite all of these difficulties the experimental work has supplied to us much vital information about the behavior of antenna impedance in plasma. In this part of the report, we will summarize those important measurements made in the ionosphere and in laboratory plasma and their comparison with theory.

Since the sheath effect is inevitable in any experiment concerning antennas in plasma and since theoretical consideration of this effect has not been considered in the first part of this report, a brief description of the sheath problem relevant to experiments is included. Also, because most of the measurement has been done in the ionosphere, a brief survey of ionospheric parameters is pertinent.

2. IMPEDANCE MEASUREMENTS IN THE IONOSPHERE

A high percentage of the impedance measurements have been done in the ionosphere, a natural source of plasma, and they were mainly meant for the determination of medium properties---the electron density in particular. Antennas in the ionosphere may also have other uses: to measure fields, as in radio astronomy applications, or as transmitters of radio signals. When used as receivers, knowledge of their impedance is important in order to calibrate the measurements. As transmitters, they pose another problem nonlinear effects and high temperature due to the high field strength associated with the near field. In fact, the possibility of plasma breakdown places a limit on the strength of the transmitter and thus restricts the usefulness of high power transmission. A serious experimental study of antenna impedance properties for such uses has not been found in the literature.

For measurements in the ionosphere, rockets have to be launched carrying probing antennas and measuring and recording instruments. Any launched rocket travels along the familiar parabolic path reaching a maximum altitude in the ionosphere termed the "apogee." Since the ascent and descent paths traverse different regions of the ionosphere, measurements at the same altitude usually differ in the two cases. This indicates that the ionosphere is not horizontally uniform. The measurements are recorded against a time scale. By knowing the time after leaving the ground, the position of the rocket in the ionosphere can be determined rather accurately, and the results may then be reduced to describe the variation of the ionospheric parameters against altitude.

The electron density in the ionosphere ranges from 10^3 to about 10^6

electrons per cm^3, corresponding to plasma frequencies of 280 KHz to 9.0 MHz, respectively. It increases rapidly to a maximum at an altitude of 300 km and drops slowly to 10^2 or 10^3 at a few earth radii. The geomagnetic field strength depends on both altitude and latitude. At the earth's surface it is about 0.6 gauss (f_h = 1.7 MHz) near the poles and about 0.3 gauss in the equatorial regions. At an altitude of 500 km, it reduces to about 0.4 and 0.2 gauss respectively. The collision effect is often neglected in interpreting antenna impedance in the ionosphere. The collision frequency decays rapidly from about 100 MHz at 50 km altitude to about 1 KHz at 150 km.

(A) Plasma Resonances

As we have seen in part I, the theory predicts that antenna behavior is complicated whenever any of the various plasma resonances is excited. In addition to the fundamental resonances ω_p, ω_h and ω_u, ionospheric measurements revealed resonance effects at still other frequencies, the harmonics of the cyclotron frequency. The launching of the Canadian ionospheric topside sounder satellite, Alouette I, on September 29, 1962, ushered in a new era of ionospheric measurements. Topside sounders were designed to explore the ionosphere from above by measuring the time delay between transmitted R.F. pulses and their received echoes as a function of frequency. Ionograms obtained by these sounders showed not only the presence of expected echo traces but also the existence of immediately returned signals at certain characteristic frequencies and often decaying slowly in time. Figure 2.1a is a sketch of a typical ionogram showing the virtual (range) of the echoes versus sounding frequency.[130] The spikes,[278] splashes,[542] or resonances[130,543] were associated with the

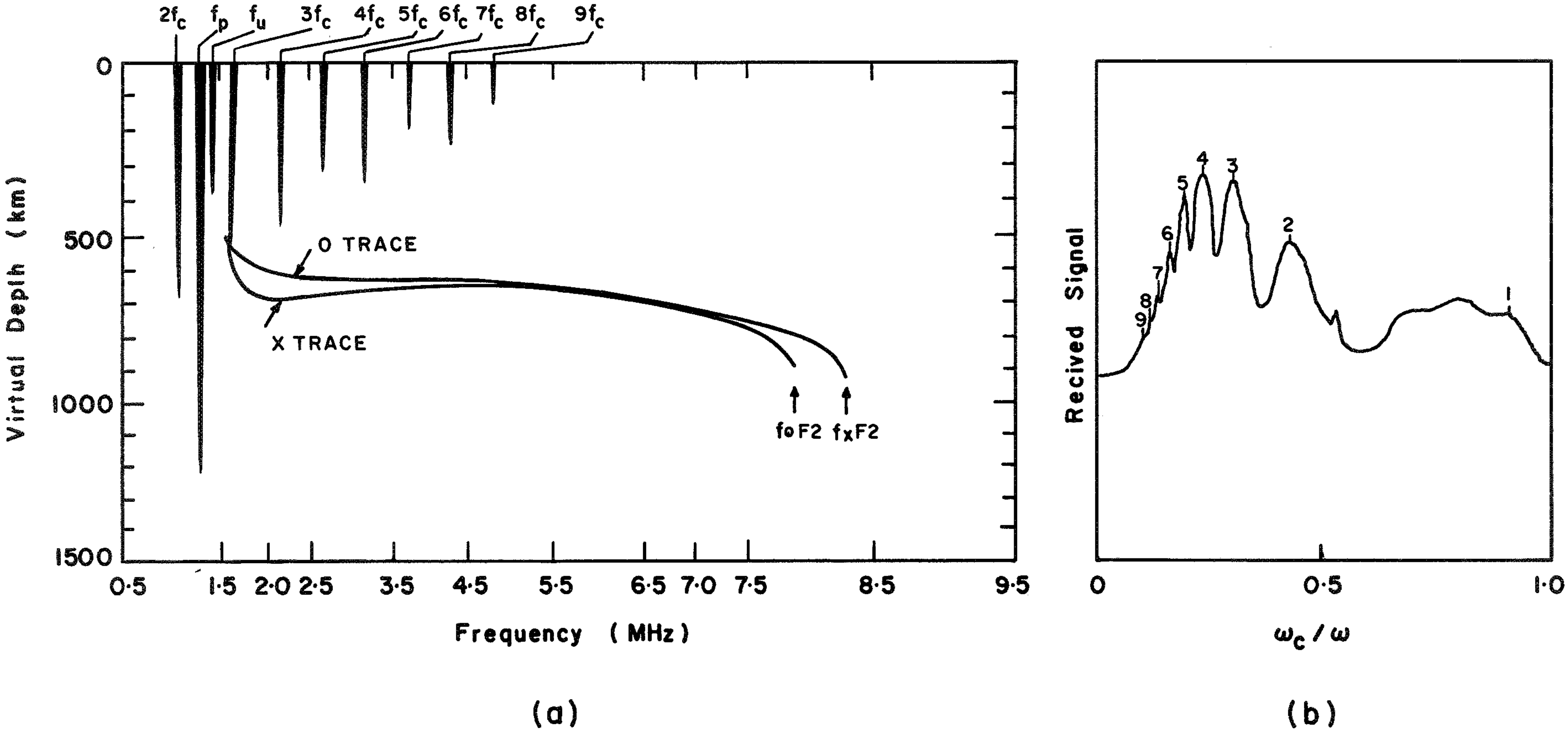


Figure 2.1 (a) Sketch of Alouette II ionogram showing various resonances as recorded at 14.37 UT, April 7, 1963 (b) Laboratory experiment results showing cyclotron harmonics resonances (after Crawford et al.[544])

properties of the magnetoionic medium in the vicinity of the satellite, and were identified[103,278] as corresponding to the local ω_p, ω_h, ω_u and the harmonics of ω_h. Later, up to 19 cyclotron harmonics have been observed. A laboratory experiment closely related to the Alouette gyro-resonance phenomena has been conducted by Crawford, et al.[544]. A typical result is shown in Figure 2.1b where the cyclotron harmonics are clearly evident.

The interpretation of the fundamental resonances and their effect on antenna impedance has been extensively surveyed in part I of this report. The cyclotron harmonics, however, received relatively little attention in the literature. Their occurrence was first interpreted as due to phase bunching of the electrons as they gyrate around the earth's magnetic field.[39] It was later explained on the basis of electrostatic oscillation[130] it was concluded that the condition for the long persistence of these local oscillations was that the group velocity should be very small compared to the phase velocity. There has been no truly comprehensive treatment of the problem of excitation and reception of these resonant frequencies by satellite antennas and, moreover, almost all experiments concerned with the antenna impedance have avoided measurements at the frequencies of the cyclotron harmonics.

(B) The Ion Sheath

The most important factor affecting antenna impedance measurements is that any material body immersed in plasma disturbs it. The reason for this is that electrons move much faster than ions; they are absorbed at the surface of the conductor which then takes a negative potential and becomes surrounded by an excess of positive ions. This is the sheath. Its nature depends on the body material (conductor or insulator) and on the body geometry. Its existence renders the surrounding medium inhomogeneous and hence its effect on the antenna impedance should be taken into account. The physical processes at the sheath boundaries are complicated and a rigorous formulation of the boundary conditions for an antenna in plasma is, in general, a formidable task. Theoreticians who are more concerned with the electromagnetic theory than the relevant plasma physics of the boundary condition often resort to simplified boundary conditions. The approaches usually considered are reviewed by Bachynschi[11] and summarized below:

(i) The sheath region is neglected entirely and the antenna is assumed to be in direct contact with the plasma with a rigid boundary condition.[402] This assumption is obviously not realistic, although analysis using this assumption may yield useful qualitative results in some idealized cases.

(ii) The sheath is represented by a dielectric layer included between the antenna and the plasma, corresponding to a simplified model of an insulated antenna.[405]

(iii) The "rigidity" boundary condition for a warm plasma is made in which the sheath is visualized as a hypothetical double barrier formed from infinitely heavy positive and negative ions, which prevents the penetration of electrons into the metal.[127] Other attempts represented the sheath by an electron depletion layer or vacuum adjacent to the sheath edge[414]. Many ionospheric measurements of the antenna impedance are interpreted with this assumption. Therefore a brief theoretical analysis of this approach will be presented below. However, since it is known that charged particles cross the transition region and are absorbed by the antenna; this boundary condition is physically restrictive.

(iv) Under a "sheath collapse" condition, to be discussed later, the electron density is assumed uniform up to the antenna surface. The boundary condition assumes that there is a continuous flux of electrons to the surface and, in an idealized case, the surface is imagined to be completely absorptive such that no electrons are emitted. In some cases, impedance measurements under this boundary condition yield satisfactory results.

While the sheath has been extensively studied by physicists and solutions for potential profiles, ion currents, energy distributions and space potentials of boundaries for plane, cylindrical, and spherical geometries have been developed, these results have not been seriously used for direct application to antenna problems because inhomogeneous layers complicate the problem considerably. Most papers assume a homogeneous sheath.

RF Sheath

Consider a long cylindrical antenna* of radius a and embedded in an isotropic plasma. As a first-order approximation, the sheath is represented by a uniform depletion layer of thickness r_o and dielectric constant 1, sandwiched between the antenna and a uniform plasma. A simple analysis[217] proceeds as follows: First, the antenna potential† V is computed from a knowledge of the electron density N and temperature T of the plasma. Second, this potential is used to derive the sheath thickness by solving the following transcendental equation

$$2\varepsilon_o V = Ne(r_o^2 + 2ar_o)\ln\frac{a+r_o}{a} \quad . \tag{2.1}$$

---

[*] A direct application of this analysis will be made in the discussion of antenna impedance measurements in the ionosphere.

[†] The potential at radius $a+r_o$ is taken to be zero and called the space or plasma potential.

Among the effects of the ionosphere, thermal and photoemission effects change the actual potential of the vehicle in an uncertain manner and an actual measurement of this potential is necessary. This is usually done by means of Langmuir probes. Measurements[51,101,226] indicate that the vehicle potential is, generally, less that -1 Volt. Solutions to Equation (2.1)[517] are shown in Figure 2.2a. Once the sheath radius is determined, the capacitance of the sheath may be easily found to be

$$C_s = \frac{2\pi \varepsilon_o h}{\ell n \frac{r_o + a}{a}} \tag{2.2}$$

The measured input impedance is then taken as the series combination of C_s and the capacitance of the antenna in a homogenous plasma medium.

Since the sheath thickness r_o depends on the potential V, it will increase if the antenna is biased negatively with respect to the vehicle and vice versa. If the antenna voltage varies slowly, for example, when a small signal with a frequency much below plasma frequency is applied, the sheath thickness will vary accordingly. This in-phase variation yields a conductance which was found to be[315]

$$G_s = \frac{2\pi a h N e^2}{2\pi m \kappa T} \tag{2.3}$$

where κ is the Boltzmann's constant. From (2.2) and (2.3) it may be seen that for small sheath thickness $C_s \propto N$ and $G_s \propto N$.

At radio frequencies close to the plasma frequency or higher, the sheath cannot follow the voltage variation well and electrons at the sheath edge will have an irregular oscillation around the edge. An approximate time-average sheath thickness may be found by describing electrons' motion and solving the resulting nonlinear differential equation[517]. Figure 2.2b shows the dependence of the effective sheath radius $\bar{r} = a + r_o$ on frequency

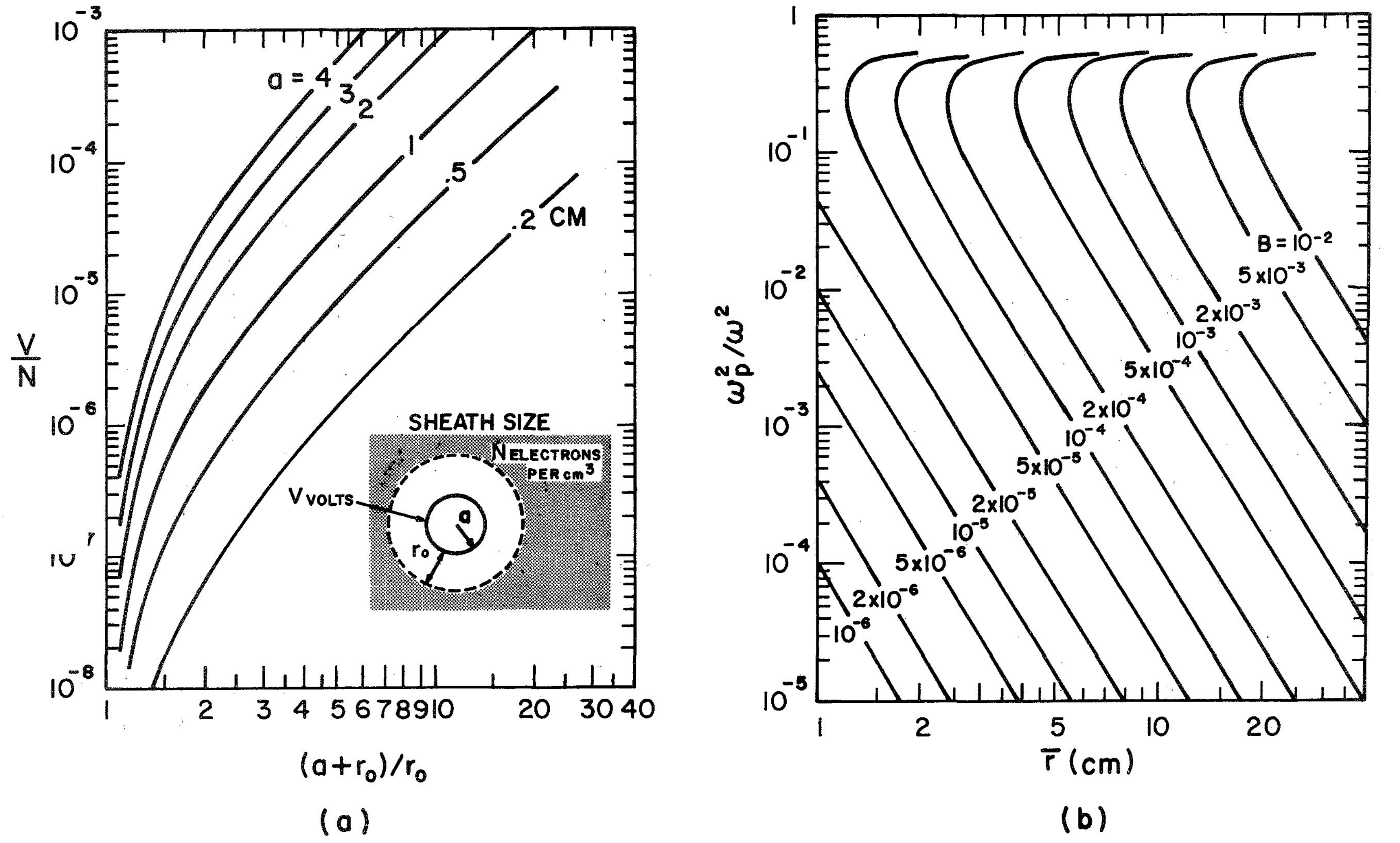


Figure 2.2 (a) Effective sheath size around cylindrical antennas as a function of antenna static potential and electron density (after Whale^{517}) (b) Effective sheath size around cylindrical antennas as a function of X for various values of the parameter $B = eE_0/m\omega^2$ (after Whale^{517})

and strength E_o. The parameter B is defined by $B = eE_o/m\omega^2$. Typical values of sheath thickness range between 1-10 cm. The simple illustration of the uniform sheath is usually not realistic for moving antennas in the ionosphere. Asymmetries are introduced in two ways: First, the motion of the vehicle or the rocket with a velocity greater than the mean thermal velocity of the ions and less than the mean electron thermal velocity results in a net collection of ions primarily on the forward surfaces of the vehicle and in a deficiency of ions behind. This is termed the "ram" sheath. It modifies the normal sheath and results in a complicated distribution of charged-particle concentration around the vehicle.[11,572] Second, the motion across the earth's magnetic field of long antennas on satellites orbiting at a high velocity $\vec{v}$ may produce an appreciable potential gradient ($\vec{v} \times \vec{B} \cdot L$) along the antennas. This potential gradient results in that the tip of one antenna attains a positive potential and thus collects electrons and exhibits the smallest sheath radius. The rest of the antenna system is below the floating potential and collects ions, as shown in Figure 2.3.[573] This is known as the $\vec{v} \times \vec{B}$ sheath. The effect of these two sheaths is usually disregarded in the interpretation of antenna impedance measurements in the ionosphere.

A phenomenon of the sheath often made use of is the "sheath collapse". This may be achieved when a dc bias just sufficient to bring the potential of the antenna to zero is applied. This point can be identified approximately from an examination of the dc current-voltage characteristics. Under a collapsed sheath condition the electron density is taken as uniform up to the surface, and this surface is assumed absorptive.[25,127] In general, cool and clean metal surfaces do not give off electrons and the above assumption is adequate for many practical purposes. Sheath

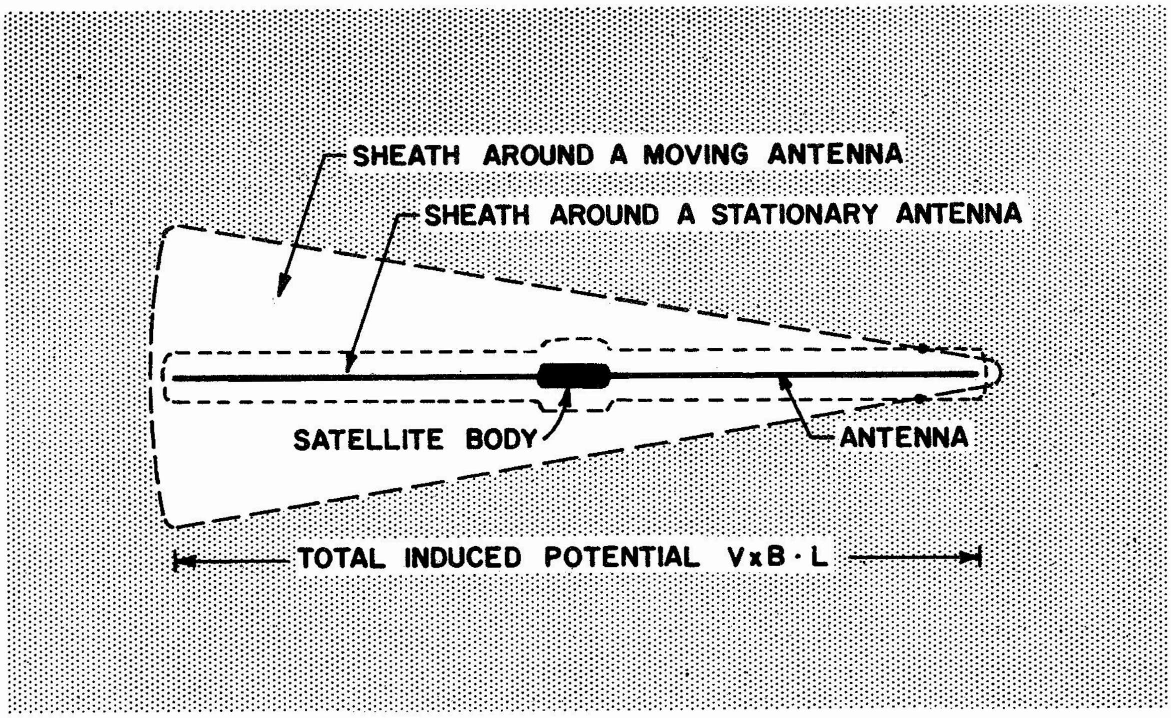


Figure 2.3 The $\vec{v} \times \vec{B}$ sheath (after Osborne et al.[573])

collapse is usually easy to achieve in the laboratory but not so easy in the ionosphere due to the lack of a stable reference potential and effects of the vehicle motion.

(C) Other Ionospheric Effects

The ionosphere is a very complicated medium, even the above considerations are regarded insufficiently accurate in some cases. The sheath problem, in particular, is still not complete and no definite conclusion has been found. Many phenomena are often idealized or ignored in order to simplify the formulation and analysis of the antenna problem. Among these is the absence of a stable reference potential[183] other than the plasma itself, and complications result from the local perturbations in plasma properties caused by the probe and vehicle. Photoelectric emission effect is usually ignored, but in full sunlight it may produce currents of the order of 3×10^{-13} amp/cm^2 from metallic surfaces. This current is in the same direction as a positive ion current to the surface. When the electron density is low it may exceed the random electron current and then produces a positive potential at the vehicle. In a real situation, other complicating processes should be kept in mind: outgassing of rockets or payload components, ablation off the vehicle, contamination from rocket exhaust, presence of electrostatic or electromagnetic fields, shock wave disturbances, meteor and cosmic ray bombardment, etc.

(D) Measurements at High Frequencies

Since about 1957 a great deal of work has been done toward developing a reliable probe for the measurements of the ionospheric parameters, the electron density in particular. Early rocket flights[213,215,178] have employed an RF impedance probe. This is a dipole antenna operated at frequencies well above the local plasma frequency and hence the dipole is considered electrically short. The input impedance of such an antenna is known to have a dominant capacitive reactance term with small radiation resistance. When put in plasma, the change in capacitance is taken to be a direct measure of the local electron density, i.e.

$$\Delta c = -\frac{80.6\ N}{f^2} \tag{2.4}$$

where f is the signal frequency in KHz and N is the local electron density per cm^3. Results based on this idea were not satisfactory,[214,221] of course, since the effect of many other parameters was ignored. The strongest of these is the effect of the sheath. Later measurements[51,226] with reduced RF voltages and regulated dc bias voltage yielded electron density results which were closer to those obtained by the propagation method.[19 and others] The sheath capacitance could be approximately determined after an actual measurement of antenna potential using a Langmuir probe mounted flush with the surface. As a first order approximation, the measured capacitance is taken as the parallel combination of the antenna and sheath capacitances, and in this way the electron density may be calculated. In some cases where the sheath thickness is very small, the sheath capacitance is consequently small and the measured value may well be taken as the sheath capacitance itself.[51] The measurement is then a direct indication of the electron density. However, in the lowest part of the ionosphere, where the collision frequency effect cannot be ignored, the change in the resistive part of the measured impedance had to be taken into account simultaneously. An appreciable change of resistance was, by the way, observed even in the high ionosphere where the collision effect is negligible and the observation stimulated the study of possible excitation of electroacoustic waves by the antenna. The electron density may then be found from[21,237]

$$N = \frac{f^2}{80.6} \, \frac{\Delta X + (\Delta R)^2 / \Delta X}{X_o + [\Delta X + (\Delta R)^2/\Delta X]} \tag{2.5}$$

where X_o is the free space reactance. However, probes so far have not provided good measurements of collision frequency because of the sensitivity problems in the weakly ionized lower region of the ionosphere where collisions are important.

(E) Measurements at Low Frequencies

At extremely low frequencies (very high X and Y), a dipole antenna may in fact be considered a symmetrical Langmuir probe, and the input impedance is purely resistive (Equation(2.3)). At slightly higher frequencies, it becomes necessary to consider the charge balance between the probe and the sheath resulting in the sheath capacitance (Equation(2.2)). Measurement at low frequencies demonstrates the dominant role of the sheath and its usefulness in determining the electron density. From a rocket flight in the D region, measured admittance values for a short dipole at 16.5 KHz were compared with values calculated on the basis of Equations (2.2) and (2.3)[315] as shown in Figure 2.4. The agreement is qualitatively very good. Results from another flight in the E region using three orthogonal dipoles and operating at three distinct frequencies 175, 204 and 250 KHz,[475] also indicated the importance of the sheath characteristics at low frequencies. However, due to large fluctuations in the results caused by spinning of the rocket and hence fluctuating antennas orientation, a clear quantitative effect on the sheath could not be deduced. In general, low frequency probes could be used as useful means to measure electron density and possibly the temperature of the ionosphere.

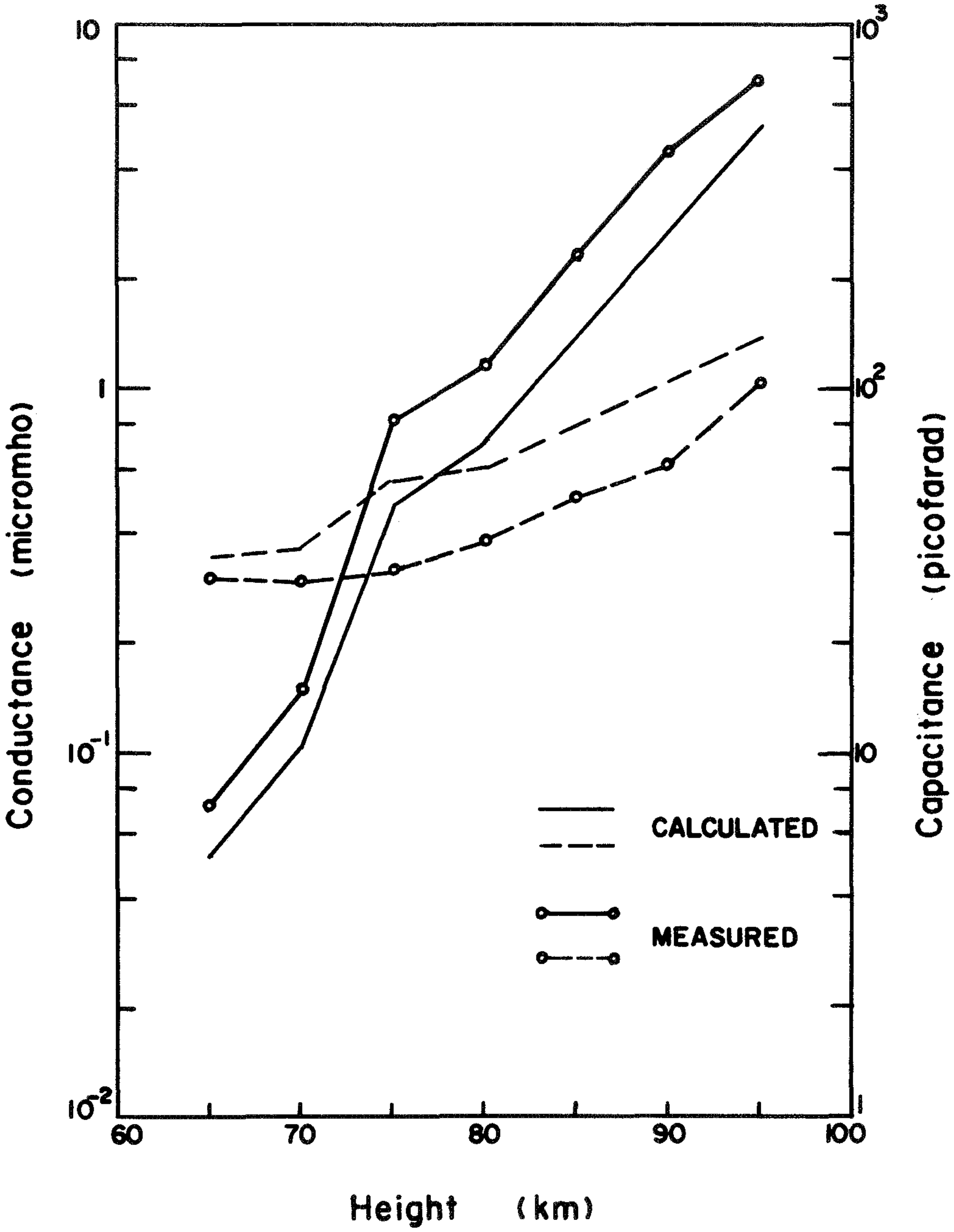


Figure 2.4 Conductance and capacitance of a short dipole in the ionosphere at 16.5 kHz (after Mlodnosky and Garriott[135])

(F) Measurements at Intermediate Frequencies

At frequencies where the various plasma resonances may be excited, the impedance characteristics are more complicated and the effect of the antenna orientation is more pronounced. According to the theory (Figures 1.17, 1.18 and 1.19), the input admittance of a short dipole in a lossless magnetoplasma and oriented parallel to the dc magnetic field has a real part only in regions 3, 7 and 8 (Figure 2.9b). The imaginary part is infinite on the line $x = 1 - Y^2$, capacitive in regions 1, 2, 6, 7, and 8 and inductive in regions 3, 4 and 5. Moreover, as the orientation angle θ [Equations (6.5) and (6.6), part I] is increased from 0 to 90° the conductance, in general, increases while the susceptance decreases.[23,224] The rocket spinning effect usually appears in the form of cyclic changes in the data.[51,337] Several measurements have been carried out[51,438,439,337,316,185] to demonstrate the properties mentioned above. The sheath has been a problem in all these measurements although not serious in some. In the following, only data obtained under sheath collapse condition or sheath corrected data will be mentioned.

Resonance at the upper-hybrid frequency has been clearly observed by some experimentalists.[336,439] So has been the resonance at cyclotron frequency,[337] particularly by the Topside Sounder, Alouette II. Resonance at the plasma frequency, however, has been less easy to detect by linear antennas. The most systematic set of measurements by a dipole antenna, perhaps, was reported by Stone et al.[438,439] From two flights, one at low altitudes (up to 137 km) and the other at high altitudes (up to 1068 km), two sets of measurements were obtained using short dipoles 2.6 m long. The rocket trajectories identified by different frequencies are shown in Figure 2.5. Figure 2.6 shows the collected data for both the resistance

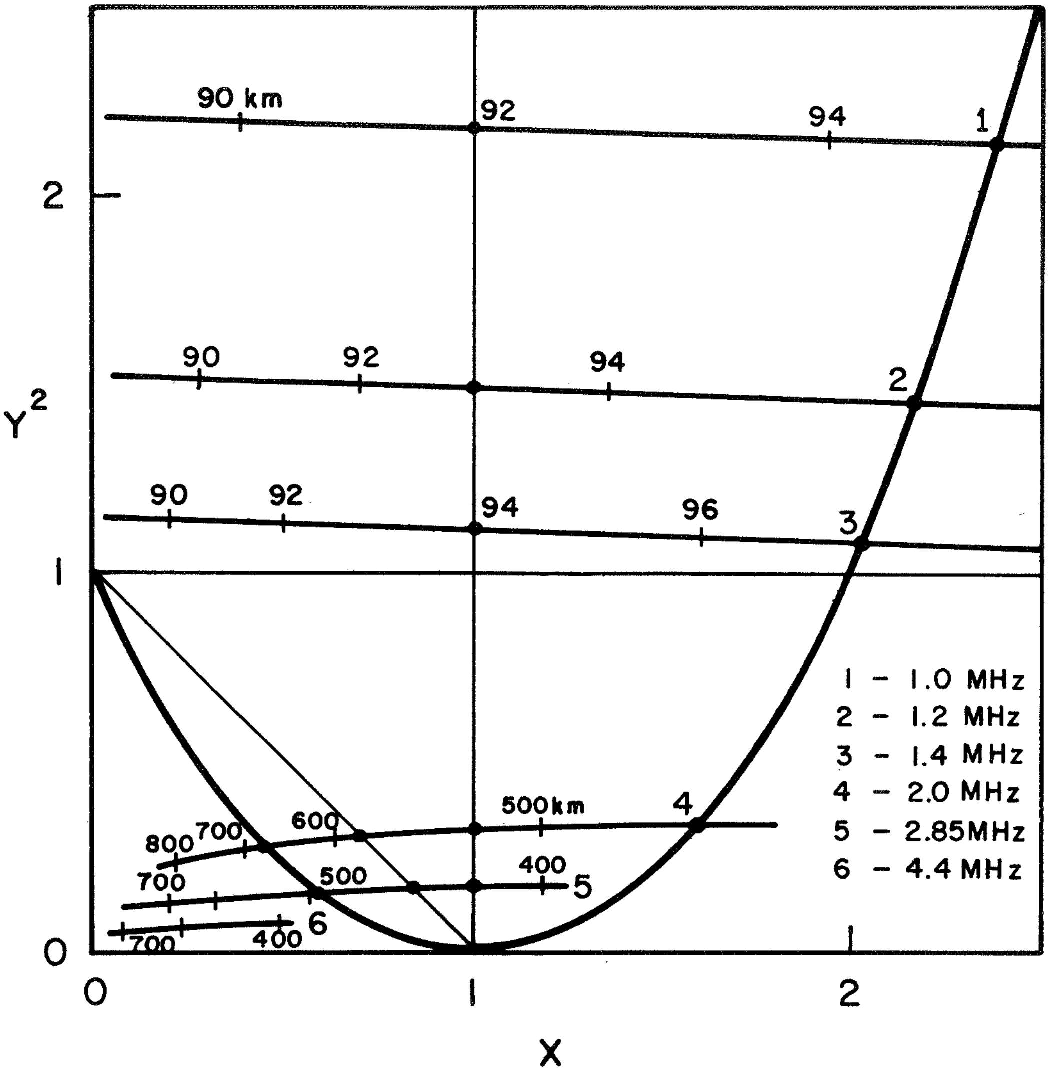


Figure 2.5 Trajectories of impedance measurements in the ionosphere corresponding to the data in figures 2.6(a) and (b) (after Stone et al.[437,439])

and the reactance. It may be noticed that at the lower frequencies, peaks in the reactance near X = 1, as predicted by the theory, are not easy to identify. Moreover, the peaks in the resistance were noticed to be substantially lower than theoretical values based on the quasi-static approximation. This expected discrepancy may be attributed partly to uncertainties in the effects of collisions, inhomogeneities in the surrounding medium and orientation of the antenna with the geomagnetic field. At high altitudes, where collisions may be neglected, the measurement revealed better qualitative agreement with the theory, although at X = 1 the observation is not consistent. It was thought that the rate of sampling used in the measurement was too slow to definitely establish this point.[439]

The importance of finding the plasma frequency for determining electron density in the ionosphere and the partial failure of linear antenna impedance measurement techniques to achieve this purpose led to the development of new tools which have sharp responses at the plasma resonances. Some of these tools are briefly discussed below:

1. Resonance Probe: It was found by experiment[545] that the RF impedance between two electrodes immersed in a plasma exhibits a minimum at a frequency ω_r which appeared to be, at first, the same as the plasma frequency obtained from probe measurements of electron density. A later experiment[446] studied the variation with frequency of the incremental dc component of the current of a simple Langmuir probe when modulated with an RF voltage. A peak was observed at a frequency which was also believed to be the plasma frequency. This interesting result stimulated an extensive study of this phenomenon[54,101,168, and others] and a conclusion was reached that the frequency of this resonance, sometimes called "sheath resonance,"

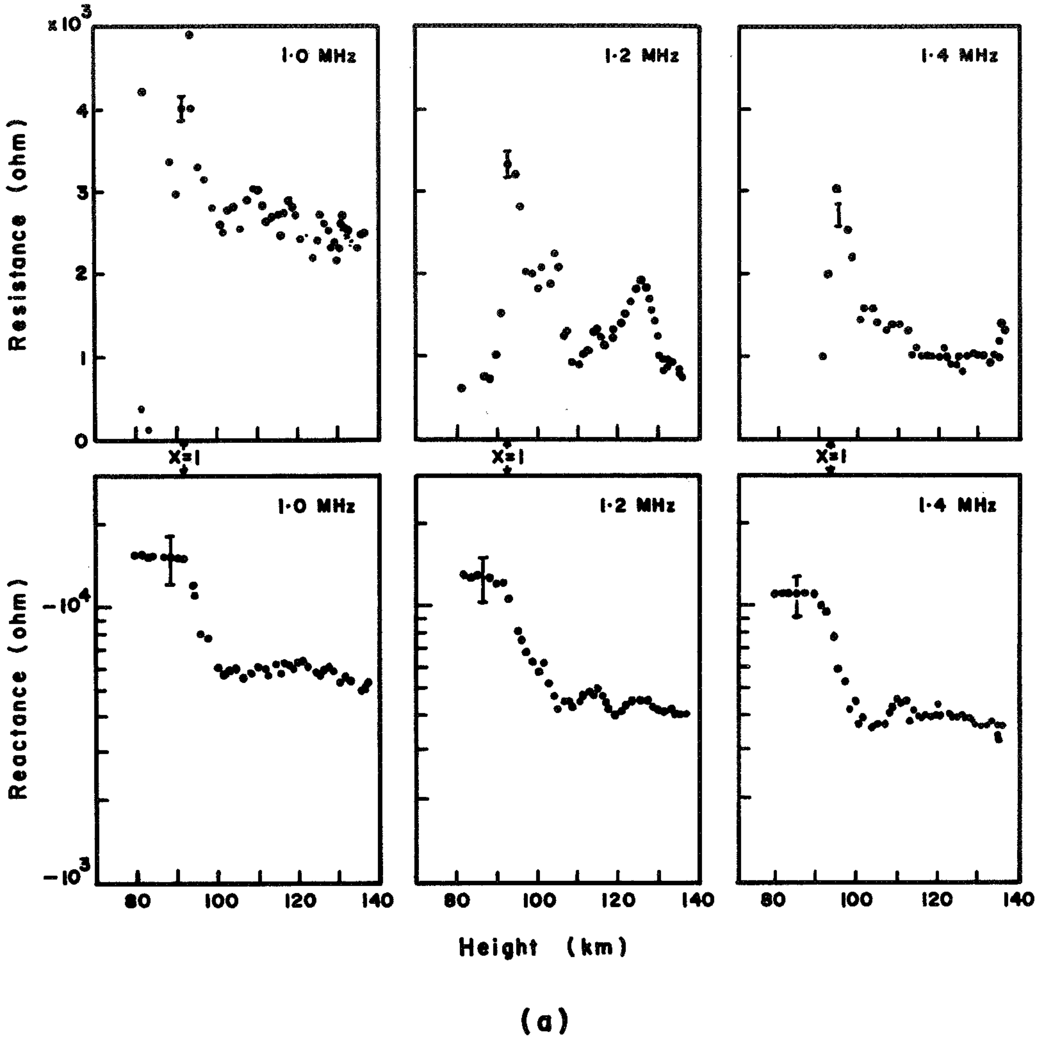
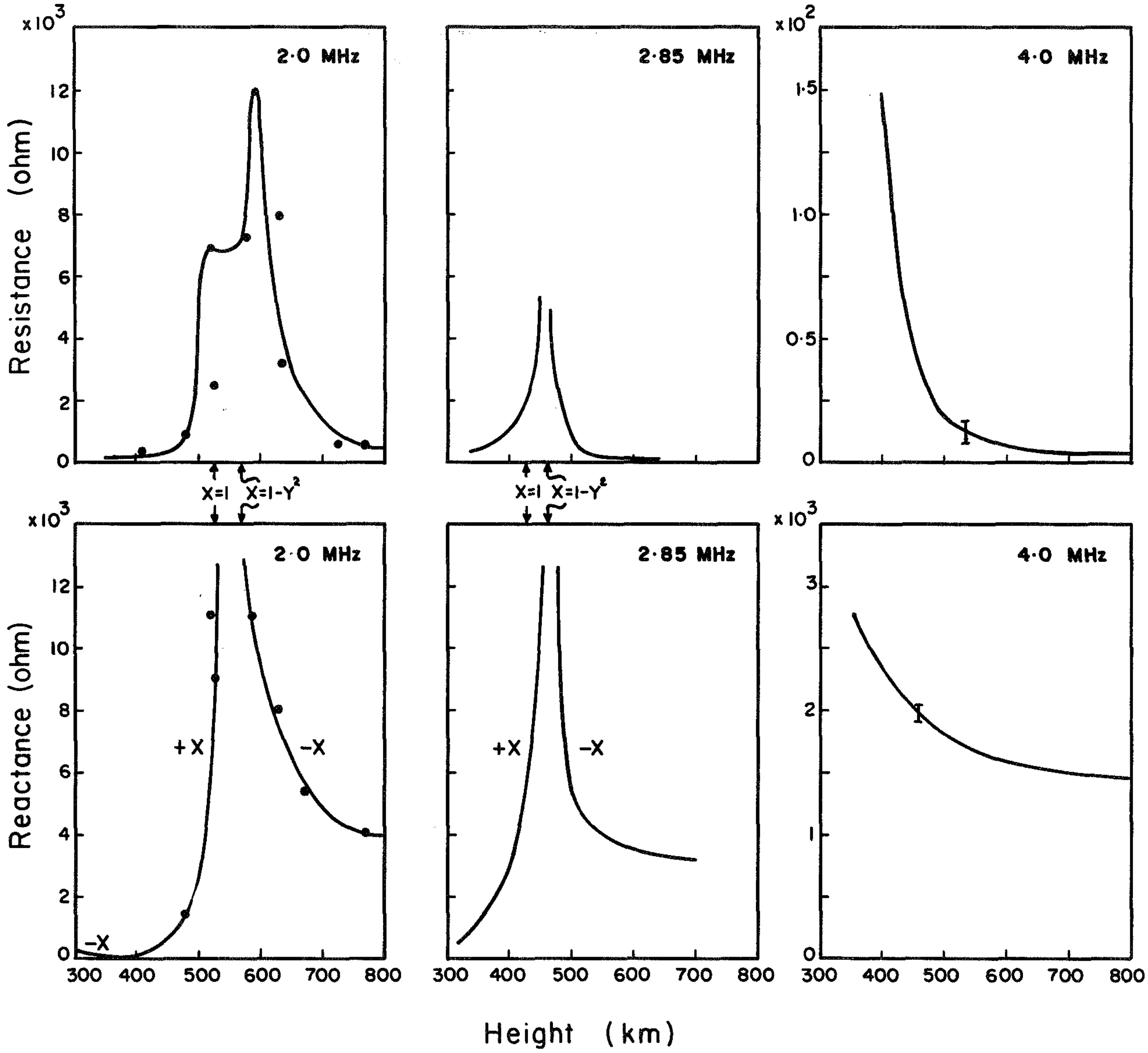


Figure 2.6(a) Impedance of a short dipole measured at low altitudes in the ionosphere (after Stone et al.[439])



(b)

Figure 2.6(b) Impedance of a short dipole measured at high altitudes in the ionosphere (after Stone et al.[437])

depends on the thickness of the sheath and is related to the plasma frequency by[169]

$$\omega_r = \frac{\omega_p}{1 + R/k\lambda_D} \tag{2.6}$$

for a spherical probe of radius R. The electronic Debye length is λ_D and k is an empirical constant for the RF sheath thickness expressed in Debye lengths. A further study showed that a "dumbbell probe", which consists of two spheres on the tips of a dipole of length 2ℓ, has the same resonant frequency if $\ell >> r_o$, where r_o is the sheath thickness. The effect of the static magnetic field was found to be negligible if B is small and uniform. However, if the gyro frequency ω_c is comparable with the zero-field value ω_r, then ω_r increases and rapidly tends to the limit ω_c.[546] The impedance characteristics of a single sphere immersed in an isotropic lossy plasma is shown in Figure 2.7.[54] Finally, from examination of Equation (2.6), it may be deduced that for a clear resonance R should be large enough, and further more, in far ionospheric and space measurements where Debye length becomes long, probes as big as 100 m may be needed![101]

It should be mentioned that the probe described above is also called the "Resonance Rectification Probe" due to resonance observed with the dc current mentioned earlier.

2. Resonance Relaxation Probe:[185] This is a sounder which sweeps frequency over a wide range for possible detection of ω_p, ω_c and ω_u. The entire frequency range must be swept in a very short time in order to relate the three resonant frequencies correctly. The probe is designed to detect slowly decaying plasma oscillations of the type observed by the Alouette satellite mentioned earlier.

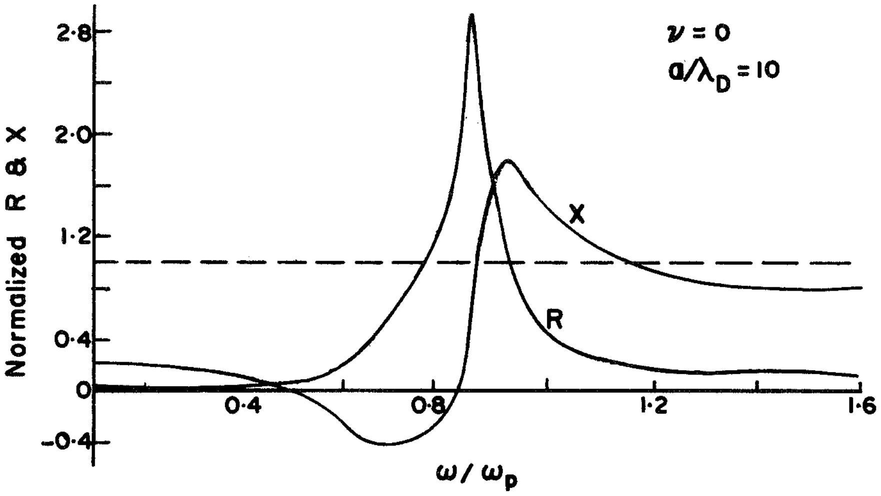


Figure 2.7 Impedance characteristics of a single sphere in an isotropic lossy cold plasma (after Buckley[54])

3. Gyro-plasma Impedance Probe:[336] This is a combination of a spherical probe and a cylindrical boom. The length of the boom is large compared to the size of the sphere. On the other hand, the radius of the boom is much smaller than the radius of the sphere. When the collision frequency is small, it was found that the input combination capacitance at W_n is minimum, and approximately equal to the sum of the sphere and boom capacitances and independent of the ion sheath. Moreover, at this frequency the cylindrical probe capacitance does not vary with the orientation relative to the static magnetic field. Therefore, a more reliable measurement of W_u may be obtained with this probe and knowing W_c, the local electron density can be determined.

In addition to the above probes, various types of RF impedance probes have been used which may be distinguished by the technique of measuring the impedance. These include the standing wave impedance probe,[178] the plasma frequency probe[179] and capacitance probes.[464]

Perhaps, the most extensive set of admittance results measured with several probes simultaneously, has been reported by Heikkila, et al.[185] The probe arrangement shown in Figure 2.8a was used for a frequency sweep from 0.1 - 3.0 MHz and in the E-region. Resonances excited by the resonance relaxation probe are shown in (b) which seem to be quite consistent. Measured results for the complex admittance of the sphere are shown in (d) reduced from raw data shown typically in (c). The reasonance behavior exhibited at intermediate frequencies with an inductive component of reactance at some frequencies has been identified as the sheath resonance described earlier. It occurs at a frequency below the plasma frequency as predicted by the theory. Data at the top of Figure 2.8c, which are called mutual admittances, have been obtained by connecting a receiver to a monopole

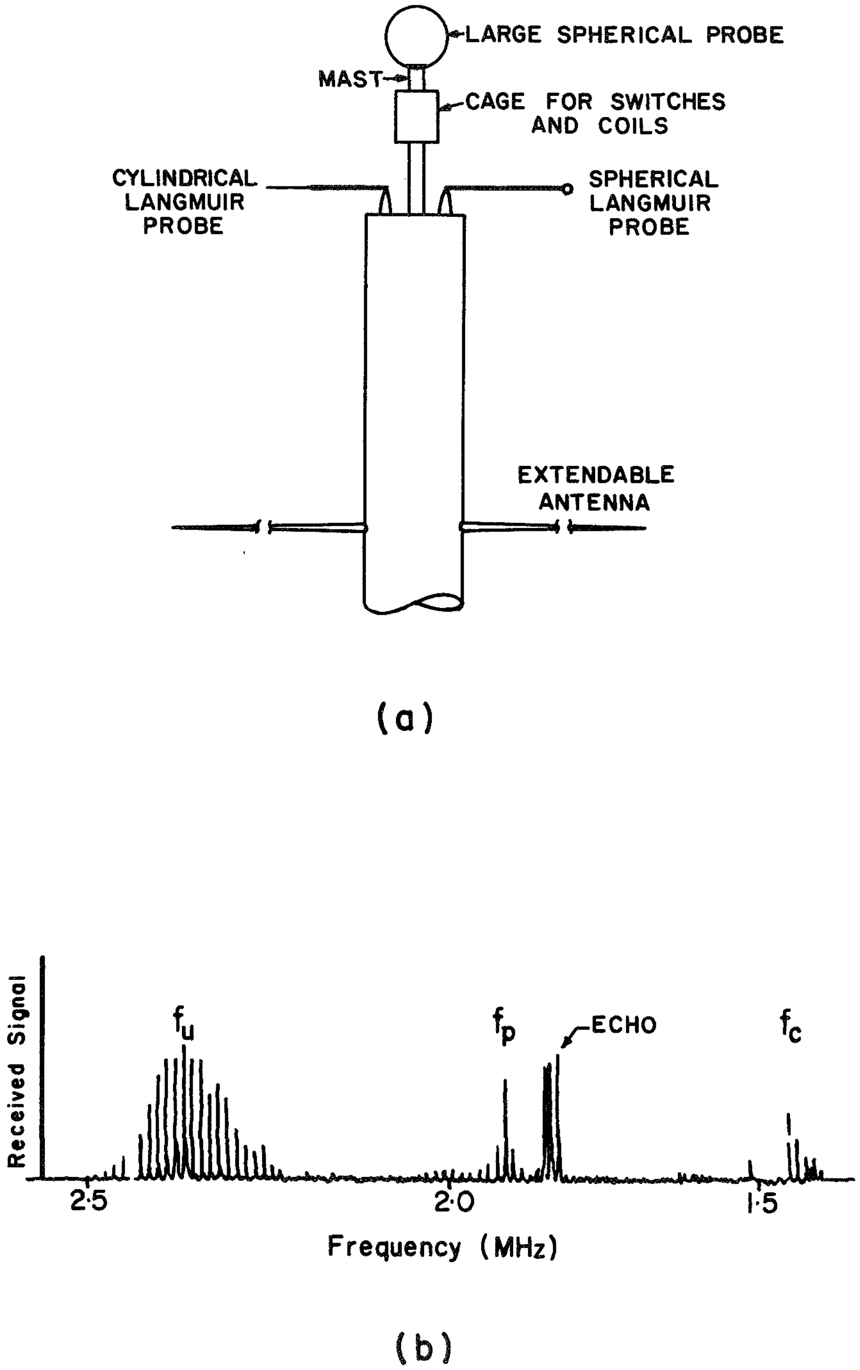


Figure 2.8 (a) Probe arrangement on MIP rocket for measurements in the ionosphere. (b) Resonances observed in the relaxation experiment (after Heikkila et al.[185])

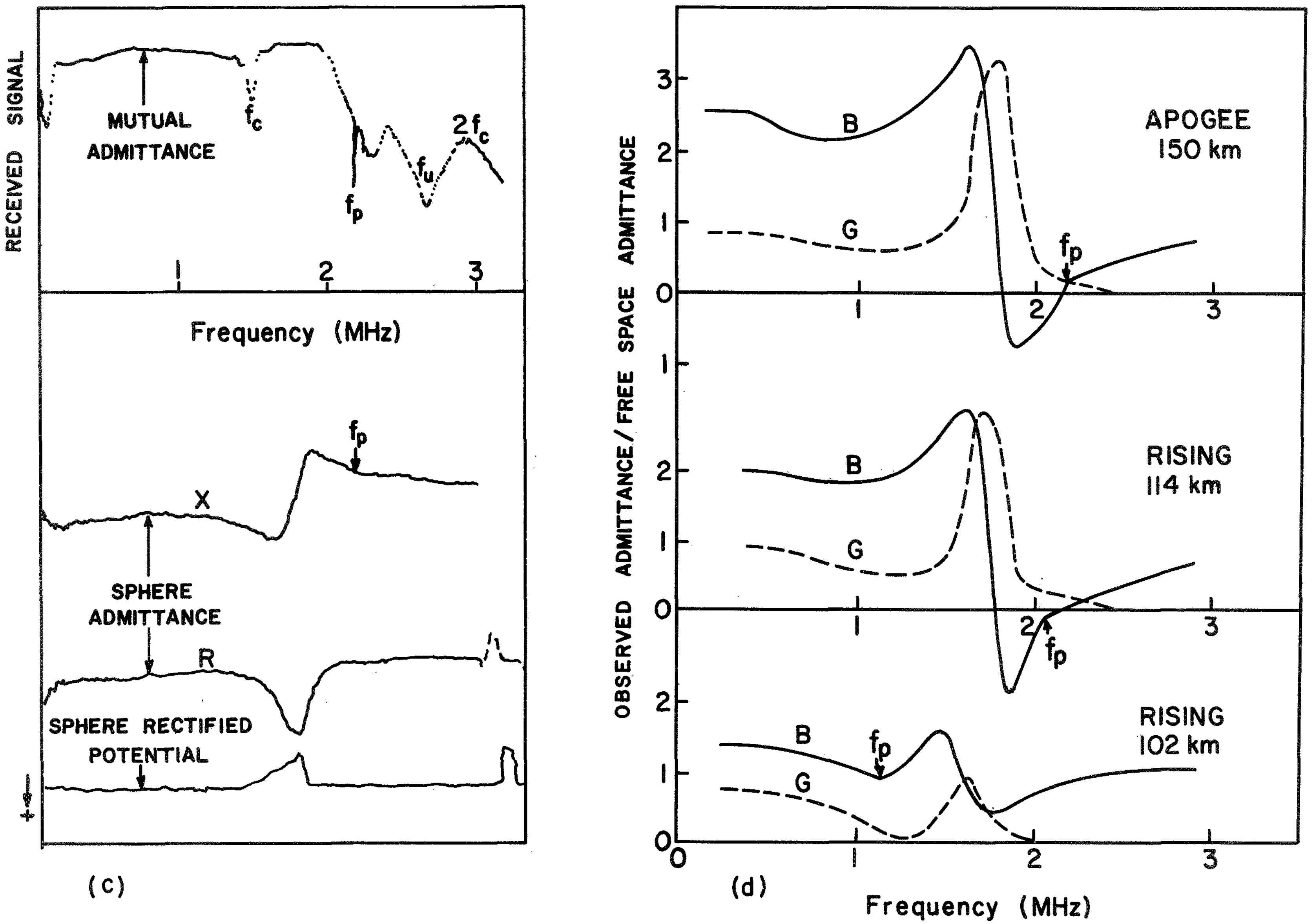


Figure 2.8 (c) Raw data obtained in swept frequency admittance measurement (after Heikkila et al.[185])

(d) Reduced admittance behavior for a large spherical probe (after Heikkila et al.[185])

antenna about a meter away from the sphere on which the constant amplitude signal was applied. Some of the minima have been identified as the fundamental plasma resonances. In (c) is also seen the effect of a resonant increase in d.c. electron current resulting in a change in floating potential. This occurs at a frequency below the plasma frequency as expected.

In general, simultaneous probe measurements are more reliable because a mutual check of results under the same circumstances is possible. Similar conclusions have been reached by Baker et al.[21]

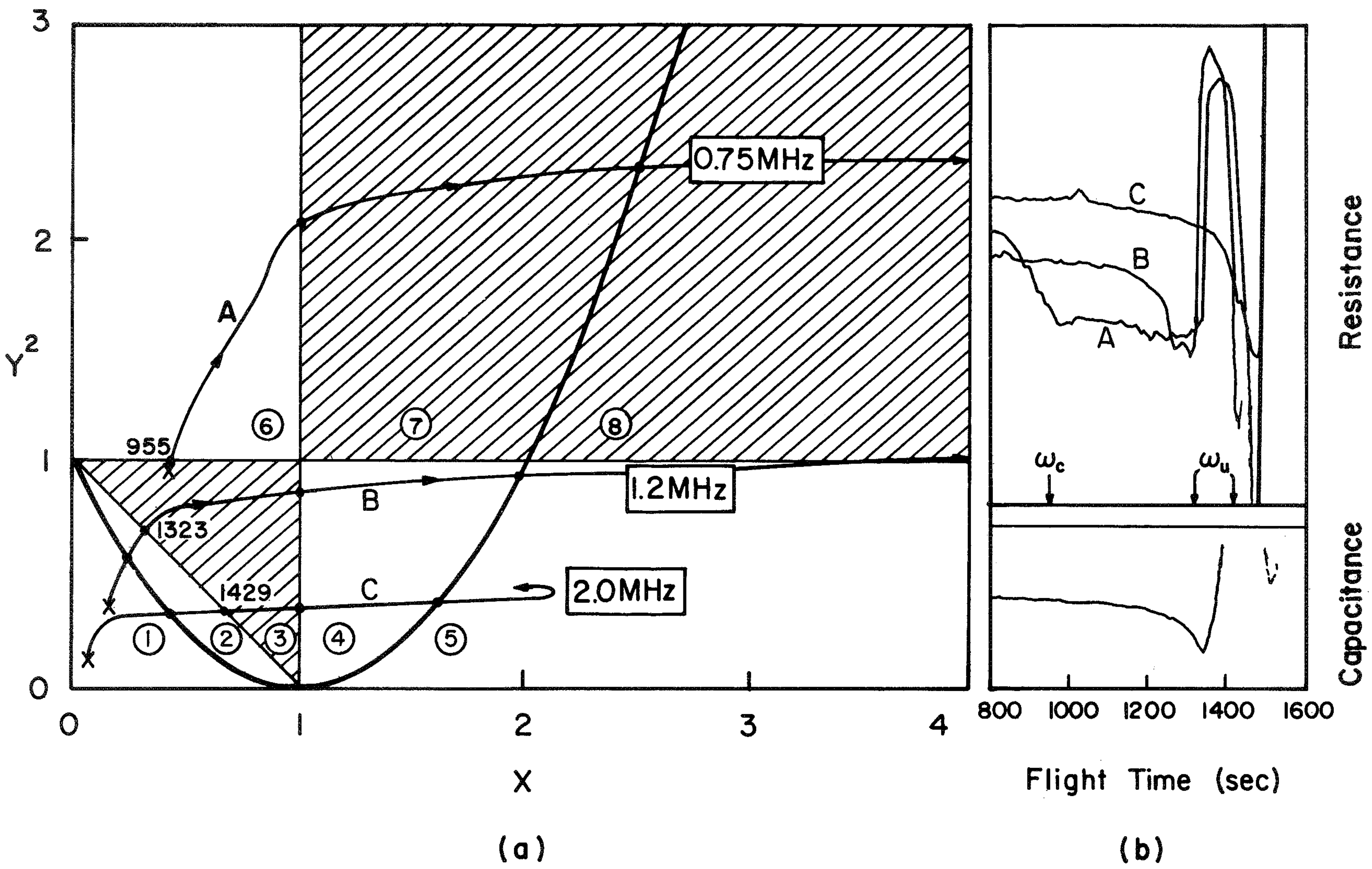
(G) Measurements Related to Radio Astronomy Problems

An important application of the precise knowledge of antenna impedance in plasma is realized in the measurement of sky brightness temperature and cosmic noise in the outer layers of the ionosphere. It is known that because of ionospheric shielding, it is impossible to measure the radiation from outer space at frequencies below about 8 MHz at the surface of the earth. A well calibrated antenna may then be carried to high altitudes of the ionosphere where the brightness temperature of the sky may be found by detecting the noise power developed in the radiation resistance of the antenna whose radiation pattern is directed at the point of interest. It may be shown that for a short dipole of length 2h, the average brightness temperature T is related to the average detected noise voltage V by

$$T = \frac{3\lambda^2}{32\pi k B Z_o} \frac{V^2}{h^2} \tag{2.7}$$

where k is the Boltzmann's constant and B is the bandwidth. The voltage V may be measured accurately enough by a well-designed circuit making use of the prior knowledge of the impedance properties of the antenna. Early measurements carried out with loop antennas at 3.8 MHz revealed an average sky brightness tenperature of 8.1×10^6 °K at about 1000 km altitude.[551,552]

Later measurements, using a short dipole, deduced temperatures of 2.1×10^7 °K and 1.7×10^7 °K at 1.225 MHz and 2.0 MHz respectively when the satellites were raised to about 1700 km altitude.[502] Changes in the resistance corresponding to changes in the noise level were observed to be consistent with the theory[502,176] (Sec.6, part I). In particular, sharp changes in the signal strength were observed at the upper hybrid frequency, and very strong noise in regions 3, 7 and 8 (See Figure 2.9), where the trajectories of three receivers during the descending portion of the flight after apogee corresponding to the curves in (a), are also shown.



(a) (b)

Figure 2.9 (a) Trajectories for cosmic radiation measurement at three frequencies (after Walsh et al.[502]) (b) Radiometer output and measured antenna capacitance corresponding to trajectories in (a) (after Walsh et al.[502])

3. IMPEDANCE MEASUREMENTS IN LABORATORY PLASMA

It may be realized from the previous section that there is a great need for careful laboratory experiments on antennas and probes in plasma. Not only better plasma diagnosis techniques are available, but more accurate knowledge about the impedance may be known. The main difference between measurements in the laboratory plasma and in the ionosphere may be summarized as follows:

(i) In the laboratory the ground reference potential is well established. Grounded parts of the experimental system form a stable reference for plasma and probe potential measurements. On the other hand, there is no such stable reference on a vehicle in the ionosphere, other than the plasma itself. The different local perturbations in plasma properties caused by the probe and the vehicle contribute to the complication of this problem.

(ii) Electron densities in laboratory plasmas are usually very high (10^8 to about $10^{18}/\text{cm}^3$ in lasers). This fact leads in turn to measurements at very high frequencies, even beyond the microwave and millimeter regions to the laser region. Moreover, the density at any time may be varied within a certain range by varying the pressure in the tube or the discharge current. The laboratory plasma is usually more stable than that of the ionosphere.

(iii) While electron temperatures in the ionosphere do not exceed about 3000° K, a plasma with temperature 40,000° K or more may be obtained in the laboratory. If the Debye length is small enough to be compared with the antenna length, the effect of plasma waves on the antenna characteristics may be studied more easily. In the ionosphere, although the reduction in electron temperature is partly compensated for by a smaller electron density, the wavelength is still large compared to the antenna length. Plasma effects on the radiation properties of the antenna are, therefore, not so strong.

(iv) The ion sheath is easier to control in laboratory measurements, and a state of sheath collapse may easily be achieved. Then the medium around the antenna is practically uniform unless the antenna is very near to the anode of the discharge tube as in the case of a monopole antenna. In the ionosphere, and due to the motion of the rocket with respect to the magnetic field, the voltage induced along the rocket renders the plasma inhomogeneous and adds to the difficulty of interpreting measured quantities, as we have seen earlier.

(v) There is no spinning effect in laboratory measurements, unless it is arranged. Moreover, the strength and the direction of the dc magnetic field may be changed very easily and as desired.

(vi) One convenience in laboratory measurements is that they can be repeated. In the ionosphere, it may mean firing another rocket! A fault in the measuring device occurring soon after take off may cause a complete failure to the whole mission.

In spite of these and other merits in laboratory plasma experiments, there are still some limitations whose effects cannot be ignored, in some cases. Many experiments are made to investigate the validity of theoretical analysis based on assuming a plasma medium of infinite extent. This cannot be realized in the laboratory. However, it may be considered so if the plasma container is large enough to have negligible effect on the near field of the antenna <u>and</u> if the radiation is weak enough to neglect reflections from the walls of the container. If these conditions are not well met the boundedness of the medium should be taken into consideration. The plasma may be nonuniformly distributed in the discharge tube and the electron density may have high fluctuation with temperature. Some other nonlinear effects also contribute to the difficulty of obtaining reliable results.[11,27]

Two methods of generating plasma in the laboratory have been used for antenna studies, the pulsed-discharged decaying plasma[23,164] and the steady-state discharge.[553,430,451,223,274] The first has a principal advantage that the temperature is low (about 300°K), but this advantage is offset in part by the requirement that all measuring equipment should respond in a very short time, less than a millisecond. Steady discharges, on the other hand, may be obtained and used with a considerable degree of success and still maintaining a low temperature of 1000°K or so. Rare gases have usually been used in hot-cathode or brush-cathode discharge tubes. The brush cathode plasma has been found highly uniform and exhibits fairly low electron temperature. Furthermore, since most of the anode to cathode voltage drop occurs very near the cathode, the rest of the chamber is essentially field-free. Also, in the negative glow region the pressure is low enough to allow the negative glow to extend all the way to the anode. The negative glow is independent of the location and of the anode which allows flexibility in the design of the chamber.

Helium and neon have been commonly used in discharge. Neon has a lower diffusion coefficient and a higher recombination coefficient than Helium. This means that in a pulsed-discharge plasma, neon after glow has a greater tendency to decay by recombination instead of diffusion, and therefore it tends to produce a uniform plasma. Helium is used because of its higher diffusion coefficient which allows plasma to fill the chamber completely at relatively low discharge voltages. Moreover, helium discharge requires shorter time to attain electron thermal equilibrium, and impedance measurements can be done faster.

(A) Plasma Diagnostics Techniques

Several diagnostic techniques have been described in the literature.[574,575] Some measurements involve internal probing, such as Langmuir and magnetic probes, which may perturb the plasma, while other external measurements, such as optical diagnostics, are nonperturbing. Some techniques are useful for dense plasmas, like optical scattering, while others are useful for collision dominated plasma and so on. Extensive details about these techniques and the ranges of applicability may be found in the literature.[574,575] Electrostatic probes, commonly known as Langmuir probes, are perhaps most commonly used in laboratory and the simplest devices of all. Their theory however, is extremely complicated. It may be sufficient here to describe just how electron density can be obtained from the V-I characteristics of double probes. When the areas of two probes are equal, a typical V-I characteristic is shown in Fig. 2.10a. The temperature may be approximately found from

$$KT_e \approx m\left(\frac{2I}{NA}\right)^2 \qquad (3.1)$$

The quantity kT_e may be found from the V-I characteristics

$$\left.\frac{dI}{dV}\right|_o = \frac{e}{kT_e} \; \frac{i_{1+} \cdot i_{2+}}{i_{1+} + i_{2+}} \qquad (3.2)$$

Then substituting in Eq. (3.1), the electron density may be obtained.

The collision frequency ν in a plasma is given by the sum of the electron-molecule collision frequency ν_{em} and the electron-ion collision frequency ν_{ei}. These are given by[577]

$$\nu_{en} = \frac{4}{3} N_m Q \sqrt{\frac{8KT_e}{\pi m}}$$

$$\nu_{ei} \approx 3.63 \times 10^{-6}\, NT_e^{-3/2} \ln\left[\frac{3.3 \times 10^7\, T_e^{3/2}}{N}\right] \qquad (3.3)$$

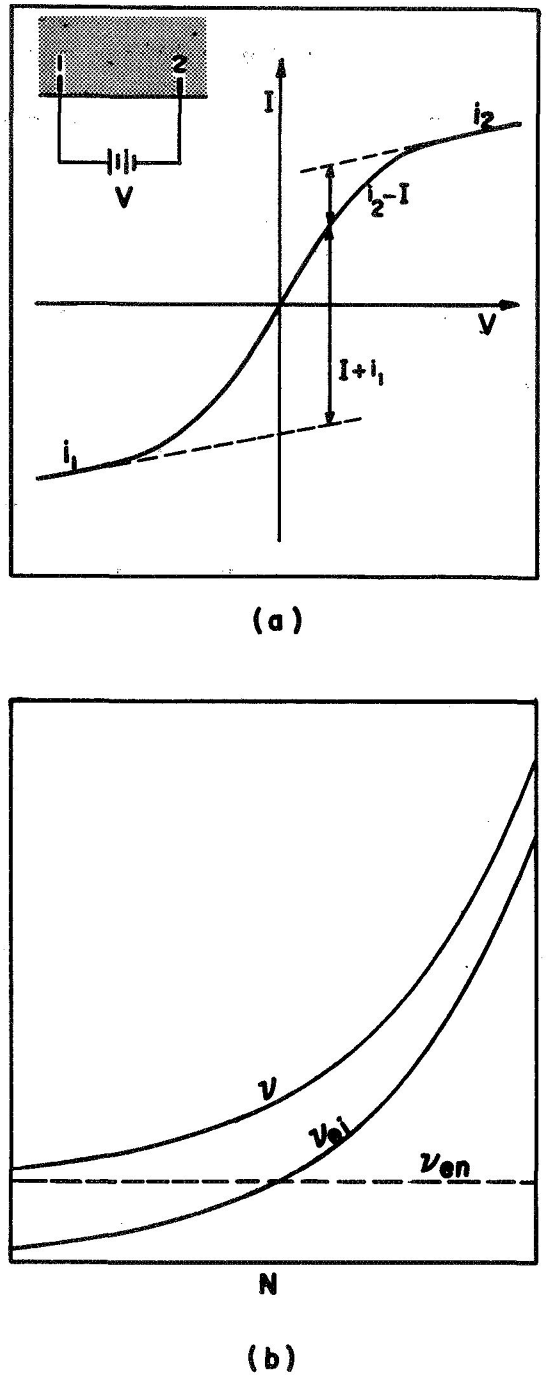


Figure 2.10 (a) V-I characteristics of double Langmuir probes
(b) Collision frequency as a function of electron density

where Q is the collision cross section for momentum transfer and κ is the Boltzmann constant. A typical sketch of Eq.(3.3)is shown in Fig. 2.10b.

In spite of its simplicity, the Langmuir probe has many limitations and is liable to error[576] and therefore the better microwave techniques for plasma diagnosis should be used whenever possible.

(B) Antenna Fabrication

Having to work at rather high frequencies, antennas in laboratory plasma pose many problems arising from feeds, joints, container size, etc. Generally, it is natural to measure the dipole impedance by using a coaxially fed monopole over an end-plate. However, with a plasma present, a balanced dipole has been found preferable for two reasons: First, if a monopole is used, the end-plate would necessarily be used as the anode of the discharge. The discharge near either electrode is known to be highly non-uniform and, therefore, the impedance obtained can hardly be considered for comparison with theory based on uniform plasma. Second, since the image principle is not valid in a warm plasma, the impedance of a dipole cannot be simply deduced from results for a monopole.[274,368]

For a monopole antenna, the inner conductor of a coaxial cable is usually extended above the end plate while the outer conductor and the dielectric are flush with the end plate. Provision of a vacuum tight cable has been no problem, where the outer conductor is sealed to the end-plate. Impedance measurement is then done using the usual slotted-line technique. When a dipole, which has a balanced current distribution, is used the arrangement is more elaborate. For one thing, the most common types of balanced dipoles, the chock (balum)-fed dipoles and the slot (balun)-fed dipoles, are extremely sensitive to any frequency variations, and accurate impedance measurements in plasma are difficult to obtain. A model dipole

Figure 2.11 Dipole construction for laboratory plasma measurements

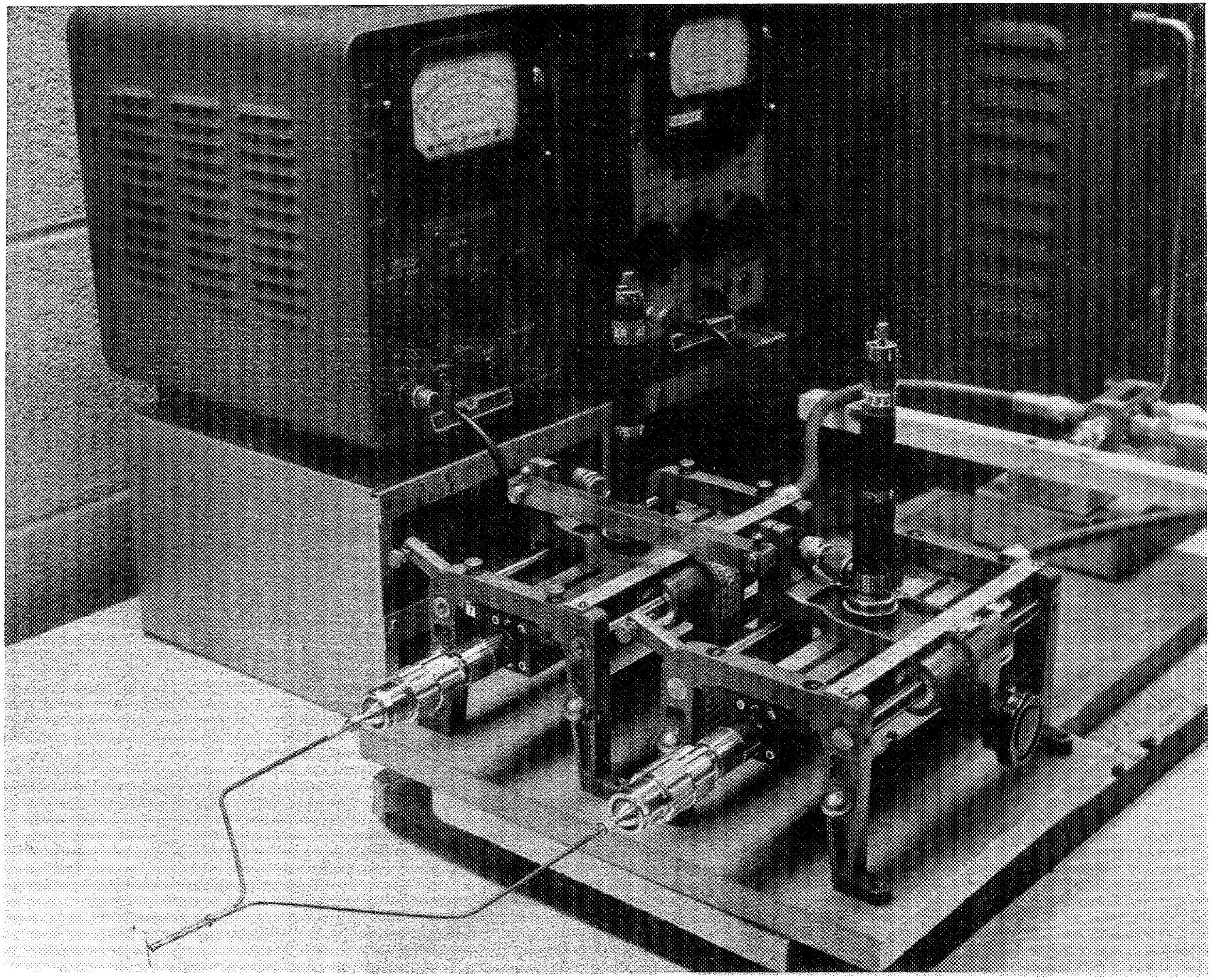


Figure 2.12 Double slotted-line feed system (after Liang[274]).

construction as shown in Fig. 2.11 is, therefore, preferable. A pair of coaxial cables is used as feed-lines to the antenna arms. The arms are soldered to the inner conductors of the cables. Since a single slotted-line, which is an unbalanced system, cannot be used to couple a balanced dipole, a "double slotted-line" technique[578] is necessary. The cables have to be carefully matched over the frequency range of operation in order to insure a current balance in the dipole arms. Fig. 2.12 shows a model for the "double slotted-line" feed system to the dipole. The slotted lines are identical and fed 180° out of phase by means of a hybrid junction. Since these slotted lines are on the dipole side of the hybrid, the effect of discontinuities through the hybrid is eliminated. Moreover, any mismatch in the feed-lines causes difference in the slotted-lines readings and can therefore be corrected.

Finally, the entry of the antenna to the antenna should be carefully sealed to prevent leakage and reduce reflections. Experience[274,430] has shown that this is not a trivial routine job.

(C) Measurements in Isotropic Cold Plasma

Laboratory measurements in isotropic cold plasma are supposed to be relatively the easiest to perform. However, in real situations difficulties arise from plasma nonlinearities, diagnostic troubles, reflections from container walls, sheath effect, etc. Also, having to work at rather high frequencies, errors in recording results are likely sometimes. Impedance measurements in isotropic cold plasma have been conducted in an afterglow plasma using a dipole[164] and a monopole[216] of lengths comparable to the free space wavelength. Fig. 2.13 shows typical results obtained for a quarter wavelength monopole. The theoretical curves have been calculated using the first-order King-Middleton theory adapted to an ionized medium.

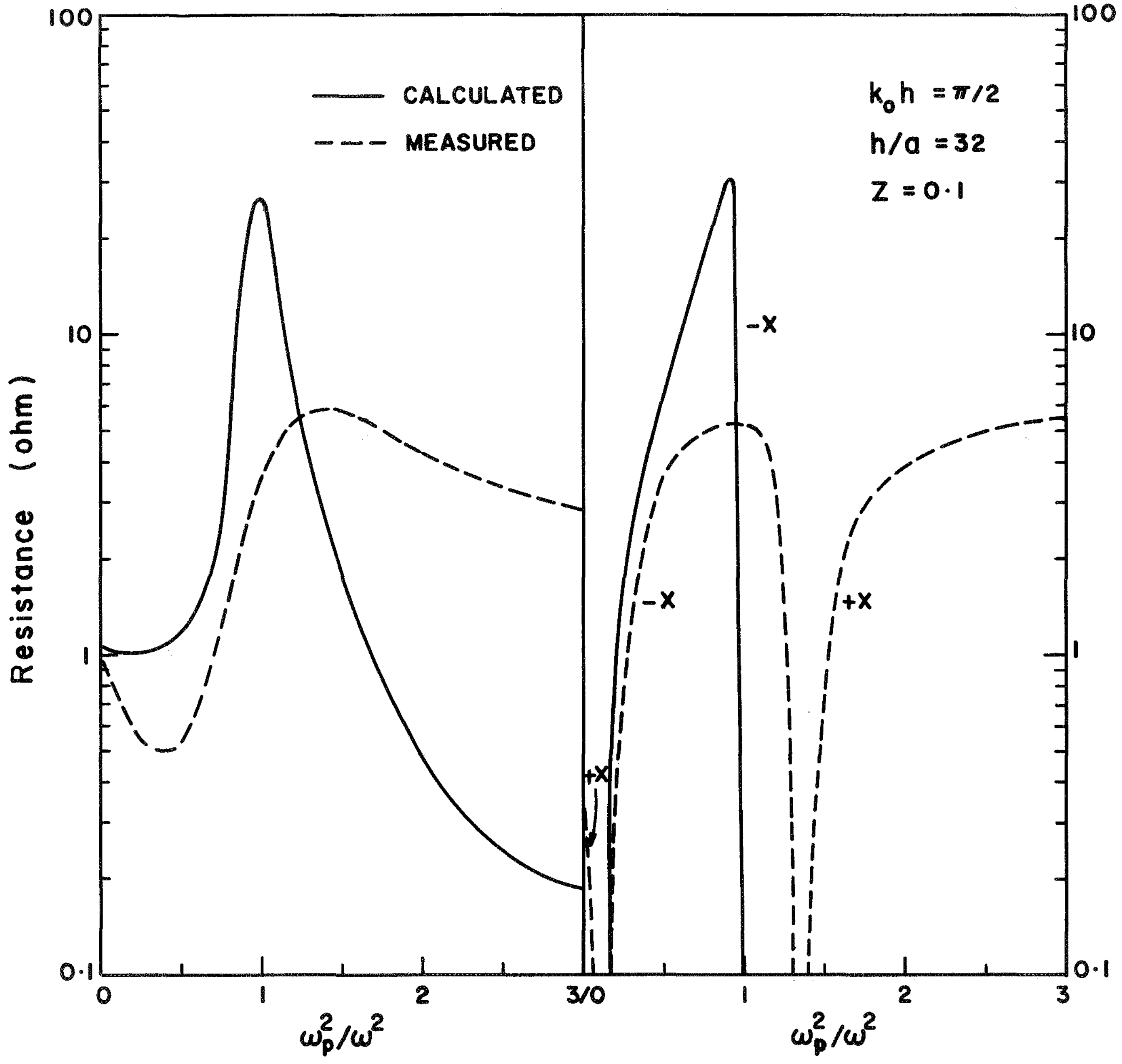


Figure 2.13 Impedance of a monopole immersed in isotropic cold laboratory plasma (after Jassby[216])

Except for $X < 0.5$, agreement between theory and experiment is generally poor, although improved layer diagnosis of the plasma inhomogeneities near the monopole were reported.[216] Discrepancies may be attributed to sheath effect, which has not been corrected for, possible longitudinal electron waves or surface waves and deformed current distribution along the monopole. It should be mentioned here that in a separate investigation, the current distribution and input admittance of a monopole has been measured in a column of isotropic cold plasma.[451] An extensive set of data has been obtained which shows the effect of plasma on the current distribution. But, since the present report is concerned with antennas in plasma media of infinite extent, results are not presented here and the interested reader is referred to the original paper.[451]

(D) Measurements in Anisotropic Cold Plasma

The earliest impedance measurements in laboratory plasma have been reported by Balmain where he experimented with a short monopole in a cold anisotropic plasma.[23] In spite of his significant theoretical formulation (Eqs.(6.5-6.7)part I), the experimental results were somewhat ambiguous. In particular, no unusual behavior in the impedance was observed at the upper-hybrid frequency perhaps due to the relatively high collision frequency in his experiment. A recent experimental investigation[553] revealed a better identification of resonances at ω_p and ω_u. Some results are shown in Fig. 2.14 where theoretical values based on Eq.(6.5)(part I) have been added. In spite of the good qualitative agreement between theory and experiment, the results are confusing, however, mainly due to a possible wrong choice of the plasma model used. The temperature has been mentioned to be $2.72 \times 10^4\ ^\circ K$. This yields a c/u ratio of about 270, which suggests a warm plasma rather than a cold one as assumed in the paper.[553] In that

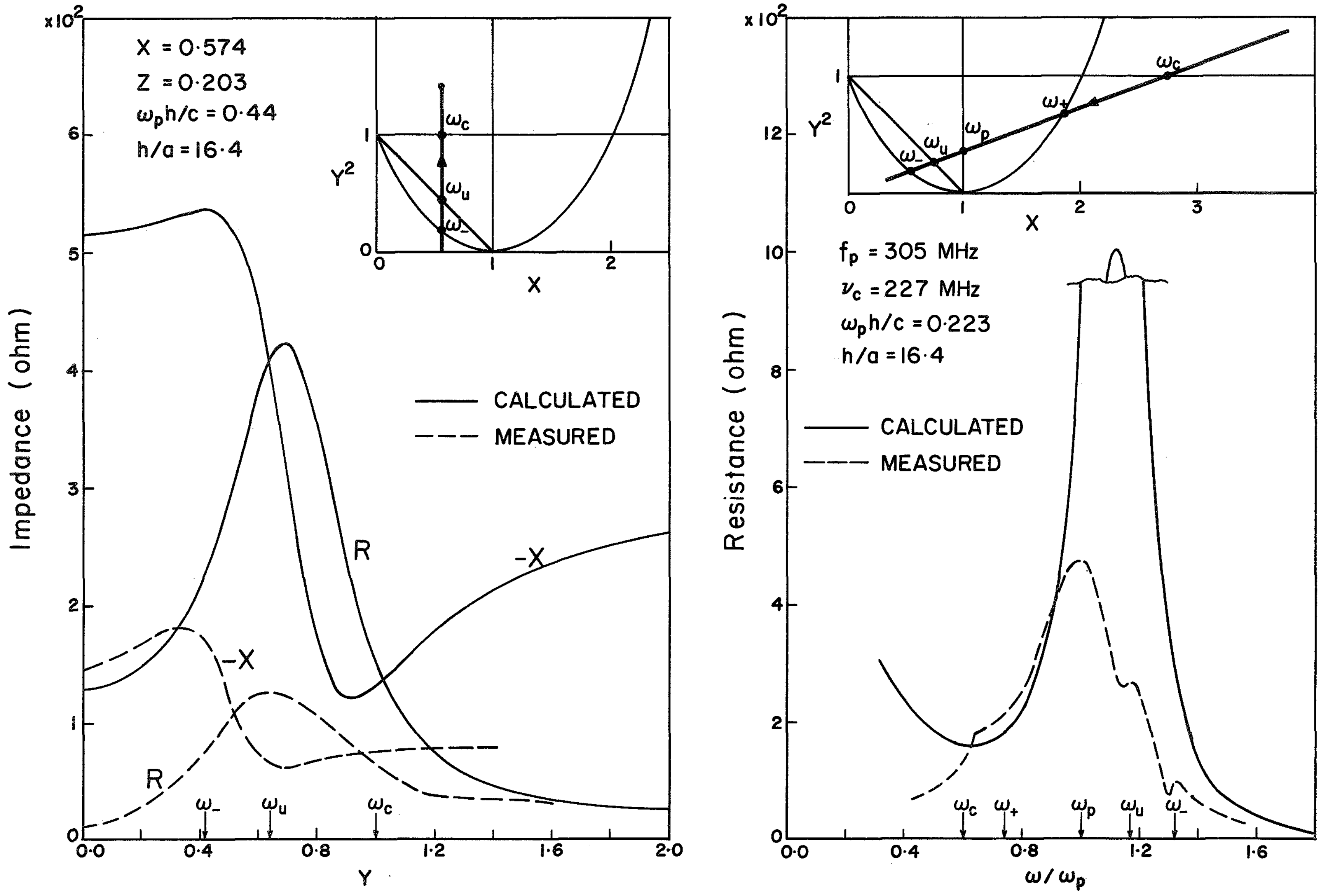


Figure 2.14 Impedance of a monopole immersed in anisotropic cold laboratory plasma (after Bhat and Rama Rao[553])

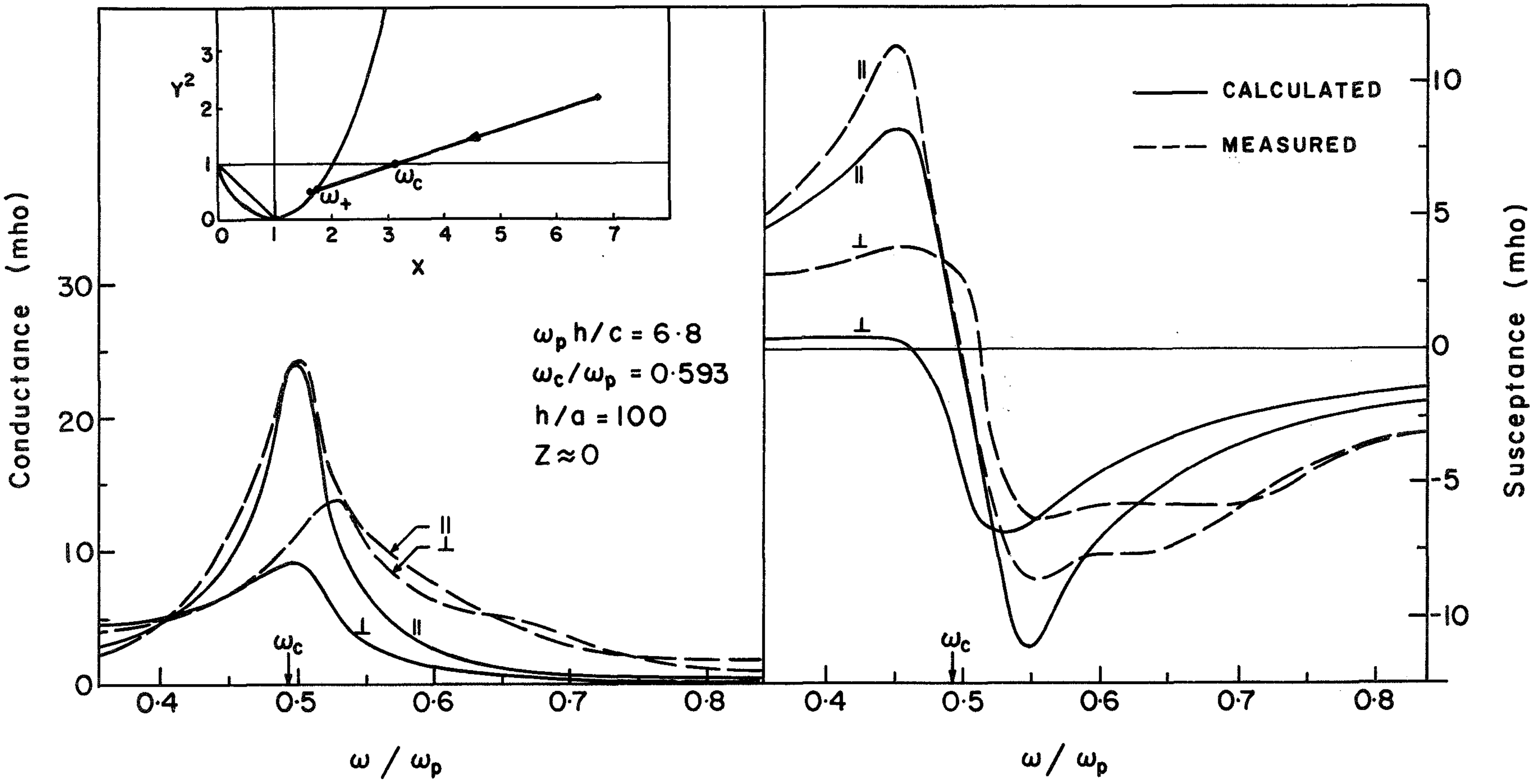


Figure 2.15 Admittance of a dipole immersed in anisotropic cold laboratory plasma with parallel and perpendicular orientations (after Snyder and Mittra[430])

case, the analogy in Fig. 2.14 fails and computations based on an anisotropic warm plasma model have to be done. Unfortunately, there is no suitable impedance formulation yet available for short antennas in anisotropic warm plasma.

The effect of antenna orientation with the static magnetic field on the input impedance has been investigated using a dipole.[430] Some results are shown in Fig. 2.15 where a very good agreement between theory and experiment may be noticed. In particular, the resonance at ω_c is clearly observed. As has been pointed out earlier, the effect of changing the orientation from parallel to perpendicular is to reduce the resonant peak of the conductance and to reduce the excursion of the susceptance.

4. CONCLUSIONS

The conclusion of this review is that although there is substantial agreement between theory and experiment in most areas, much remains to be done to gain a full understanding of the phenomena involved.

This is not surprising because of the difficulties of both the experiments and the theory. Many idealizations are necessary in the theory. Many unknown parameters remain in most experiments.

Experimental determination of the plasma sheath effect on the performance of antennas still needs careful attention. This particularly applies to measurements in the ionosphere where the sheath formed around the antenna maybe nonuniform. Future research should perhaps concentrate on determining the role played by the sheath and the present data may be reinterpreted to reveal more realistic information about the antenna impedance in plasma.

Electroacoustic waves are more likely to be excited by antennas in the ionosphere than in laboratory plasma due to operation at low frequencies. However, except in few cases, interpretation of ionospheric data has not considered these waves.

In carefully controlled laboratory plasma, the effect of acoustic waves on the current distribution and impedance of antennas should be studied. Some work on this line has started recently.

Plasma diagnostics is a significant problem by itself. Langmuir probes and other perturbing probes may be simple and convenient but in many cases they cannot yield sufficiently accurate results. Nonperturbing plasma diagnostic techniques are generally more efficient and reliable and should be used whenever possible.

PART III

BIBLIOGRAPHY ON SOURCES IN PLASMA

by

M. J. Al-Hakkak

Even though the presnt report discusses only the impedance of cylindrical antennas in plasma, this bibliography is prepared to include papers on the subject of electromagnetic sources situated in plasma. Some remarks about this part of the report are in order:

(A) This bibliography is the result of a search in the literature published in English. In particular, the following journals have been systematically searched for the period 1960 - 1969.

1. IEEE Transactions on Antennas and Propagation
2. Proceedings of the IEEE
3. Proceedings of the IEE (London)
4. Radio Science - Journal of Research NBS
5. Canadian Journal of Physics
6. Physics of Fluids
7. Journal of Geophysical Research
8. Planetary and Space Science
9. Report on Ionospheric and Space Research in Japan
10. Space research
11. Journal of Applied Physics
12. Applied Physics Letters
13. Applied Scientific Research
14. Electronics Letters
15. Soviet Physics - Technical Physics (Translate from Russian)
16. Radio Engineering and Electronics Physics (Translated from Russian)
17. Nuovo Cimento

(B) A limited number of papers presented in conferences, and reports published by various institutions are included, but they are far from being exhaustive.

(C) The number of papers (only those included in this bibliography) published in each year from 1960 - 1969 is shown in Figure 3.1.

(D) The group of papers pertaining to the subject discussed in parts I and II of this report (i.e. impedance of cylindrical antennas in plasma) has been classified as given in Table I.

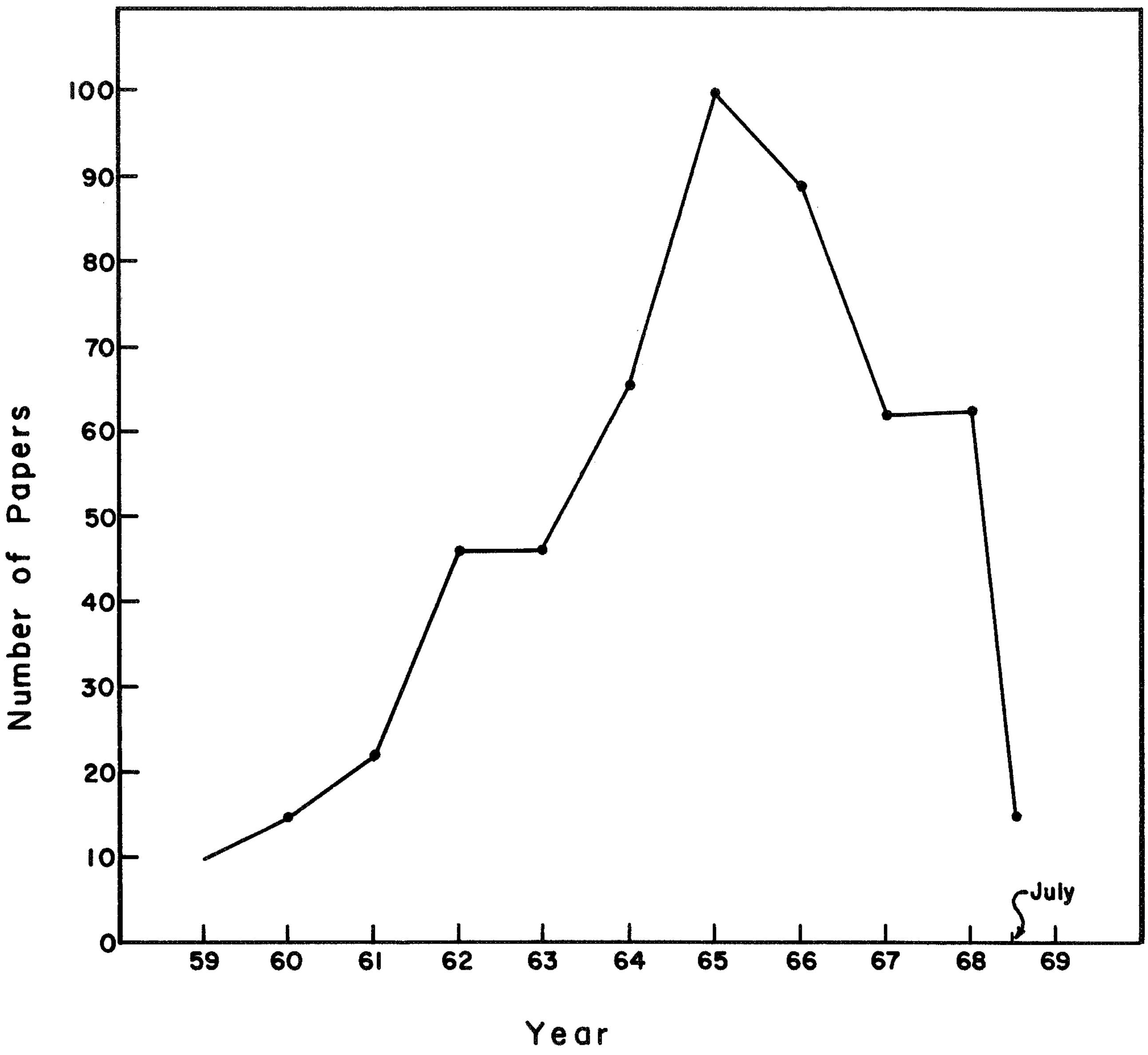


Figure 3.1 Rate of growth of papers about sources in plasma during the years 1960-1969

BIBLIOGRAPHY ON SOURCES IN PLASMA*

1. Abraham, L. G., "Extensions of the magnetoionic theory for radio-wave propagation in the ionosphere including antenna and plane wave scattering," School of Electrical Engineering, Cornell University, Ithaca, N. Y., Tech. Rept. No. 13, 1953.

2. Aggson, T. L., and C. A. Kapitankos, "On the Impedance of a Satellite Borne VLF Electric Field Antenna," Goddard Space Flight Center, Greenbelt, Maryland, Report X-612-66-380, 1966.

3. Ament, W. S., "The impedance of a cylindrical dipole in a homogeneous anisotropic medium II," Electromagnetic Research Corp., College Park, Md., Sci. Rept. No. 3, 1963.

4. Ament, W. S., J. C. Katzin, M. Katzin, and Y. C. Koo, "Impedance of a cylindrical dipole having a sinusoidal current distribution in homogeneous anisotropic ionosphere," J. Res. NBS, <u>68D</u>, 4, April 1964, 379-405.

5. Ament, W. S., M. Katzin, J. R. Malaughlin, and W. W. Zachary, "Satellite antenna radiation properties at VLF in the ionosphere," Electromagnetic Research Corp., College Park, Md., Final Report, Contract Nonr-4250(00)(X), April 1965.

6. Andreasen, M. G., and R. L. Tanner, "Radiation from a generalized antenna in a stratified medium," IEEE Trans., <u>AP-12</u>, 5, Sept. 1964, 522-529.

7. Aoki, K., "On a cylindrical antenna in a homogeneous anisotropic medium," Can. J. Phys., <u>44</u>, 6, June 1966, 1239-1266.

8. Aoki, K., "Eigenvalues of the axially symmetrical electromagnetic waves along an infinitely long and conductive circular in a homogeneous magnetoionic medium," Can. J. Phys., <u>47</u>, 11, June 1969, 1159-1166.

9. Arbel, E., and L. B. Felsen, "Theory of radiation from sources in anisotropic media," in <u>Electromagnetic Theory and Antennas</u>, ed. E. C. Jordan, Pergamon Press, 1963, 391-459.

---

*Entries 538-555 are added without being in alphabetical order.

10. Atzinger, E. M., A. F. Pensa and M. T. Pigott, "On the application of a calculation by Wait and Campbell: The fields of an oscillating magnetic dipole immersed in a semi-infinite conducting medium," J. Geoph. Res., 71, 23, Dec. 1966, 5765-5769.

11. Bachynski, M. P., "Sources in plasmas," RCA Rev., 23, 1, March 1967, 111-152.

12. Bachynski, M. P., and G. G. Cloutier, "Antenna radiation patterns in the presence of a plasma sheath," Proc. Symp. on the Plasma Sheath, Plenus Press.

13. Bachynski, M. P., G. G. Cloutier and K. A. Graf, "Antenna properties in the presence of ionized media," AFCRL Report No. 62-191, March 1962.

14. Bachynski, M. P., I. P. French and G. G. Cloutier, "Antenna Noise Temperature in Plasma Environment," Proc. IRE, 49, 12, Dec. 1961, 1846-1857.

15. Bachynski, M. P., and B. W. Gibbs, "Antenna pattern distortion by an isotropic plasma slab," IEEE Trans., AP-16, 5, Sept. 1968, 583-588.

16. Bachynski, M. P., and B. W. Gibbs, "Antenna radiation properties in presence of anisotropic plasmas," Radio Science, 3, 9, Sept. 1968, 920-935.

17. Bailey, M. C., and C. T. Swift, "Input admittance of a circular waveguide aperture covered by a dielectric slab," IEEE Trans., AP-16, 4, July 1968, 386-391.

18. Bain, W. C., and P. G. Davies, "Rocket studies of aerial admittance and resonance rectification," Planet. Spac. Sci., 13, 7, July 1, 1965, 723-726.

19. Bain, W. C., and P. G. Davies, "Rocket-borne experiments on resonance rectification," Planet. Space Sci., 13, 10, Oct. 1965, 969-977.

20. Baker, K. D., A. M. Despain, W. Pfister, and J. C. Ulwick, "Experiences with antenna impedance measurements in the ionosphere," Fall URSI meeting, Dartmouth College, Hanover, New Hampshire, October 1965.

21. Baker, K. D., A. M. Despain and J. C. Ulwick, "Simultaneous comparison of RF probe techniques for determination of ionospheric electron density," J. Geophys. Res., 71, 3, Feb. 1966, 935-944.

22. Baker, K. D., E. F. Pound and J. C. Ulwick, "Digital plasma frequency probe for fine scale ionospheric measurements," Space Research IX, (North-Holland Publishing Company, Amsterdam), 1963.

23. Balmain, K. G., "The impedance of a short dipole antenna in a magnetoplasma," IEEE Trans., AP-12, 5, Sept. 1964, 605-617.

24. Balmain, K. G., "Impedance of a short dipole in a compressible plasma," J. Res. NBS 69D, 4, April 1965, 559-566.

25. Balmain, K. G., "Impedance of a radio frequency plasma probe with an absorptive surface," Radio Science, 1, 1, Jan. 1966, 1-12.

26. Balmain, K. G., "Impedance of a spherical probe in a magnetoplasma," IEEE Trans., AP-14, 3, May 1966, 402-403.

27. Balmain, K. G., "Impedance measurements in laboratory plasma," in Electromagnetics and Antennas, ed. P. E. Mayes, University of Illinois, Feb. 1967, 513-529.

28. Balmain, K. G., G. Oksiutik and J. Fejer, "RF Probe Admittance in the Ionosphere: Comparison of Theory and Experiment," Spring URSI meeting, Ottawa, Ontario, Canada, 1967.

29. Barsukov, K. A., "Radiation of electromagnetic waves from sources in a gyrotropic medium with a separation boundary," Radio Eng. & Elect., 4, 11, Nov. 1959, 1759-1764.

30. Bates, C., and R. Mittra, "Plane-Wave spectrum representation of a field in a magnetoionic medium due to a plane distribution of source currents," Elec. Letters, 1, 3, May 1965, 47.

31. Bates, C. P., and R. Mittra, "Principles of Scaling in a Uniaxial Medium" Nuovo Cimento, 43B, 1, May 1966, 101-118.

32. Benning, C. J., "Impedance of a loop antenna in a conducting medium," IEEE Trans., AP-14, 2, March 1966, 242-243.

33. Bergeson, J. E., "Radiation from an oscillating magnetic dipole in a streaming plasma," Radio Science, 3, 2, Feb. 1968, 191-200.

34. Bergeson, J. E., "Power radiated by oscillating magnetic and oscillating electric dipoles in a cold, streaming plasma," J. Appl. Phys., 40, 1, Jan. 1969, 152-158.

35. Bertoni, H. L., and A. Hessel, "Ray description for point source excited surface waves in stratified anisotropic media," Radio Science, 4, 1, Jan. 1969, 73-81.

36. Bettinger, R. T., and A. A. Chen, "An end effect associated with cylindrical Langmuir probes moving at satellite velocities," J. Geoph. Res., 73, 7, April 1968, 2513-2528.

37. Bettinger, R. T. and E. H. Walker, "Relationship for plasma sheaths about Langmuir probes," Phys. Fluids, 8, 4, April 1965, 748-751.

38. Biggs, A. W. and H. M. Swarm, "Radiation fields of an inclined electric dipole immersed in a semi-infinite conducting medium," IEEE Trans., AP-11, 3, May 1963, 306-310.

39. Biggs, A. W., and H. M. Swarm,"Radiation fields in the ionosphere from a VLF horizontal electric dipole in Antarctica," Symp. Electromagnetic Wave Theory, Delft, The Netherlands, Sept. 1965 (Pergamon Press, 1967), 225.

40. Birmingham, T., J. Dawson and C. Oberman, "Radiation processes in plasmas," Phys. Fluids, 8, 2, Feb. 1965, 297-307.

41. Blair, W. E., "Experimental verification of dipole radiation in a conducting half-space,"IEEE Trans., AP-11, 3, May 1963, 269-275.

42. Blair, W. E., "The driving-point impedance of an electrically short cylindrical antenna in the ionosphere," Engineering Experiment Station, University of New Mexico, Albuquerque, Tech. Rept. No. EE-109, 1964.

43. Blair, W. E., "Resonances in the driving-point impedance of an electric dipole in the ionosphere," Contract NAS5-9309, SRI project 6045, Stanford Research Institute, Menlo Park, California, 1967.

44. Blair, W. E., "Ionospheric diagnostics using resonances of an electric dipole impedance," Radio Science, 3, 2, Feb. 1968, 155-162.

45. Bogges, R. J., L. H. Brace and N. M. Spencer, "Langmuir probes for plasma measurements in the ionosphere," J. Geoph. Res., 64, 10, Oct. 1959, 1627-1630.

46. Bohley, P., and R. Caldecott, "Antenna impedance measurements during the hypersonic reentry of a Trailblazer rocket vehicle," Int. Symp. Ant. & Prop., University of Michigan, Ann Arbor, Oct. 1967, 17-19.

47. Bourdeau, R. E., J. E. Jackson, J. A. Kane and G. P. Serbu, "Ionospheric measurements using environmental sampling techniques," Space Research I (North-Holland Publishing Company, Amsterdam), 1960, 328-339.

48. Boyd, T. J. M., "Theory of a radio-frequency plasma probe for electron-density measurements in the ionosphere and exosphere," J. Geoph. Res., 68, 17, Sept. 1963, 5089-5092.

49. Bramley, E. N., "The impedance of a short cylindrical dipole in the ionosphere," Planet. Space Sci., 9, 8, Aug. 1962, 445-454.

50. Bramley, E. N., "Rocket studies of aerial admittance and resonance rectification," Planet. Space Sci., 13, 7, July 1965, 723-726.

51. Bramley, E. N., "Measurements of aerial admittance in the ionosphere," Planet. Space Sci., 13, 10, Oct. 1965, 976-995.

52. Brandstatter, J. J., and A. J. Panico, "A study of the impedance of a cylindrical dipole in an anisotropic plasma," Final Report, SRI Project PMU-3417, Stanford Research Institute, Menlo Park, California, 1964.

53. Brueckmann, H., "Antenna pattern measurement by satellite," IEEE Trans., AP-11, 2, March 1963, 143-147.

54. Buckley, R., "A theory of resonance rectification--the response of a spherical plasma probe to alternating potentials," Proc. Roy. Soc., 290A, 1421, Feb. 1966, 186-219.

55. Budden, K. G., "The impedance of an aerial immersed in an anisotropic medium," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 513-516.

56. Bunkin, F. V., "On radiation in anisotropic media," Soviet Phys. - Tech Phys., 5, 3, Sept. 1957, 277-283.

57. Burman, R., "Resonances of a cylindrical cavity in a lossy magnetoionic medium," Proc. IEEE, 53, 8, Aug. 1965, 1147-1148.

58. Burman, R., "Radiation from a slot antenna into a stratified magneto-plasma half-space," IEEE Trans., AP-13, 5, Sept. 1965, 816-817.

59. Burman, R., "Electromagnetic radiation from a slotted-cylinder antenna with an inhomogeneous sheath," Elec. Letters, 2, 3, March 1966, 102-103.

60. Burt, D. A., and E. F. Pound, "A plasma frequency probe for high resolution electron density measurements," American Astronautical Society Symposium, Denver, Colorado, July 1967.

61. Butler, H. S. and G. S. Kino, "Plasma sheath formation by radio-frequency fields," Phys. Fluids, 6, 9. Sept. 1963, 1346-1355.

62. Campbell, J. J., "Radiation from a center-fed cylindrical antenna surrounded by a plasma sheath," IEEE Trans., AP-14, 3, May 1966, 336-344.

63. Carlin, J. W., "Variational formula for antenna impedance in a warm magnetoplasma," Elec. Letters, 2, 6, June 1966, 199-201.

64. Carlin, J. W., and R. Mittra, "Acoustic waves and their effects on antenna impedance," Can. J. Phys., 45, 3, March 1967, 1251-1269.

65. Carlin, J. W., and R. Mittra, "Effects of induced acoustic sources on the impedance of a cylindrical dipole in a warm plasma," Radio Science, 2, 11, Nov. 1967, 1327-1338.

66. Casey, K. F., "Dipole radiation in a periodically stratified medium," Can. J. Phys., 46, 22, Nov. 1968, 2543-2551.

67. Chapman, J. H., "Effects of the ionosphere on radio noise measurements from an earth satellite," Space Research II (North-Holland Publishing Company, Amsterdam), 1961, 597-608.

68. Chapman, J. H., W. J. Heikkila and R. K. Brown, "Two high altitude rocket experiments," Space Research I (North-Holland Publishing Company, Amsterdam), 1960, 366-370.

69. Chapman, J. H., and A. R. Molozzi, "Interpretation of cosmic noise measurements at 3.8 Mc/s from satellite 1960ηI," Nature, 191, 4787, July 1961, 480.

70. Chen, C. L., and R. W. P. King, "The small bare loop antenna immersed in a dissipative medium," IEEE Trans., AP-11, 3, May 1963, 266-269.

71. Chen, C. L., and S. R. Seshadri, "Infinite cylindrical antenna in a simple anisotropic medium," IEEE Trans., AP-14, 6, Nov. 1966, 715-726.

72. Chen, H. C., "Spectral resolution and solution of field problems in an anisotropic and compressible medium," IEEE Trans., AP-16, 6, Nov. 1968, 741-745.

73. Chen, H. C., and D. K. Cheng, "Radiation from an axially slotted anisotropic plasma-clad cylinder," IEEE Trans., AP-13, 3, May 1965, 395-401.

74. Chen, H. C., and D. K. Cheng, "Dyadic Green's function for magnetic current source in compressible anisotropic plasma," Elec. Letters, 1, 7, Sept. 1965, 186-187.

75. Chen, K. M., "Discussion on basic equations with source terms in compressive and incompressive plasmas," J. Res. NBS, 69D, 2, Feb. 1962, 243-245.

76. Chen, K. M., "Interaction of a radiating source with a plasma," Proc. IEE (London), 111, 10, Oct. 1964, 1668-1678.

77. Chen, K. M., "Electroacoustic waves excited by a space vehicle in ionized atmosphere and its effect on radar return," J. Res. NBS, 69D, 2, Feb. 1965, 235-241.

78. Chen, K. M., H. Judson and C. C. Lin, "Experimental study of an electroacoustic wave excited by an antenna in a hot plasma," Proc. IEEE, 55, 9, Sept. 1967, 1656-1657.

79. Chen, K. M., H. Judson and C. C. Lin, "Experimental study of the input impedance and the radiation field of cylindrical antennas in a compressible plasma," Radio Science, 1, Oct. 1967, Int. Symp. on Antennas and Propagation, Ann Arbor, Michigan.

80. Chen, K. M., and C. C. Lin, "Enhanced radiation from a plasma-imbedded antenna," Proc. IEEE, 57, 9, Sept. 1968, 1595-1597.

81. Cheng, D. K., and H. C. Chen, "Sequel to Reciprocity Relations in a compressible plasma," IEEE Trans., AP-14, 4, July 1966, 519.

82. Chetaev, D. N., "On the Field of a Low-Frequency Electric Dipole Situated on the Surface of a Uniform Anisotropic Conducting Half-Space," Sov. Phys.-Tech. Phys., 7, 11, May 1963, 991-995.

83. Chow, Y., "A note on radiation in a gyro-electric-magnetic medium--an extension of Bunkin's calculation," IRE Trans., AP-10, 4, July 1962, 464-469.

84. Chow, Y., T. T. Wu and C. P. Wu, "On calculation of the tensorial Green's functions for the general case of gyro-electric magnetic media," IEEE Trans., AP-12, 4, July 1964, 514-515.

85. Clemmow, P. C., "On radiation from sources in a magnetoionic medium," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 461-475.

86. Clemmow, P. C., "The theory of electromagnetic waves in a simple anisotropic medium," Proc. IEE (London), 110, 1, Jan. 1963, 101-106.

87. Cloutier, G. G., M. P. Bachynski and K. A. Graf, "Antenna properties in the presence of ionized media," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 537-548.

88. Cohen, M. H., "Radiation in a plasma, I. Cerenkov effect," Phys. Rev., 123, 3, Aug. 1961, 711-721.

89. Cohen, M. H., "Radiation in a plasma, II. Equivalent Sources," Phys. Rev., 126, 2, April 1962, 389-397.

90. Cohen, M. H., "Radiation in a plasma, III. Metal boundaries," Phys. Rev., 126, 2, April 1962, 398-404.

91. Compton, R. T., "The admittance of aperture antennas radiating into lossy media," Antenna Laboratory, Ohio State Research Foundation, Columbus, Ohio, Report No. 1691-5, 1964.

92. Connolly, D. J., and B. S. Tanenbaum, "Radiation from current sources in an isotropic plasma," J. Appl. Phys., 38, 6, May 1967, 2557-2562.

93. Cohn, G. I., and G. T. Flesher, "Theoretical radiation pattern and impedance of a flush mounted coaxial aperture," Proc. Nat. Elec. Conf., 14, 1958, 150-168.

94. Cook, K. R., "Radiation characteristics for a magnetic line source in homogeneous electron plasma," IEEE Trans., MTT-12, 11, Nov. 1964, 617-618.

95. Cook, K. R., and B. C. Edgar, "Current distribution and impedance of a cylindrical antenna in an isotropic compressible plasma," Radio Science, 1, 1, Jan. 1966, 13-19.

96. Cook, K. R., and G. L. Johnson, "On the problem of the infinite antenna in anisotropic plasma," Radio Science, 2, 5, May 1967, 495-502.

97. Corti, E., G. Franceschetti and G. Latmiral, "New class of antennas in conducting media," Elec. Letters, 3, 9, Sept. 1967, 398-400.

98. Crawford, F. W., "An RF technique for plasma number density measurement," IEEE Trans., NS-11, 1, Jan. 1964, 12-22.

99. Crawford, F. W., "Plasma resonance probe characteristics in a magnetic field," J. Appl. Phys., 36, 10, Oct. 1965, 3142-3145.

100. Crawford, F. W., and R. Grard, "Low-frequency impedance characteristics in a magnetic field," J. Appl. Phys., 37, 1, Jan. 1966, 180-183.

101. Crawford, F. W., and R. S. Harp, "The resonance probe--a tool for ionospheric and space research," J. Geoph. Res., 70, 3, Feb. 1963, 587-596.

102. Crawford, F. W., and R. S. Harp, "The plasma resonance probe in a magnetic field," Phys. Lett., 11, 2, Feb. 1964, 126-127.

103. Crawford, F. W., R. S. Harp and T. D. Mantei, "Resonance-rectification effects in warm magnetoplasma," J. Appl. Phys., 38, 13, Dec. 1967, 5077-5082.

104. Crawford, F. W., and R. F. Mlodnosky, "Langmuir probe response to periodic waveforms," J. Geoph. Res., 69, 13, July 1964, 2765-2773.

105. Croswell, W. F., and M. C. Bailey, "A study of the effect of boundary layer plasma profile shapes upon the admittance of aperture antennas," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

106. Croswell, W. F., W. C. Taylor, C. T. Swift, and C. R. Cockrell, "The input admittance of a rectangular waveguide fed aperture under an inhomogeneous plasma, Theory and Experiment," IEEE Trans., AP-16, 4, July 1968, 475-487.

107. Crozier, W. D., "Measuring atmospheric potential with passive antennas," J. Geoph. Res., 68, 18, Sept. 1963, 5173-5179.

108. Cutler, S., "The effects of a plasma sheath on the impedance properties of some slot antennas, Part I. Analytical formulation," Tech. Res. Group, Inc., Syosett, N. Y. Report No. TRG-127-SR-1, 1959.

109. Daly, P., K. S. H. Lee and C. H. Papas, "Radiation resistance of an oscillating dipole in a moving medium," IEEE Trans., AP-13, July 1965, 583-587.

110. Davidovskii, V. G., L. V. Dubovoi and A. G. Ponomarenko, "Resonance probing of a plasma in a magnetic field," Sov. Phys. - Tech. Phys., 9, 7, Feb. 1965, 961-967.

111. Deering, W. D., and J. A. Fejer, "Excitation of plasma resonances by a small pulsed dipole," Phys. Fluids, 8, 11, Nov. 1965, 2066-2075.

112. Deschamps, G. A., "Impedance of an antenna in a conducting medium," IRE Trans., AP-10, 5, Sept. 1962, 648-650.

113. Deschamps, G. A., "Impedance of antennas in ionized media," in *Electromagnetics and Antennas*, ed. P. E. Mayes, University of Illinois, Feb. 1967, 498-512.

114. Deschamps, G. A., and O. Kesler, "Radiation field of an arbitrary antenna in a magnetoplasma," IEEE Trans., AP-12, 6, Nov. 1964, 783-785.

115. Deschamps, G. A., and O. B. Kesler, "Radiation of an antenna in a compressible plasma," Radio Science, 2, 8, Aug. 1967, 757-767.

116. Despain, A. M., "The theory of cylindrical antenna impedance as a function of plasma frequency and temperature," University of Utah, Salt Lake City, Sci. Rept. No. 1, March 1965.

117. Despain, A. M., "Antenna impedance in the ionosphere," University of Utah, Salt Lake City, Sci. Rept. No. 3, May 1966.

118. Despain, A. M., and W. Pfister, "Ionospheric electron temperature from antenna impedance measurements," Spring URSI Meeting, National Academy of Sciences, Washington, D. C., April 1966.

119. Dote, T., and H. Amemiya, "Negative characteristics of a cylindrical probe in a magnetic field," J. Phys. Soc., Japan, 19, 1964, 1915.

120. Dote, T., H. Amemiya and T. Ichimiya, "Effect of the geomagnetic field on an ionospheric sounding probe," J. Geoph. Res., 70, 9, May 1965, 2258-2261.

121. Dote, T., and T. Ichimiya, "The mechanism of resonance probe," Proc. IEEE, 52, 10, Oct. 1964, 1240-1241.

122. Dote, T., and T. Ichimiya, "Characteristics of resonance probes," J. Appl. Phys., 36, 6, June 1965, 1866-1872.

123. Duff, G. L., and R. Mittra, "Input impedance of a small loop of uniform electric current in an anisotropic cold plasma," Elect. Letters, 1, 5, July 1965, 127-128.

124. Duff, G. L., and R. Mittra, "The theoretical and experimental determination of the input impedance of a small loop of electric current immersed in an anisotropic plasma," Antenna Lab., University of Illinois, Sci. Rept. No. 8, Oct. 1966.

125. Fante, R. L., "The effect of thin plasmas on an aperture antenna in an infinite conducting plane," Radio Science, 2, 1, Jan. 1967, 87-100.

125. Fante, R. L., "The effect of an offset impedance sheet on the admittance of a slot antenna," IEEE Trans., AP-15, 4, July 1967, 516-518.

126. Fante, R. L., and Mullin, "Effect of plasma on small tuned dipoles," IEEE Trans., AP-15, 3, May 1967, 495.

127. Fejer, J. A., "Interaction of an antenna with a hot plasma and the theory of resonance probes," J. Res. NBS, 68D, 11, Nov. 1964, 1171-1176.

128. Fejer, J. A., "Excitation of plasma resonances by an antenna in the ionosphere," The Second American Astronautical Society Symposium on the Interactions of Space Vehicles with an Ionized Atmosphere, University of Miami, Coral Gables, Florida, Nov. 1965.

129. Fejer, J. A., "Excitation of the lower hybrid resonance by an antenna in the ionosphere," Radio Science, 1, 4, April 1966, 447-456.

130. Fejer, J. A., and W. Calvert, "Resonance effects of electrostatic oscillations in the ionosphere," J. Geophys. Res., 69, 23, Dec. 1964, 5049-5062.

131. Felsen, L. B., "Radiation from a uniaxially anisotropic plasma half space," IEEE Trans., AP-11, 4, July 1963, 469-484.

132. Felsen, L. B., "Radiation from plasmas," J. Res. NBS, 68D, 4, April 1964, 480-485.

133. Felsen, L. B., "On the use of refractive index diagrams for source-excited anisotropic region," J. Res. NBS, 69D, 2, Feb. 1965, 155-169.

134. Felsen, L. B., and B. Rulf, "Radiation from a directive antenna embedded in an anisotropic half space," Electrophysics Dept., Polytechnic Inst. of Brooklyn, Report No. PIBMRI-1183-63, Aug. 1963.

135. Felsen, L. B., and H. Staras, "Comment on the impedance of an electric dipole in a magnetoionic medium," IEEE Trans., AP-13, 4, July 1965, 637-638.

136. Ford, G. W., "Electromagnetic radiation from a source in a plasma," Ann. of Physics, 16, 2, Nov. 1961, 185-200.

137. Franchi, P., and A. Orefice, "The near field of an antenna in a magnetoactive plasma," Nuovo Cimento, 44, 1, July 1966, 95-106.

138. Fujioka, H., and H. Kumagai, "Electromagnetic radiation in a moving lossy medium," Radio Science, 2, 12, Dec. 1967, 1449-1458.

139. Galejs, J., "Excitation of slots in a conducting screen above a lossy dielectric half space," IEEE Trans., AP-10, 2, March 1962, 436-443.

140. Galejs, J., "Small electric and magnetic antennas with cores of a dielectric," J. Res. NBS, 67D, 4, April 1963, 445-451.

141. Galejs, J., "Admittance of an annular slot antenna radiating into a plasma layer," J. Res. NBS, 68D, 3, March 1964, 317-324.

142. Galejs, J., "Slot antenna impedance for plasma layers," IEEE Trans., AP-12, 6, Nov. 1964, 738-745.

143. Galejs, J., "Admittance of a waveguide radiating into stratified plasma," IEEE Trans., AP-13, 1, Jan. 1965, 64-70.

144. Galejs, J., "Self and mutual admittance of waveguides radiating into plasma layers," J. Res. NBS, 69D, 2, Feb. 1965, 179-189.

145. Galejs, J., "Propagation along an insulated cylindrical wire in a compressible plasma," IEEE Trans., AP-13, 4, July 1965, 644-645.

146. Galejs, J., "Driving point impedance of linear antennas in the presence of a stratified dielectric," IEEE Trans., AP-13, 5, Sept. 1965, 725-737.

147. Galejs, J., "Mutual impedance of linear antennas in the presence of a stratified dielectric," IEEE Trans., AP-14, 2, March 1966, 195-202.

148. Galejs, J., "Slot admittance for compressible plasma layers," Radio Science, 1, 4, April 1966, 457-474.

149. Galejs, J., "Impedance of an insulated linear antenna between layers of compressible plasma," Radio Science, 1, 9, Sept. 1966, 1057-1065.

150. Galejs, J., "Guided waves supported by layers of a lossy compressible plasma," Can. J. Phys., 44, 11, Nov. 1966, 2875-2891.

151. Galejs, J., "Impedance of a finite insulated cylindrical antenna in a cold plasma with a longitudinal magnetic field," IEEE Trans., AP-14, 6, Nov. 1966, 727-736.

152. Galejs, J., "Impedance of a finite insulated antenna in a cold plasma with a perpendicular magnetic field," IEEE Trans., AP-14, 6, Nov. 1966, 737-748.

153. Galejs, J., "Impedance of a strip antenna in a dielectric layer above a ground plane and below a half-space of cold plasma," IEEE Trans., AP-15, 2, March 1967, 326-327.

154. Galejs, J., "Power flow from a short antenna in a lossy uniaxial medium," Radio Science, 2, 12, Dec. 1967, 1419-1430.

155. Galejs, J., "The insulated cylindrical antennas in a cold plasma with a longitudinal magnetic field," IEEE Trans., AP-16, 2, March 1968, 378-380.

156. Galejs, J., "On antenna impedances in a cold plasma with a perpendicular static magnetic field," IEEE Trans., AP-16, 6, Nov. 1968, 728-737.

157. Galejs, J., "Insulated cylindrical antenna immersed in a compressible plasma," Radio Science, 4, 3, March 1969, 269-278.

158. Galejs, J., and M. H. Mentzoni, "Waveguide admittance for radiation into plasma layers--Theory and Experiment," IEEE Trans., AP-15, 3, May 1967, 465-470.

159. Genchev, Zh. D., and S. S. Kalmykova, "Excitation of Electromagnetic Waves in Plasma by a Bounded Source," Sov. Phys. - Tech. Phys., 12, 9, March 1968, 1199-1203.

160. Ghose, R. N., "Plasma antenna in a nuclear environment," IEEE Trans., AP-15, 5, Sept. 1967, 713-714.

161. Golden, K. E., and T. M. Smith, "Simulation of a thin plasma sheath by a plane of wires," Plasma Res. Lab., Aerospace Corp. Contract No. AF 04(695)-269, March 1964.

162. Golden, K. E., and G. E. Stewart, "Admittance and isolation of a slot antenna exposed to nonuniform plasma layer," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

163. Gooch, D. W., C. W. Harrison, Jr., R. W. P. King and T. T. Wu, "Impedance of long antennas in air and in dissipative media," J. Res. NBS, 67D, 3, May-June 1963, 355-360.

164. Graf, K. A., and D. L. Jassby, "Measurements of dipole antenna impedance in an isotropic laboratory plasma," IEEE Trans., AP-15, 5, Sept. 1965, 681-688.

165. Grard, R. J. L., and J. K. E. Tunaley, "The impedance of the electric dipole aerial on the FR-1 satellite," Annales de Geophysique, 24, 1, Jan. 1968, 1-13.

166. Gregory, B. C., and G. Mouries, "Nonlinear effects in the dipole resonance of a plasma column at higher R.F. powers," Can. J. Phys., 45, 11, Nov. 1967, 3649-3662.

167. Hamm, J. M., and G. Tyras, "Further experimental study of plasma sheath effects on antennas," Radio Science, 1, 11, Nov. 1966, 1263-1271.

168. Harp, R. S., "The behavior of the resonance probe in a plasma," Appl. Phys. Letters, 4, 11, Nov. 1964, 186-188.

169. Harp, R. S., and F. W. Crawford, "Characteristics of the plasma resonance probe," J. Appl. Phys., 35, 12, Dec. 1964, 3436-3446.

170. Harris, J. H., "Radiation through cylindrical plasma sheaths," J. Res. NBS, 67D, 6, Dec. 1963, 717-733.

171. Harris, J. H., "Electromagnetic radiation-pattern effects of dielectric layers," Can. J. Phys., 45, 9, Sept. 1967, 3119-3128.

172. Harris, J. H., A. T. Villensuve, and L. A. Broca, "Radiation patterns from plasma enclosed cylindrical hypersonic vehicles," J. Res. NBS, 69D, 10, Oct. 1965, 1335-1343.

173. Harrison, Jr., C. W., "Physical limitations on the measurements of transient fields in air and in dissipative media using electric and magnetic probes," IEEE Trans., AP-12, 5, Sept. 1964, 530-533.

174. Harrison, Jr., C. W., and D. H. Denton, Jr., "Impedance of a dipole in an ionized medium, I and II," Sandia Corp., Technical Memoranda, 1959.

175. Harrison, Jr., C. W., and C. D. Taylor, "Transmission and reception properties of an equatorial slot antenna on a reentry sphere," Radio Science, 2, 3, March 1967, 337-350.

176. Harvey, C. C., "Results from the UK-2 satellite (VII-5)," Annales D'Astrophysique, 28, 1, Jan. 1965, 248-254.

177. Hasserjian, G., "Fields of a curved plasma layer excited by a slot," IEEE Trans., AP-13, 3, May 1965, 389-395.

178. Haycock, O. C., and K. D. Baker, "Measuring Antenna Impedance in the Ionosphere," Electronics, 34, 2, Jan. 1961, 88-92.

179. Haycock, O. C., and K. D. Baker, "New Ionosphere Measurement Technique: Plasma Frequency Probe," Electronics, 35, 48, Nov. 1962, 81-83.

180. Haycock, O. C., K. D. Baker and J. C. Ulwick, "Experiences with the impedance probe on satellites," Proc. IEEE, 52, 9, Sept. 1964, 1029-1033.

181. Haycock, O. C., J. I. Swigart and D. J. Baker, "Electron Densities of the Ionosphere Utilizing High-Altitude Rockets," IRE Trans., AP-7, 4, Oct. 1959, 414-418.

182. Hazama, K., T. Shiozawa and I. Kawano, "Effect of a moving dielectric half-space on the radiation from a line source," Radio Science, 4, 5, May 1969, 483-488.

183. Heikkila, W. J., "Measurement of impedance in the ionosphere," in Electromagnetics and Antennas, ed. P. E. Mayes, University of Illinois, Feb. 1967, 540-563.

184. Heikkila, W. J., N. Eaker, J. A. Fejer, K. R. Tipple, J. Hugill, D. E. Schneible and W. Calvert, "Comparison of several probe techniques for ionospheric electron concentration measurements," J. Geoph. Res., 73, 11, June 1968, 3511-3535.

185. Heikkila, W. J., J. A. Fejer, J. Hugill and W. Calvert, "Comparison of Ionospheric Probe Techniques," Space Research VII, 1, (North-Holland Publishing Company, Amsterdam), 1966, 395-405.

186. Herman, J. R., "A Method for Determining D-Region Electron-Density Profiles Utilizing a Capacitive Impedance Rocket Probe," J. Geoph. Res., 69, 11, June 1964, 2329-2336.

187. Herman, J. R., "The Impedance of a Rocket-Borne Capacitive Ionospheric Probe," J. Geoph. Res., 69, 15, Aug. 1969, 3299-3300.

188. Hessel, A., and J. Shmoys, "Excitation of plasma waves in a homogeneous isotropic plasma by a dipole," Proc. Symp. on Electromagnetics and Fluid Dynamics of Gaseous Plasma, Polytechnic Press, Brooklyn, N. Y., 1962, 173-184.

189. Hirsch, E. H., "Plasma probes and the Langmuir paradox," Int. J. Elec., 19, 6, June 1965, 537-548.

190. Ho, B., and K.-M. Chen, "Electroacoustic resonance in plasma layer surrounding a metallic cylinder," Proc. IEEE, 57, 9, Sept. 1968, 1600-1602.

191. Hodara, H., "Radiation pattern of a slit in a ground plane covered by a plasma layer," Air Force Cambridge Research Lab., AFCRL-62-958, Dec. 1962.

192. Hodara, H., "Radiation from a gyro-plasma sheathed aperture," IEEE Trans., AP-11, 1, Jan. 1963, 2-12.

193. Hodara, H., and G. I. Cohn, "Radiation from a gyro-plasma coated magnetic line source," IRE Trans., AP-10, 5, Sept. 1962, 581-593.

194. Hoo, K. M. S., "Radiation from an insulated monopole partially immersed in an inhomogeneous plasma," Int. Symp. on Ant. & Prop., Ann Arbor, Michigan, Oct. 1967.

195. Hugill, J., "The Measurements of Random Radio Frequency Fields by the Use of Short Electric and Magnetic Dipoles," Planet. Space Sci., 8, 1, Jan. 1961, 68-70.

196. Hugill, J., "Some measurements of aerial impedance in the ionosphere," Annales D'Astrophysique, 28, 1, Jan. 1965, 255-262.

197. Huguenin, G. R., A. E. Lilly, W. H. McDonough and M. D. Papageannis, "Measurements of radio noise at 0.700 Mc and 2.200 Mc from high-altitude rocket probe," Planet. Space Sci., 12, 12, Dec. 1964, 1157-1167.

198. Hurd, R. A., "A note on the field of a dipole in a uniaxial medium," Can. J. Phys., 43, 4, April 1965, 684-688.

199. Hurd, R. A., "The admittance of a linear antenna in a uniaxial medium," Can. J. Phys., 43, 12, Dec. 1965, 2276-2308.

200. Hyatt, J. S., "Transmission line parameter measurements--standing wave impedance probe," University of Utah, Salt Lake City, Sci. Rept. No. 9, Aug. 1967.

201. Ichimiya, T., K. Takayama and Y. Aono, "A probe for measuring ion density in the ionosphere," Space Research I (North-Holland Publishing Company, Amsterdam), 1960, 397-416.

202. Iizuka, K., "An experimental study of the insulated dipole antenna immersed in a conducting medium," IRE Trans., AP-11, 5, Sept. 1963, 518-532.

203. Iizuka, K., "Technique of fabricating inhomogeneous medium and the behavior of a dipole in such a medium," Proc. IEE (London), 114, 5, May 1967, 595-603.

204. Iizuka, K., "Method of obtaining the impedance of an antenna in a dissipative medium from that of air," Proc. IEE (London), 115, 9, Sept. 1968, 1240-1244.

205. Iizuka, K., and R. W. P. King, "The dipole antenna immersed in a homogeneous conducting medium," IRE Trans., AP-10, 4, July 1962, 384-392.

206. Iizuka, K., and R. W. P. King, "An experimental study of the half-wave dipole antenna immersed in a stratified conducting medium," IEEE Trans., AP-10, 4, July 1962, 393-399.

207. Iizuka, K., and R. W. P. King, "The dipole antenna as a probe for determining the electric properties of a stratified medium," IRE Trans., AP-10, 6, Nov. 1962, 783-784.

208. Ionov, N. I., and A. Ya. Tontegode, "Plasma Probe Characteristics Obtained with Various Types of Probes in Gas-Discharge Mercury Cesium Plasmas," Sov. Phys.-Tech. Phys., 9, 2, Aug. 1964, 279-283.

209. Iyer, H. M., and V. W. Punton, "A computer program for plotting wavefronts and rays from a point source in dispersive mediums," J. Geophys. Res., 68, 11, June 1963, 3473-3482.

210. Jacavanco, D. J., "Electromagnetic properties of a plasma covered antenna," J. Res. NBS, 69D, 7, July 1965, 965-967.

211. Jacavanco, D. J., and R. S. Elliot, "An experimental investigation of antenna pattern distortion due to plasma layer," IRE Trans., AP-12, 3, May 1964, 365-366.

212. Jackson, J. E., and J. A. Kane, "Breakdown and detuning of transmitting antennas in the ionosphere," Naval Res. Lab. Report No. 5345, 1959.

213. Jackson, J. E., and J. A. Kane, "Measurement of ionosphere electron-density using an RF probe technique," J. Geophys. Res., 64, 8, Aug. 1959, 1074-1075.

214. Jackson, J. E., and J. A. Kane, "Performance of an RF impedance probe in the ionosphere," J. Geophys. Res., 65, 7, July 1960, 2209-2210.

215. Jackson, J. E., and A. D. Pickar, "Performance of a rocket-borne 7.75 Mc/s transmitting antenna in the ionosphere," Naval Res. Lab. Report No. 4940, 1957.

216. Jassby, D. L., "Experimental impedance of a quarterwave monopole in an isotropic plasma," IEEE Trans., AP-16, 2, March 1968. 282-283.

217. Jastrew, R., and C. A. Pearse, "Atmospheric drag on the satellite," J. Geophys. Res., 62, 3, March 1957, 413-423.

218. Johnson, G. L., "The distribution of current on an infinite antenna in an anisotropic incompressible plasma," Ph. D. Dissertation, Oklahoma State University, Stillwater, Okla., July 1966.

219. Johnson, G. L., and K. R. Cook, "Current distribution for a cylindrical dipole in a homogeneous anisotropic ionosphere," IEEE Trans., AP-13, 3, May 1965, 471-472.

220. Johnson, G. L., and K. R. Cook, "Current distribution for a cylindrical dipole in an inhomogeneous anisotropic ionosphere," IEEE Trans., AP-13, 6, Nov. 1965, 971-973.

221. Jordan, A. K., and G. Pinski, "The effects of electron collisions on electric dipole radiation through a conical plasma sheath," IEEE Trans., AP-16, 1, Jan. 1968, 118-123.

222. Judson, H., and K.-M. Chen, "Measurement of antenna current distribution in a hot plasma," Proc. IEEE, 57, 4, April 1968, 753-754.

223. Judson, H., K.-M. Chen and R. Lundquist, "Measurement of the current distribution on monopoles in a large volume of hot plasma," Elec. Letters, 4, 14, July 1968, 289-291.

224. Kaiser, T. R., "The admittance of a short dipole antenna in a magnetoionic environment," Planet. Space Sci., 9, Oct. 1962, 639-657.

225. Kane, J. A., J. E. Jackson and H. A. Whale, "The simultaneous measurement of ionospheric electron densities by CW propagation and RF probe techniques," NASA Tech. Note, D-1098, 1962.

226. Kane, J. A., J. E. Jackson and H. A. Whale, "RF impedance probe measurements of ionospheric electron densities," J. Res. NBS, 66D, 6, Nov. 1962, 641-648.

227. Karas, N. V., and J. D. Antonucci, "An experimental study of simulated plasma-covered slots on cylinders and cones," IEEE Trans., AP-16, 2, March 1968, 242-246.

228. Katzin, J. C., and M. Katzin, "The impedance of a cylindrical dipole in a homogeneous anisotropic ionosphere," Electromagnetic Research Corp., College Park, Md., Report No. 2NAS585-2, Sept. 1961.

229. Katzin, M., "Radiation from an electric dipole into an ionized sheath," Electromagnetic Research Corp., College Park, Md., Report 60175-7, Dec. 1957.

230. Katzin, M., "Radiation and impedance of a slotted sphere antenna surrounded by a strongly ionized sheath," Electromagnetic Research Corp., College Park, Md., Report 60301-4, March 1958.

231. Katzin, M., J. W. Marinin and B. Y. C. Koo., "Effects of re-entry plasma sheath on antenna characteristics," Electromagnetic Research Corp., College Park, Md., Report 61527-3, June 1960.

232. Kaufman, I., and W. H. Steier, "A plasma antenna and wave filter," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 1207-1221.

233. Kazyulin, A. F., "Far-zone radiation field in a homogeneous anisotropic lossless medium," Radio Eng. Elec. Phys., 9, 10, Oct. 1964, 1571-1573.

234. Kihara, T., O. Aono and R. Sugihara, "Energy loss by a sequence of fact charges in a plasma," J. Phys. Soc., Japan, 19, 6, June 1964, 986-989.

235. King, R. W. P., "Theory of terminated insulated antenna in a conducting medium," IEEE Trans., AP-12, 3, May 1964, 305-318.

236. King, R. W. P., and C. W. Harrison, Jr., "Half-wave cylindrical antenna in a dissipative medium: current and impedance," J. Res. NBS, 64D, 4, April 1960, 365-380.

237. King, R. W. P., C. W. Harrison, Jr., and D. H. Denton, "The electrically short antenna as a probe for measuring free electron densities and collision frequencies in an ionized medium," J. Res. NBS, 65D, 4, July-August 1961, 371-384.

238. King, R. W. P., C. W. Harrison, Jr., and D. G. Tingley, "The admittance of bare circular loop antennas in a dissipative medium," IEEE Trans., AP-12, 7, July 1964, 434-438.

239. King, R. W. P., and K. Iizuka, "The complete electromagnetic field of dipoles in dissipative media," Trans. IRE, AP-11, 3, May 1963, 275-285.

240. King, R. W. P., S. S. Sandler and K. Iizuka, "Coupled dipoles in a dissipative medium," IEEE Trans., AP-14, 3, May 1966, 275-282.

241. King, R. W. P., S. S. Sandler, and T. T. Wu, "Cylindrical antennas as probes for determining the properties of media," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

242. Knop, C. M., "The radiation fields from a circumferential slot on a metal cylinder coated with a lossy dielectric," IRE Trans., AP-9, 6, Nov. 1961, 535-545.

243. Knop., C. M., and G. I. Cohn, "Radiation from an aperture in a coated plane," J. Res. NBS, 68D, 4, April 1964, 363-378.

244. Kogelnick, H., "The radiation resistance of an elementary dipole in anisotropic plasmas," 4th International Conf. on Ionization Phenomena in Gases, North-Holland Publishing Co., Amsterdam, The Netherlands, 1960.

245. Kogelnick, H., "On electromagnetic radiation in magnetoionic media," J. Res. NBS, 64D, Sept.-Oct. 1960, 515-523.

246. Kogelnick, H., and H. Motz, "Electromagnetic radiation from sources embedded in an infinite anisotropic medium and the significance of the Poynting vector," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 477-493.

247. Kononov, B. P., A. A. Pukhadze, and G. V. Soledukhov, "Electric field of a radiator in a plasma in an external magnetic field," Sov. Phys.-Tech. Phys., 6, 5, Nov. 1961, 405-410.

248. Kostelnicek,R. J., "The admittance and resonance probe characteristics of a spherical plasma probe," Department of Electrical Engineering, University of Illinois, Urbana, Illinois, Aeronomy Report No. 8, Nov. 1965.

249. Kraichman, M. B., "Impedance of a circular loop in an infinite conducting medium," J. Res. NBS, 66D, 4, July-Aug. 1962, 499-503.

250. Kristal, R., and P. Shigume, "Antenna plasma interaction in a conical geometry," IEEE Trans., AP-15, 5, Sept. 1967, 710-712.

251. Kuehl, H. H., "Radiation from a gap-excited cylinder surrounded by a uniform plasma sheath," Univ. of Southern California, School of Eng., Report No. 71-202, June 1960.

252. Kuehl, H. H., "Electromagnetic radiation from an electric dipole in an anisotropic cold plasma," Phys. Fluids, 5, 9, Sept. 1962, 1095-1103.

253. Kuehl, H. H., "Excitation of waves in a warm plasma by current sources," Phys. Fluids, 6, 10, Oct. 1963, 1465-1469.

254. Kuehl, H. H., "The kinetic theory of waves in a warm plasma excited by a current source," J. Math. Phys., 43, 3, Sept. 1964, 218-226.

255. Kuehl, H. H., "Resistance of a short antenna in a warm plasma," Radio Science, 1, 8, Aug. 1966, 971-976.

256. Kuehl, H. H., "Computation of the resistance of a short dipole antenna in a warm plasma," Radio Science, 2, 1, Jan. 1967, 73-76.

257. Langlier, R. M., "Radiation from a vertical dipole in a warm plasma above a conducting plane," Ph. D. Thesis, Purdue University, Lafayette, Ind., 1964.

258. Langlier, R. M., and F. V. Schultz, "Radiation from a vertical dipole in a warm plasma, - Parts I & II," IEEE Trans., AP-14, 2, March 1966, 207-219.

259. Larson, R. W., "Plasma imbedded antennas," Second Plasma Sheath Symposium, Boston, Mass., April 1962.

260. Larson, R. W., "A study of inhomogeneously sheathed spherical dipole in a compressible plasma," Willow Run Labs., University of Michigan, Ann Arbor, Michigan, Report No. 7000-25-T, Sept. 1966.

261. Lawson, J. D., "Guided surface waves and the radiation from charges moving in curved paths," Amer. J. Phys., 34, 7, July 1966, 601-605.

262. Lee, K. S. H., "Radiation from an oscillating source moving through a dissipative medium with particular reference to the complex Doppler effect," Radio Science, 3, 11, Nov. 1968, 1098-1104.

263. Lee, K. S. H., and C. H. Papas, "Antenna radiation in a moving dispersive medium," IEEE Trans., AP-13, 5, Sept. 1965, 799-804.

264. Lee, K. S. H., and C. H. Papas, "Radiation resistance and irreversible power of antennas in gyroelectric media," IEEE Trans., AP-13, 5, Sept. 1965, 834-835.

265. Lee, K. S. H., and C. H. Papas, "Irreversible power and radiation resistance of antennas in anisotropic ionized gases," J. Res. NBS, 69D, 10, Oct. 1965, 1313-1320.

266. Lee, K. S. H., and C. H. Papas, "A further explanation of the new theory of antenna radiation with particular reference to uniaxial media," Radio Science, 1, 9, Sept. 1966, 1020-1024.

267. Lee, K. S. H., and C. H. Papas, "On Walsh and Weil's defense of the conventional method," Radio Science, 1, 9, Sept. 1966, 1027-1028.

268. Lee, S. W., "Cylindrical antenna in uniaxial resonant plasmas," Radio Science, 4, 2, Feb. 1969, 179-189.

269. Lee, S. W., and Y. T. Lo, "Radiation resistance of an elliptical loop antenna with constant current in compressible plasma," Elec. Letters, 1, 5, July 1965, 132-133.

270. Lee, S. W., and Y. T. Lo, "Radiation in a moving anisotropic medium," Radio Science, 1, 3, March 1966, 313-324.

271. Lee, S. W., and Y. T. Lo, "Current distribution and input admittance of an infinite cylindrical antenna in anisotropic plasma," IEEE Trans., AP-15, 2, March 1967, 244-252.

272. Lee, S. W., and R. Mittra, "Transient radiation of an electric dipole in a uniaxially anisotropic plasma," Radio Science, 2, 8, Aug. 1967, 813-820.

273. Lewis, R. M., and W. Pressman, "Radiation and propagation of electromagnetic waves from moving sources," Radio Science, 1, 9, Sept. 1966, 1029-1040.

274. Liang, C. S., "Antenna in a waveguide partially-filled with plasma," University of Illinois, Ph. D. Dissertation, Feb. 1969.

275. Liemohn, H. B., "Radiation from electrons in magnetoplasma," J. Res. NBS, 69D, 5, May 1965, 741-766.

276. Lin, S. H., and K. K. Mei, "Numerical solution of dipole radiation in a compressible plasma," IEEE Trans., AP-16, 2, March 1968, 235-241.

277. Lo, Y. T., and S. W. Lee, "Current distribution and input admittance of a cylindrical antenna in anisotropic plasma," Elec. Letters, 2, 2, Feb. 1966, 72-73.

278. Lockwood, G. E. K., "Excitation of cyclotron spikes in the ionospheric plasma," Can. J. Phys., 43, 2, Feb. 1965, 291-297.

279. Lustig, C. D., and D. T. Hayes, "Observation of electroacoustic resonance in a reentry sheath," Proc. IEEE, 58, 5, May 1969, 800-802.

280. Lytle, R. J., and F. V. Schultz, "Linear antennas in plasma media," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

281. MacKenzie, E. C., and J. Sayers, "A radio frequency electron density probe for rocket investigation of the ionosphere," Planet. Space Sci., 14, 8, Aug. 1966, 731-740.

282. Majumdar, S. K., "Radiation by charged particles passing through an electron plasma in an external magnetic field," Proc. Phys. Soc. (London), 77, 6, June 1961, 1109-1120.

283. de Marchin, P. D., and G. Tyras, "Radiation from an infinite axial slot on a circular clad with magnetoplasma," J. Res. NBS, 69D, 4, April 1965, 529-538.

284. Marini, J. W., "Radiation and admittance of an insulated slotted-sphere antenna surrounded by a strongly ionized plasma sheet," J. Res. NBS, 64D, 5, Sept.-Oct. 1960, 525-532.

285. Marini, J. W., "Radiation and admittance of a slotted-sphere antenna surrounded by a plasma sheath," Planet. Space Sci., 6, 1, Jan. 1961, 116-122.

286. Marini, J. W., B. Y. C. Koo, M. Katzin, "Radiation and impedance of antennas surrounded by an ionized sheath," Electromagnetic Research Corporation, Report 60301-6, Aug. 1958.

287. Mayhan, J. W., R. Caldecott and P. Bohley, "Antenna impedance in a re-entry environment," IEEE Trans., AP-16, 5, Sept. 1968 573-577.

288. McKenzie, J. F., "Effect of the motion of a strongly magnetized plasma on the emission of radiation by a finite dipole," J. Appl. Phys., 38, 13, Dec. 1968, 5249-5255.

289. Meecham, W. G., "Source and reflection problems in magnetoionic media," Phys. Fluids, 4, 12, Dec. 1961, 1517-1524.

290. Meltz, G., P. J. Freyheit and C. D. Lustig, "Admittance of a plasma-covered antenna," Radio Science, 2, 2, Feb. 1967, 203-224.

291. Meltz, V. J., and H. J. Schmitt, "Observations of the effect of magnetic fields on the radiation from plasma-covered antennas," IEEE Trans., AP-13, 1, Jan. 1965, 169-173.

292. Mentzoni, M. H., R. V. Row and J. Donohoe, "Microwave diagnostics of the plasma sheath produced by slot antenna breakdown," IEEE Trans., AP-16, 2, March 1968, 277-279.

293. Messiaen, A. M., and P. E. Vandenplas, "High-frequency dielectric resonance probe for the measurement of plasma densities," J. Appl. Phys., 37, 4, March 1966, 1718-1724.

294. Messiaen, M. M., and P. E. Vandenplas, "Theory and experiments of the enhanced radiation from a plasma-coated antenna," Elec. Letters, 3, 1, Jan. 1967, 26-27.

295. Meyer, P., "Impedance of a sphere in a magnetoplasma," IEEE Trans., AP-15, 2, March 1967, 331-332.

296. Midgley, J. E., and L. Davis, Jr., "Computation of the bounding surface of a dipole field in a plasma by a moment technique," J. Geophys. Res., 67, 2, Feb. 1962, 499-504.

297. Miller, E. K., "Surface current excitation on an inhomogeneously sheathed-immersed cylinder by electromagnetic and electrokinetic waves," Can. J. Phys., 45, 5, May 1967, 1925-1945.

298. Miller, E. K., "The admittance of the infinite cylindrical antenna in a lossy, isotropic, compressible plasma," University of Michigan, Ann Arbor, Michigan, Sci. Rept. No. 05627-10-S, 1967.

299. Miller, E. K., "The admittance of an infinite cylindrical antenna in a lossy, incompressible anisotropic plasma," Can. J. Phys., 45, 12, Dec. 1967, 4019-4038.

300. Miller, E. K., "The admittance of the cylindrical antenna immersed in a lossy, compressible plasma," IEEE Trans., AP-16, 1, Jan. 1968, 111-117.

301. Miller, E. K., "The admittance of an infinite cylindrical antenna in a lossy, compressible, anisotropic plasma," Can. J. Phys., 46, 9, May 1968, 1109-1118.

302. Miller, E. K., "Admittance of an inhomogeneously sheathed infinite cylindrical antenna immersed in an isotropic, compressible plasma," IEEE Trans., AP-16, 4, July 1968, 501-502.

303. Miller, E. K., "Characteristic waves on an infinite cylindrical antenna in a plasma medium," Radio Science, 3, 12, Dec. 1968, 1175-1178.

304. Miller, E. K., "Infinite cylindrical antenna in a uniaxial compressible plasma," Can. J. Phys., 46, 24, Dec. 1968, 2846-2849.

305. Miller, E. K., and A. Olte, "Excitation of surface currents on a plasma-immersed cylinder by electromagnetic and electrokinetic waves. I - The vacuum sheath," Radio Science, 1, 8, Aug. 1966, 977-993.

306. Miller, E. K., and A. Olte, "Excitation of surface currents on a plasma-immersed cylinder by electromagnetic and electrokinetic waves. II - The inhomogeneous sheath," Radio Science, 1, 12, Dec. 1966, 1425-1433.

307. Miller, E. K., and H. F. Schulte, Jr., "Antenna Admittance in an Ionospheric-Type Plasma," University of Michigan, Ann Arbor, Michigan, Sci. Rept. No. 05627-18-S, 1968.

308. Mittra, R., "Solution of Maxwell's equations in a magneto-ionic medium with sources,"Antenna Lab., University of Illinois, Sci. Rept. No. 4, Jan. 1962.

309. Mittra, R., "Antennas in anisotropic media," in Electromagnetics and Antennas, ed. P. E. Mayes, University of Illinois, Jan. 1964, 424-452.

310. Mittra, R., "Radiation resistance of antennas in anisotropic media," Elec. Letters, 1, 9, Nov. 1965, 258-259.

311. Mittra, R., and G. A. Deschamps, "Field solution for a dipole in an anisotropic medium," in Electromagnetic Theory and Antennas, ed. E. C. Jordan, Pergamon Press, 1963, 495-512.

312. Mittra, R., and G. L. Duff, "A systematic study of the radiation patterns of a dipole in magnetoplasma based on a classification of the associated dispersion surfaces," J. Res. NBS, 69D, 5, May 1965, 681-692.

313. Mittra, R., and G. L. Duff, "Input impedance of a uniform current loop in an anisotropic cold plasma," Elec. Letters, 1, 5, July 1965, 117-118.

314. Miyazaki, S., K. Hirao, Y. Aono, K. Takayama, H. Ikegami and T. Ichimiya, "Resonance probe--a new probe method for measuring electron density and electron temperature in the ionosphere," Rept. Ionos. Space Res., Japan, 14, 2, June 1960, 148-159.

315. Mlodnosky, R. F., and Garriott, "The V. L. F. admittance of a dipole in the lower ionosphere," Proc. Int. Conf. on the Ionosphere, Inst. Phys. & Physical Society, London, England, 1963, 484-491.

316. Molozzi, A. R., and J. R. Richardson, "The measured impedance of a dipole antenna in the ionosphere," Space Research VII, Vol. 1, (North-Holland Publishing Company, Amsterdam), 1966, 489-505.

317. Monroe, R. L., "Current distribution on a thin cylindrical antenna immersed in an isotropic compressible plasma," Can. J. Phys., 46, 8, April 1968, 1013-1017.

318. Motz, H., "On electromagnetic radiation from a magnetic dipole of arbitrary orientation embedded in a lossless magnetoionic medium," J. Res. NBS, 69D, 5, May 1965, 671-679.

319. Mushiake, Y., "Electromagnetic waves along an infinitely long and thin conducting wire in a magnetoionic medium," J. Res. NBS, 69D, 4, April 1965, 503-510.

320. Nagy, A. F., and A. Z. Faruque, "Ionospheric electron density and body potential measurements by a cylindrical Langmuir probe," J. Geophys. Res., 70, 19, Oct. 1965, 4847-4858.

321. Nguyen, D. T., "Input impedance of a short antenna in a warm plasma driven from a coaxial line," Elec. Letters, 5, 2, Jan. 1968, 33.

322. Nguyen, D. T., "Current waves on an infinite cylindrical antenna in a warm plasma," Elec. Letters, 4, 5, March 1968, 94-95.

323. Nguyen, D. T., "The infinite cylindrical antenna in a compressible plasma," Can. J. Phys., 46, 11, June 1968, 1311-1321.

324. Nguyen, D. T., "Linear antennas in a warm plasma driven from a coaxial air-filled transmission line," Elec. Letters, 4, 22, Nov. 1968, 475-477.

325. Nguyen, D. T., "Input admittance of an insulated antenna in a plasma medium," Elec. Letters, 4, 25, Dec. 1968, 561-563.

326. Nisbet, J. S., "Rocket measurements of electron density in the D-region during and after a solar eclipse," University of Illinois, Urbana, Illinois, Aeronomy rept. No. 1, Dec. 1963, 159-161.

327. Ohba, Y., "Radiation from a current filament clad by an anisotropic plasma sheath," Can. J. Phys., 41, 6, June 1963, 858-862.

328. Oliner, A. A., and T. Tamir, "Radiation from semi-infinite slot-excited plasma sheath configuration," Microwave Research Lab., Polytechnic Inst. of Brooklyn, Report No. 1029-62, 1962.

329. Olte, A., "The radiation pattern of an electric line current enclosed by an axially slotted plasma sheath," 3rd Symposium on Plasma Sheaths, Boston, Mass., Symp. Proc., Spartan & Books, Inc., Sept. 1965.

330. Omura, M., "Radiation pattern of a slit in a ground plane covered by a plasma layer," Air Force Cambridge Research Lab., Report No. AFCRL-62-958, Dec. 1962.

331. Osborne, F. J. Fitz, "A multiple-probe microwave system for plasma studies," Can. J. Phys., 40, 11, Nov. 1962, 1620-1625.

332. Osborne, F. J. F., F. H. C. Smith, R. E. Barrington and W. E. Mather, "Plasma-induced interference in satellite V. L. F. receivers," Can. J. Phys., 45, 1, Jan. 1967, 47-56.

333. Ott, E., and J. Shmoys, "Transient radiation in a plane stratified dispersive medium. I. Half-space configuration," Can. J. Phys., 46, 9, May 1968, 1059-1071.

334. Owyang, G. H., and S. R. Seshadri, "Radiation conductance of a slot covered with anisotropic plasma," Proc. IEE (London), 113, 12, Dec. 1966, 1920-1926.

335. Oya, H., "Effect of Resonance on the Admittance of an RF Probe Surrounded by an Ion Sheath," Rep. Ionos. Space Res., Japan, 19, 3, Sept. 1965, 243-271.

336. Oya, H., and T. Obayashi, "Measurements of Ionospheric Electron Density by a Gyro-Plasma Probe: A Rocket Experiment by a New Impedance Probe," Rep. Ionos. Space Res., Japan, 20, 2, June 1966, 199-213.

337. Oya, H., and T. Obayashi, "Measurements of ionosphere electron density by gyro-plasma probe," Space Research VII, Vol. 1, (North-Holland Publishing Company, Amsterdam), 1966, 480-488.

338. Oya, H., and T. Obayashi, "Rocket measurements of the ionospheric plasma by gyro-plasma probe," Rep. Ionos. Space Res., Japan, 21, 2, June 1967, 1-8.

340. Padhi, T., and S. R. Seshadri, "Symmetry properties of the dyadic Green's function for a magnetoionic medium," Elec. Letters, 3, 11, Nov. 1967, 521-523.

341. Padhi, P., and S. R. Seshadri, "Radiated and reactive powers in a magnetoionic medium," Proc. IEEE, 57, 6, June 1968, 1089-1090.

342. Pavkovich, J. M., "Numerical calculations related to the RF properties of the plasma sheath," Aerospace Res. Lab., Office of Aerospace Research, U. S. Air Force, Report No. ARL 64017, Jan. 1964.

343. Pavlov, P. P., "The electromagnetic field and the distribution of current along an infinitely long uninsulated wire in a conducting medium," Radio Eng. Elec. Phys., 6, 7, July 1961, 985-992.

344. Pavlov, P. P., "Electromagnetic field and distribution of current along an infinitely long insulated wire in a conducting medium," Radio Eng. Elec. Phys., 6, 8, Aug. 1961, 1148-1161.

345. Pavlov, P. P., "Electromagnetic field and input resistance of a loop with infinitely long cylindrical ferrite core placed in a conducting medium," Radio Eng. Elec. Phys., 7, 3, March 1962, 411-421.

346. Pavlov, P. P., "Electric field and input impedance of a loop with an infinitely long cylindrical ferrite core encased in a dielectric sheath and immersed in a conducting medium," Radio Eng. Elec. Phys., 7, 8, Aug. 1962, 1245-1254.

347. Pavlov, P. P., "Insulated loop antenna with a spherical ferrite core in a conducting medium," Radio Eng. Elec. Phys., 8, 9, Sept. 1963, 1461-1466.

348. de Pazzis, O., "Shot noise in antennas," Radio Science, 4, 1, Jan. 1969, 91-92.

349. Peale, S. J., "Plasma sheaths and their effects on antennas," Cornell University, CRSR Report No. 116, May 1962.

350. Pfister, W., J. C. Ulwick and R. P. Vancour, "Some results of direct probing in the ionosphere," J. Geophys. Res., 66, 4, April 1961, 1293-1297.

351. Pound, E. F., and D. A. Burt, "Satellite Plasma Frequency Probe for High Spatial Resolution Electron Density Measurement," University of Utah, Salt Lake City, Utah, Sci. Rept. No. 11, Aug. 1967.

352. Pridmore-Brown, D. C., "The radiation field of a magnetic dipole antenna in a conical sheath," M. I. T., J. Math. & Phys., 43, 1964, 199-217.

353. Pridmore-Brown, D. C., "Electric dipole radiation through a finite conical plasma sheath," IEEE Trans., AP-14, 4, July 1966, 428-433.

354. Pyati, V. P., "Determination of capacitance in anisotropic media," IEEE Trans., AP-14, 6, Nov. 1966, 803.

355. Pyati, V. P., and H. Weil, "Capacitance of biconical antennas in magnetoionic media: elliptic cone capacitance," J. Res. NBS, 69D, 2, Feb. 1965, 291-298.

356. Raemer, H. R., "Radiation from linear electric or magnetic antennas surrounded by a spherical plasma shell," IRE Trans., AP-10, 1, Jan. 1962, 69-78.

367. Rama Rao, B., "Antenna with an anisotropic sheath inside a parallel-plate waveguide--theoretical and experimental studies," Proc. IEE (London), 112, 9, Sept. 1965, 1669-1682.

368. Rama Rao, B., and T. T. Wu, "On the applicability of image theory in anisotropic media," IEEE Trans., AP-13, 5, Sept. 1965, 814-815.

369. Richards, P. I., "Transients in conducting media," IRE Trans., AP-6, 2, April 1958, 178-182.

370. Robinson, L. C., "Modulated Dipole Plasma Probes," J. Appl. Phys., 35, 10, Oct. 1964, 2843-2845.

371. Row, R. V., "Radiation efficiency of electric and magnetic dipole antennas surrounded by a small spherical shell of lossy dielectric," IEEE Trans., AP-12, 5, Sept. 1964, 646-647.

372. Row, R. V., "Insulated loop antenna in a conducting spherical shell," IEEE Trans., AP-13, 2, March 1965, 216-218.

373. Rusch, W. V. T., "Propagation constants of surface waves on a plasma-clad cylinder," IRE Trans., AP-10, 2, March 1962, 213-214.

374. Rusch, W. V. T., "Radiation from a plasma-clad axially-slotted cylinder," J. Res. NBS, 67D, 2, March 1963, 203-214.

375. Rusch, W. V. T., "Radiation from an axially slotted cylinder with a radially inhomogeneous plasma coating," Can. J. Phys., 42, 1, Jan. 1964, 26-41.

376. Samaddar, S. N., "Wave propagation in an anisotropic column with ring source excitation, Part I," J. Elec. and Control, 16, 3, March 1964, 273-303.

377. Samaddar, S. N., "Excitation of electro-acoustical waves in a two-fluid compressible plasma," J. Elec. and Control, 17, 3, Sept. 1964, 267-272.

378. Samaddar, S. N., "An approach to improve re-entry communications by suitable orientations of antenna and static magnetic field," J. Res. NBS, 69D, 6, June 1965, 851-863.

379. Samaddar, S. N., "Radiation from a vertical magnetic dipole in inhomogeneous stratified media above a horizontal conducting plane," Int. J. Elect., 19, 3, Sept. 1965, 279-299.

380. Samaddar, S. N., "Radiation from a dielectric coated cylindrical core loop antenna surrounded by a lossy plasma sheath," Int. J. Elect., 20, 1, Jan. 1965, 65-80.

381. Samaddar, S. N., "Mathematical analysis of the radiation from a magnetic line source on a cylindrically capped wedge covered by a plasma sheath," Appl. Sci. Res., 16, 2, 1966, 81-101.

382. Samaddar, S. N., and M. Yildiz, "Excitation of coupled electro-acoustical waves by a ring source in a compressible plasma," Can. J. Phys., 42, 4, April 1964, 638-656.

383. Savic, P., F. T. Stock and T. J. Goldman, "Performance of an electrodeless conductivity probe in anisotropic plasma," Can. J. Phys., 46, 23, Dec. 1968, 2595-2600.

384. Sayers, J., "A radio-frequency electron density probe for a wide range of ionospheric measurements," University of Illinois, Urbana, Illinois, Aeronomy Report No. 1, Dec. 1963, 52-56.

385. Schmitt, H., "Plasma resonances excited by antennas," Proc. IEEE, 52, 5, May 1964, 622-623.

386. Schultz, F. V., and R. W. Groff, "The Radiation Produced by An Arbitrarily Oriented Dipole in an Infinite Homogeneous Anisotropic Plasma," Purdue University, Tech. Report No. EE66-22, 1966.

387. Scott, L. D., and Rama Rao, B., "A short cylindrical antenna as a diagnostic probe for measuring collision frequencies in a collision-dominated plasma," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

388. Sengupta, D. L., "Radiation field produced by an infinite slot in an infinite cylinder surrounded by a homogeneous plasma sheath," Proc. IEE (London) 111, 5, May 1964, 950-958.

389. Seshadri, S. R., "Excitation of plasma waves in an unbounded homogeneous plasma by a line source," IEEE Trans., MTT-11, 1, Jan. 1963, 39-50.

390. Seshadri, S. R., "Radiation from an electromagnetic source in a half-space of compressible plasma-surface waves," IEEE Trans., AP-12, 3, May 1964, 340-348.

391. Seshadri, S. R., "Radiation from elementary fluid-mechanical sources in an unbounded electron plasma," Can. J. Phys., 42, 8, Aug. 1964, 1573-1586.

392. Seshadri, S. R., "Radiation from electromagnetic sources in a plasma," IEEE Trans., AP-13, 1, Jan. 1965, 79-88.

393. Seshadri, S. R., "Radiation propagating transverse to the external magnetic field from an electromagnetic source in an unbounded plasma," IEEE Trans., AP-13, 1, Jan. 1965, 106-115.

394. Seshadri, S. R., "Radiation from an electric dipole in a plasma column," Proc. IEE (London), 112, 2, Feb. 1965, 249-253.

395. Seshadri, S. R., "Guided waves on a dielectric-coated cylinder immersed in a plasma," Elec. Letters, 1, 1, March 1965, 19.

396. Seshadri, S. R., "Propagation coefficient for the current distribution along a cylindrical antenna immersed in a warm plasma," Proc. IEE (London), 112, 5, May 1965, 877-882.

397. Seshadri, S. R., "Radiation in a warm plasma from an electric dipole with a cylindrical column of insulation," IEEE Trans., AP-13, 4, July 1965, 613-629.

398. Seshadri, S. R., "Radiation from an electric dipole in an infinite column of warm plasma," Proc. IEE (London), 112, 7, July 1965, 1279-1290.

399. Seshadri, S. R., "Guided waves on perfectly conducting infinite cylinder in a magnetoionic medium," Proc. IEE (London), 112, 8, Aug. 1965, 1497-1500.

400. Seshadri, S. R., "Infinite cylindrical antenna immersed in a warm plasma," IEEE Trans., AP-13, 5, Sept. 1965, 789-799.

401. Seshadri, S. R., "Radiation resistance of a linear current filament in a simple anisotropic medium," IEEE Trans., AP-13, 5, Sept. 1965, 819-820.

402. Seshadri, S. R., "Radiation resistance of elementary electric current sources in a magnetoionic medium," Proc. IEE (London), 112, 10, Oct. 1965, 1856-1868.

403. Seshadri, S. R., "Radiation from a current strip in a uniaxially anisotropic plasma medium," Can. J. Phys, 44, 1, Jan. 1966, 207-217.

404. Seshadri, S. R., "Radiation from an electric dipole in an axially magnetized plasma column," Elec. Letters, 2, 1, Jan. 1966, 30-33.

405. Seshadri, S. R., "Effect of insulation on the radiation resistance of an electric dipole in a simple anisotropic medium," Proc. IEE (London), 113, 4, April 1966, 593-600.

406. Seshadri, S. R., "Singularity in the radiation resistance of a point electric dipole in a magnetoionic medium," Elec. Letters, 2, 7, July 1966, 263-265.

407. Seshadri, S. R., "Radiation from an electric dipole in a magnetoplasma," Can. J. Phys., 44, 12, Dec. 1966, 3053-3067.

408. Seshadri, S. R., "Elimination of the singularity in the power radiated by a point electric dipole in an unbounded magnetoplasma," Elec. Letters, 2, 9, Sept. 1966, 336-338.

409. Seshadri, S. R., "Reciprocity and time-reversal in magnetoionic media," Proc. IEEE 55,6, June 1967, 1123-1125.

410. Seshadri, S. R., "Radiation resistance of an electric dipole in a magnetoplasma," Can. J. Phys., 46, 2, Jan. 1968, 283-285.

411. Seshadri, S. R., "Radiation resistance of an insulated current filament in a magnetoplasma," Can. J. Phys., 46, 2, Jan. 1968, 309-311.

412. Seshadri, S. R., "Input admittance of a cylindrical antenna in a magnetoionic medium," J. Appl. Phys., 39, 5, April 1968, 2407-2412.

413. Seshadri, S. R., "Admittance of an annular slot in a magnetoplasma," Can. J. Phys., 46, 12, June 1968, 1473-1489.

414. Seshadri, S. R., and K. L. Bhatnagar, "Effect of ion sheath on radiation in a magnetoionic medium, Part I," Can. J. Phys., 44, 7, July 1966, 1401-1418.

415. Seshadri, S. R., and K. L. Bhatnagar, "Effect of ion sheath on radiation in a magnetoionic medium, Part II," Can. J. Phys., 45, 1, Jan. 1967, 279-299.

416. Seshadri, S. R., and A. Hessel, "Radiation from a source near a plane interface between an isotropic and a gyrotropic dielectric," Can. J. Phys., 42, 11, Nov. 1964, 2153-2172.

417. Seshadri, S. R., G. L. Johnson, and K. R. Cook, "Comment on 'current distribution for a cylindrical dipole in an homogeneous anisotropic ionosphere,' " IEEE Trans., AP-13, 6, Nov. 1965, 971-973.

418. Seshadri, S. R., and W. F. Pickard, "Surface waves on an anisotropic plasma sheath," IEEE Trans., MTT-12, 9, Sept. 1964, 529-541.

419. Seshadri, S. R., and H. S. Tuan, "Radiation from uniformly moving charge in an anisotropic, two component plasma," J. Res. NBS, 69D, 5, May 1965, 767-783.

420. Seshadri, S. R., and H. S. Tuan, "Radiation resistance of a circular current filament in a magnetoionic medium," Proc. IEE (London), 112, 12, Dec. 1965, 2192-2198.

421. Seshadri, S. R., and G. L. Yip, "Radiation from an electric dipole in an axially magnetized plasma column," Elec. Letters, 2, 1, Jan. 1966, 30-33.

422. Seshadri, S. R., and G. L. Yip, "Effect of static magnetic field on radiation through a magnetic plasma sheath," Can. J. Phys., 44, 9, Sept. 1966, 1941-1964.

423. Shapiro, I., I. Maron and L. Kraft, Jr., "Experimental study of charge drag on orbiting dipoles," J. Geophys. Res., 68, 7, April 1963, 1845-1850.

424. Shkarofsky, I. P., "Higher order cyclotron harmonic resonances and their observation in the laboratory and in the ionosphere," J. Geophys. Res., 73, 15, Aug. 1968, 4859-4867.

425. Shore, R., and G. Meltz, "Anisotropic plasma-covered magnetic line source," IRE Trans., AP-10, 1, Jan. 1962, 78-82.

426. Sivaprasad, R, "An asymptotic solution of dipoles in a conducting medium," IEEE Trans., AP-11, 2, March 1963, 133-142.

427. Smith, T. M., and K. E. Golden, "Radiation patterns of a slot covered by a simulated plasma sheet," IEEE Trans., AP-13, 2, March 1965, 285-288.

428. Smith, T. M., and K. E. Golden, "Radiation patterns from a slotted cylinder surrounded by a plasma sheath," IEEE Trans., AP-13, 5, Sept. 1965, 775-780.

429. Smy, P. R., "Electrical impedance of electrodes immersed in moving plasma," Can. J. Phys., 41, 8, Aug. 1963, 1346-1358.

430. Snyder, D., and R. Mittra, "Experimental study of the impedance of a short dipole in a plasma for parallel and perpendicular orientations with respect to the D. C. magnetic field," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

431. Snyder, M. A., and H. Weitzner, "VLF electromagnetic radiation in a magnetoionic medium," Radio Science, 3, 9, Sept. 1968, 943-953.

432. Staras, H., "The impedance of an electric dipole in a magnetoionic medium," IEEE Trans., AP-12, 6, Nov. 1964, 695-702.

433. Staras, H., "Comment on 'Radiation resistance of a linear current filament in a simple anisotropic medium,'" IEEE Trans., AP-14, 3, May 1966, 400.

434. Staras, H., "The 'Infinity Catastrophe' associated with radiation in magnetoionic media," Radio Science, 1, 9, Sept. 1966, 1013-1019.

435. Stewart, G. E., "Laboratory simulation of reentry plasma sheath," IEEE Trans., AP-15, 6, Nov. 1967, 831-832.

436. Stewart, G. E., and P. R. Caron, "Radiation from a line source in a ground plane covered by a warm plasma slab," IEEE Trans., AP-13, 4, July 1965, 600-611.

437. Stone, R. G., J. K. Alexander and R. R. Weber, "Measurement of antenna impedance in the ionosphere - II. Observing frequency greater than the electron gyrofrequency," Planet. Space Sci., 14, 10, Oct. 1966, 1007-1016.

438. Stone, R. G., J. K. Alexander and R. R. Weber, "Magnetic field effects on antenna reactance measurements at frequencies well above the plasma frequency," Planet. Space Sci., 14, 11, Nov. 1966, 1227-1231.

439. Stone, R. G., R. R. Weber and J. K. Alexander, "Measurement of antenna impedance in the ionosphere - I. Observing frequency below the electron gyrofrequency," Planet. Space Sci., 14, 7, July 1966, 631-639.

440. Sturrock, P. A., "Dipole resonances in a homogeneous plasma in a magnetic field," Phys. Fluids, 8, 1, Jan. 1965, 88-96.

441. Sugihara, R., "Harmonic structure of the radiation from a charge moving through a magnetoplasma," J. Phys. Soc., Japan, 18, 7, July 1963, 1062-1065.

442. Sugihara, R. and Y. Itikawa, "Energy losses by a sequence of fast charges and by a gyrating charge in a magnetoplasma," J. Phys. Soc., Japan, 20, 4, April 1965, 591-597.

443. Swift, C. T., "Radiation patterns of slotted-cylinder antenna in the presence of an inhomogeneous lossy plasma," IEEE Trans., AP-12, 6, Nov. 1964, 728-738.

444. Swift, C. T., "The input admittance of a rectangular aperture covered with an inhomogeneous, lossy dielectric slab," Langley Research Center, Hampton, Virginia, NASA TN D-4197, 1967.

445. Tai, C. T., "On the transposed radiating systems in an anisotropic medium," IRE Trans., AP-9, 5, Nov. 1961, 502.

446. Takayama, T., H. Ikegami and S. Miyazaki, "Plasma resonances in a radio-frequency probe," Phys. Rev. Letters, 5, 6, Sept. 1960, 238-240.

447. Tamir, T., and A. A. Oliner, "The influence of complex waves on the radiation field of a slot-excited plasma layer," IRE Trans., AP-10, 1, Jan. 1962, 55-65.

448. Tanenbaum, B. S., "Fields produced by a current source in a partly ionized gas," J. Appl. Phys., 36, 4, April 1965, 1288-1290.

449. Taylor, W. C., "Effects of plasmas in near fields of aperture antennas," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

450. Taylor, W. C., and W. F. Croswell, "Measurements of admittance of a slot antenna exposed to nonuniform plasma layer," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

451. Ting, C. Y., B. Rama Rao, and W. A. Saxton, "Theoretical and experimental study of a finite cylindrical antenna in a plasma column," IEEE Trans., AP-16, 2, March 1968, 246-255.

452. Tuan, H. S., and R. W. P. King, "Radiation from a scattering antenna embedded in a dissipative half space," Radio Science, 3, 6, June 1968, 577-584.

453. Tuan, H. S., and S. R. Seshadri, "Radiation from a line source in a uniaxially anisotropic plasma," Can. J. Phys., 41, 2, Feb. 1963, 246-257.

454. Tuan, H. S., and S. R. Seshadri, "Radiation from a uniformly moving charge in an anisotropic plasma," IEEE Trans., MTT-11, 6, Nov. 1963, 462-471.

455. Tuan, H. S., and S. R. Seshadri, "Radiation from a uniformly moving distribution of electric charge in an anisotropic, compressible plasma," IEEE Trans., AP-13, 1, Jan. 1965, 71-78.

456. Tuan, H. S., and S. R. Seshadri, "Radiation from a phased line source in a magnetionic medium," Can. J. Phys., 43, 2, Feb. 1965, 1636-1648.

457. Tunaley, J. K. E., and T. R. Kaiser, "Low frequency probe measurements in the ionosphere," Space Research VII, Vol. 1, (North-Holland Publishing Company, Amsterdam), 1966, 407-416.

458. Tyras, G., "On the excitation of electromagnetic waves in inhomogeneous media," Symp. on EM Theory, Delft, Netherlands, Sept. 1965.

459. Tyras, G., "Field of an axially slotted circular cylinder clad with an inhomogeneous dielectric," IEEE Trans., AP-15, 2, March 1967, 222-226.

460. Tyras, G., P. C. Bargeliotes, J. M. Hamm and R. R. Schell, "An Experimental Study of Plasma Sheath Effects on Antennas," Radio Science, 69D, 6, June 1965, 839-850.

461. Tyras, G., A. Ishimaru, and H. M. Swarm, "Field of a horizontal magnetic dipole in the presence of a magneto-plasma half-space," J. Res. NBS, 67D, 5, Oct. 1963, 501-517.

462. Ulwick, J. C., W. Pfister, K. D. Baker, and A. M. Despain, "Experimental and theoretical studies of antenna impedance in the D and E regions," University of Illinois, Urbana, Illinois, Aeronomy Rept. No. 10, 1965.

463. Ulwick, J. C., W. Pfister and R. E. McInerney, "Direct satellite probe measurements of ionosphere irregularities," Space Research V, (North-Holland Publishing Company, Amsterdam), 1965, 171-178.

464. Ulwick, J. C., W. Pfister, R. P. Vancour, R. T. Bettinger, O. C. Haycock and K. D. Baker, "Firing of an astrobee 200 rocket with a multiple ionospheric experiment," Proc. IRE, 50, 11, Nov. 1962, 2272-2286.

465. Unz, H., "Electromagnetic radiation in drifting Tellegen anisotropic medium," IEEE Trans., AP-11, 5, Sept. 1963, 573-578.

466. Unz, H., "Radiation from a sphere in compressible plasma," Appl. Sci. Res., 17, 4-5, 1967, 340-354.

467. Unz, H., "RF method for determining the sheath thickness in a plasma," Proc. IEEE, 55, 10, Oct. 1967, 1767-1768.

468. Unz, H., and H. Hodara, "Comments on radiation from a gyroplasma sheath aperture," IEEE Trans., AP-11, 6, Nov. 1963, 709.

469. Van Hulsteyn, D. B., "An arbitrary current source in a homogeneous anisotropic plasma," J. Appl. Phys., 38, 4, March 1967, 1567-1573.

470. Villeneuve, A. T., "Admittance of waveguide radiating into plasma environment," IEEE Trans., AP-13, 1, Jan. 1965, 115-121.

471. Wade, H. D., and R. H. Williams, "VLF radiation in air from an electric line current source located in an ionospheric half space," Radio Science, 1, 1, Jan. 1966, 53-59.

472. Waino, D. K., and R. Mittra, "Short dipole in a uniaxial plasma," Appl. Sci. Res., 19, April 1968, 60-69.

473. Wait, J. R., "The magnetic dipole antenna immersed in a conducting medium," Proc. IRE, 40, 10, Oct. 1952, 1244-1245.

474. Wait, J. R., "Insulated loop antenna immersed in a conducting medium," J. Res. NBS, 59, 2, Aug. 1957, 133-137.

475. Wait, J. R., "Some boundary value problems involving plasma media," J. Res. NBS, 65B, 2, Feb. 1961, 137-150.

476. Wait, J. R., "The electromagnetic fields of a dipole in the presence of a thin plasma sheet," Appl. Sci. Res., 8B, 5-6, Nov. 1961, 397-417.

477. Wait, J. R., "Theory of radiation from sources immersed in anisotropic media," J. Res. NBS, 68B, 3, July-Sept. 1964, 119-136.

478. Wait, J. R., "Resonances of a spherical void in a compressible isotropic plasma," J. Geophys. Res., 69, 19, Oct. 1964, 4189-4191.

479. Wait, J. R., "Radiation from sources immersed in compressible plasma media," Can. J. Phys., 42, 9, Sept. 1964, 1760-1780.

480. Wait, J. R., "Concerning the theory of radiation from a slotted conducting plane in a plasma environment," Central Radio Propagation Lab., NBS Tech. Note No. 223, Sept. 1964.

481. Wait, J. R., "Theory of a slotted sphere antenna immersed in a compressible plasma, Part I," J. Res. NBS, 68D, 10, Oct. 1964, 1127-1136.

482. Wait, J. R., "Theory of a slotted-sphere antenna immersed in a compressible plasma, Part II," J. Res. NBS, 68D, 10, Oct. 1964, 1137-1143.

483. Wait, J. R., "On radiation of electromagnetic and electroacoustic waves in plasma, Part I," Appl. Sci. Res., 11B, 6, 1965, 423-431.

484. Wait, J. R., "On radiation of electromagnetic and electroacoustic waves in plasma, Part II," Appl. Sci. Res., 12B, 2, 1965, 130-138.

485. Wait, J. R., "Electromagnetic radiation from an acoustic point source within a plasma bubble," Can. J. Phys., 44, 3, March 1966, 467-475.

486. Wait, J. R., "Theories of prolate spheroidal antennas," Radio Science, 1, 4, April 1966, 475-512.

487. Wait, J. R., "Radiation from a spherical aperture antenna immersed in a compressible plasma," IEEE Trans., AP-14, 3, May 1966, 360-368.

488. Wait, J. R., "Dipole resonances of a magnetoplasma column," Elec. Letters, 2, 7, July 1966, 265.

489. Wait, J. R., "Network representation for spherical waves in a compressible plasma," IEEE Trans., AP-14, 4, July 1966, 517-518.

490. Wait, J. R., "Influence of a compressible plasma half-space on the impedance of an electric dipole," Proc. IEEE, 54, 9, Sept. 1966, 1193-1194.

491. Wait, J. R., "Radiation from a spherical antenna with an anisotropic plasma sheath," Can. J. Phys., 44, 10, Oct. 1966, 2303-2312.

492. Wait, J. R., "Electromagnetic fields of a dipole over an anisotropic half-space," Can. J. Phys., 44, 10, Oct. 1966, 2387-2401.

493. Wait, J. R., "Fields of a horizontal dipole over a stratified anisotropic half-space," IEEE Trans., AP-14, 6, Nov. 1966, 790-792.

494. Wait, J. R., "Quasi-static theory of a cylindrical impedance probe for magnetoplasma," Radio Science, 1, 11, Nov. 1966, 1297-1301.

495. Wait, J. R., "Theory of a plasma resonance probe in a magnetic field," J. Appl. Phys., 37, 13, Dec. 1966, 4905-4907.

496. Wait, J. R., "Further note on the quasi-static theory of a cylindrical impedance probe for magnetoplasma," Radio Science, 2, 2, Feb. 1967, 253-256.

497. Wait, J. R., and E. A. Brackett, "Bibliography on waves in plasmas," Inst. Environmental Res., Boulder, Colorado, Tech. Rept. No. IER 39-ITSA 39, April 1967.

498. Wait, J. R., and L. I. Campbell, "The fields of an oscillating magnetic dipole immersed in a semi-infinite conducting medium," J. Geophys. Res., 58, 1, Jan. 1953, 167-168.

499. Wait, J. R., and K. P. Spies, "A note on the insulated loop antenna immersed in a conducting medium," J. Res. NBS, 68D, 11, Nov. 1964, 1249-1250.

500. Wait, J. R., and K. P. Spies, "Theory of a slotted-sphere antenna immersed in a compressible plasma, Part III," Radio Science, 1, 1, Jan. 1966, 21-26.

501. Waletzko, J. A., and G. Bekefi, "RF admittance of a slotted-sphere antenna immersed in a plasma," Radio Science, 2, 5, May 1967, 489-490.

502. Walsh, D., F. T. Haddock and H. F. Schulte, "Cosmic radio intensities at 1.225 and 2.0 Mc measured up to an altitude of 1700 m," Space Research IV, (North-Holland Publishing Company, Amsterdam), 1963, 935-959.

503. Walsh, D., and F. T. Haddock, "Antenna impedance in a plasma: Problems relevant to radio astronomy measurements from space vehicles (VII-6)," Annales D'Astrophysique, 28, 3, March 1965, 605-613.

504. Walsh, D., and H. Weil, "Irreversible power and radiation resistance of antennas in magnetoionic media," Radio Science, 1, 9, Sept. 1966, 1025-1027.

505. Walsh, D., and H. Weil, "Ionosphere focusing for an antenna in the presence of the geomagnetic field," Radio Science, 3, 9, Sept. 1968, 936-942.

506. Wang, T. N. C., and T. F. Bell, "Radiation resistance of a short dipole immersed in a cold magnetoionic medium," Radio Science, 4, 2, Feb. 1969, 167-177.

507. Wasserstrom, E. C., C. H. Su and R. F. Probstein, "Kinetic theory approach to electrostatic probes," Phys. Fluids, 8, 1, Jan. 1965, 56-72.

508. Weil, H., "Complex impedance of cylindrical antennas in magnetoplasma," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

509. Weil, H., and J. P. Lafon, "Impedance of a cylindrical antenna in magnetoplasma under conditions of refractive index resonance," URSI Spring Meeting 1967.

510. Weil, H., and D. Walsh, "Radiation resistance of an electric dipole in a magnetoionic medium," IEEE Trans., AP-12, 3, May 1964, 297-304.

511. Weil, H., and D. Walsh, "Radiation of an elementary loop antenna in a magnetoionic medium," IEEE Trans., AP-13, 1, Jan. 1965, 21-27.

512. Weil, H., and D. Walsh, "Thermal radiation fields and antenna parameters in magnetoplasma," Radio Science, 2, 2, Feb. 1967, 225-239.

513. Weitzner, H., "Radiation from a point source in a plasma," Phys. Fluids, 7, 1, Jan. 1964, 72-89.

514. Wenger, N. C., "Radiation from a magnetic line source located on a conducting plane covered by a warm plasma layer," Radio Science, 1, 5, May 1966, 577-588.

515. Whale, H. A., "The impedance of an electrically short antenna in the ionosphere," Proc. Int. Conf. on the Ionosphere, London (Chapman and Hall, Ltd., London), July 1962, 472-477.

516. Whale, H., "The excitation of electroacoustic wave by antenna in the ionosphere,"J. Geophys. Res., 68, 2, Jan. 1963, 415-422.

517. Whale, H., "Ion sheath effects near antennas radiating within the ionosphere," J. Geophys. Res., 69, 3, Feb. 1964, 447-455.

518. Williams, R. H., "Insulated and loaded loop antenna immersed in a conducting medium," J. Res. NBS, 69D, 2, Feb. 1965, 287-289.

519. de Wolf, D. A., "Impedance of a small VLF dipole in the ionosphere," Radio Science, 1, 5, May 1966, 571-576.

520. Woo, R., and A. Ishimaru, "Radiation from a circularly-polarized antenna through the ionized wake of a Mars-entry capsule," Int. Symp. on Ant. & Prop., Boston, Mass., Sept. 1968.

521. Wu, C. P., "Radiation from dipoles in a magnetoionic medium," IEEE Trans., AP-11, 6, Nov. 1963, 681-689.

522. Wu, C. P., "On the applicability of the image theory," IEEE Trans., AP-12, 1, Jan. 1964, 127-128.

523. Wunsch, A. D., "Radiation from a strip of electric current in a magnetoionic medium," Can. J. Phys., 45, 5, May 1967, 1675-1691.

524. Wunsch, A. D., "Current distribution on a dipole antenna in a warm plasma," Elec. Letters, 3, 7, July 1967, 320-321.

525. Wunsch, A. D., "The infinite tubular antenna in a warm plasma," Radio Science, 3, 9, Sept. 1968, 901-919.

526. Yee, J. S., "Mutual coupling of two thin infinitely-long slots located on perfectly conducting plane in the presence of a uniform plasma layer," Proc. IRE, 49, 1961, 1837-1845.

527. Yeh, C., "Electromagnetic radiation from an arbitrary slot on a conducting cylinder coated with a uniform cold plasma sheath with an axial static magnetic field," Can. J. Phys., 42, 7, July 1964, 1369-1381.

528. Yeh, C., and W. V. T. Rusch, "Radiation through an inhomogeneous magnetized plasma sheath," IEEE Trans., AP-15, 2, March 1967, 328.

529. Yeh, Y. S., and J. R. Wait, "On the theory of radiation from an annular slot in a compressible plasma," Radio Science, 3, 2, Feb. 1968, 171-180.

530. Yildiz, M., and S. N. Samaddar, "A note on wave phenomena due to a moving and oscillating dipole in a compressible plasma column," Can. J. Phys., 41, 12, Dec. 1963, 2268-2275.

531. Yip, G. L., and S. R. Seshadri, "Singularity in the power carried by the surface waves along an axially magnetized plasma column," Proc. IEEE, 54, 12, Dec. 1966, 2030-2031.

532. Yip, G. L., and S. R. Seshadri, "Surface waves along an axially magnetized plasma column," Can. J. Phys., 45, 9, Sept. 1967, 2889-2911.

533. Yip, G. L., and S. R. Seshadri, "Radiation from an electric dipole in an axially magnetized plasma column--dipolar modes," Can. J. Phys., 45, 11, Nov. 1967, 3627-3648.

534. Young, C. E., "VLF electric and magnetic antenna impedance characteristics in the ionosphere," URSI Fall Meeting, Stanford University, Stanford, California, 1966.

535. Zachary, W. W., E. A. Wolff, and M. Katzin, "Determination of ionospheric parameters by means of a satellite antenna-type probe," Electromagnetic Research Corp., College Park, Md., Report CRC-6656-1, June 1960.

536. Zimina, V. I., "Propagation of electromagnetic waves along a conducting cylinder surrounded by a layer of ionized air with a negative dielectric constant," Radio Eng. Elec. Phys., 6, June 1962, 928-934.

537. Zisk, S. H., "Electromagnetic transients in conducting media," IRE Trans., AP-8, 2, March 1960, 229-230.

538. Bergeson, J. E., "Radiation from an oscillating magnetic dipole in a streaming plasma," Radio Science, 3, 2, Feb. 1968, 191-200.

539. McKeown, D. L., and R. L. Ferrari, "The impedance of a resonance probe," Int. J. Elec., 23, 1, July 1967, 39-68.

540. Messiaen, A. M., "Resonantly H. F. - sustained plasma around an antenna," Elec. Letters, 4, 2, Jan. 1968, 29-31.

541. Daires, P. G., "An experimental investigation into the behavior of a spherical plasma resonance probe in a magnetic field," J. Plasma Phys., 1, Nov. 1967, 451-462.

542. Knecht, R. W., T. E. VanZandt and S. Russell, "First pulsed radio soundings of the topside of the ionosphere," J. Geophys. Res., 66, 9, Sept. 1961, 3078-3081.

543. Calvert, W., and G. B. Goe, "Plasma resonances in the upper ionosphere," J. Geophy. Res., 68, 22, Nov. 1963, 6113-6120.

544. Crawford, F. W., G. S. Kino and H. H. Weiss, "Excitation of cyclotron harmonic resonances in a mercury-vapor discharge," Phys. Rev. Letters, 13, 7, Aug. 1964, 229-232.

545. Yeung, T. H. Y., and J. Sayers, "An RF probe technique for the measurement of plasma electron concentrations in the presence of negative ions," Proc. Phys. Soc., 70B, 451B, July 1957, 663-668.

546. Uramoto, J., J. Fujita, H. Ikegami and K. Takayama, "Resonance probe in a magnetic field," Inst. Plasma Phys. Nagoya University, Nagoya, Japan, Phys. Rept. No. 15, Oct. 1963.

547. Bain, V. C., "Aerials in an ionosphere of zero conductivity," Proc. IEE (London), 110, 5, May 1963, 897-898.

548. Grard, R. J., "Interpretation of impedance probe measurements in the ionosphere," EE Dept., Stanford University, Stanford, Tech. Rept. No. 2, 1965.

549. Zachary, W. W., "Determination of ionospheric parameters by means of a satellite antenna-type probe; II Analysis for spherical geometry," Electromagnetic Research Corp., College Park, Md., Sci. Rept. No. 2, Dec. 1960.

550. Whitamer, R. F., and A. D. Macdonald, "R. F. antenna breakdown conditions in the presence of the plasma sheath," Planet. Space Sci., 6, June 1961, 149-154.

551. Molozzi, A. R., C. A. Franklin and J. P. I. Tyas, "Cosmic noise measurements from 1960ηI at 3.8 Mc/s," Nature, 190, 4776, May 1961, 616.

552. Ament, W. S., "On the electromagnetic Green's function for a homogeneous anisotropic medium and certain of its applications to antenna theory," Electromagnetic Group Corp., College Park, Md., 1963.

553. Bhat, B., and B. Rama Rao, "Experimental investigation on the impedance behavior of a short cylindrical antenna in a lossy magnetoplasma," Trans. IEEE, AP-18, to be published.

554. Wait, J. R., Electromagnetics and Plasmas, Holt, Rinehart and Winston, Inc., New York, N. Y., 1968.

555. Galejs, J., Antennas in Inhomogeneous Media, Pergamon Press, New York, N. Y., 1969.

TABLE I

CLASSIFICATION OF PAPERS ABOUT THE IMPEDANCE OF CYLINDRICAL ANTENNAS IN PLASMA

	THEORY							MEASUREMENTS	
	COLD PLASMA					WARM PLASMA		In ~~the~~ Ionosphere	In Laboratory plasma
	Isotropic	Uniaxial	Anisotropic			Isotropic	Anisotropic parallel		
			parallel	perpendicular	arbitrary				
Assumed Current Distribution	2,49,55, 76,100*, 109,112, 163,174, 186*,204, 205,207, 235,286*, 290,315*, 354,392, 394,506, 517*	154,266, 401,405*, 433,472	23*,42, 44,55, 151,155*, 244,367*, 411*, 415*,422 506,509, 510,512	23*,42,44, 416*,494*, 496*,510	4,23*,49 56,135, 165*,187, 224,228, 245,264, 265,402, 406,407, 410,432	24,65,76, 90,109, 116,157*, 255,256, 321,397*, 490,516		~~20~~,21,~~36~~*, 37*,39,40, 50*,118, 165*,176, 178,179, 180,184, 196*,213, 215,226*, 316*,350, 437,438, 439,462, 464,502, 516,457*	~~23,78,79,~~ 100*,164, 202,203, 206,216, 274,290, 387,430
Boundary-Value Problem	236,237, 241,277, 325*,451	71*,199, 268	57,80, 96,271, 412		7,508*	96,276*, 298*,300*, 302*,324, 400*,469*, 525	301*		

Notes: 1. Stars over numbers means that the papers have discussed the sheath effect.

2. Papers about current loops, magnetic lines, biconical antennas, strips, slots, wtc. are not included in this table, although they may be related to cylindrical antennas.

3. The following papers are of review nature: 11, 13, 27, 132, 183, 497, 503.

ADDITIONAL REFERENCES

(The following papers are referred to in the present report but they do not belong to the group of "Sources in Plasmas.")

556. Ginzburg, V. L., The Propagation of Electromagnetic Waves in Plasmas, Pergamon Press, 1964, Sec. 38.

557. Allis, W. P., S. Buchsbaum and A. Bers, Waves in Anisotropic Plasmas, John Wiley and Sons, Inc., New York, N. Y., 1962.

558. Lighthill, M. J., "Studies on magneto-hydrodynamic waves and other anisotropic wave motions," Phil. Trans. Roy. Soc., London, A252, March 1960, 397-430.

559. Seshadri, S. R., and T. T. Wu, "Radiation condition for a magnetoplasma medium - I," Applied Research Lab., Sylvania Electronics System, Waltham, Mass., Res. Rept. No. 502, Nov. 1966.

560. Deschamps, G. A., Private communication, 1968.

561. Lee, S. W., C. Liang and Y. T. Lo, "On the coupling of modal waves in a plasma-filled parallel-plate waveguide," Radio Science, 2, 4, April 1967, 401-406.

562. King, R. W. P., The Theory of Linear Antennas, Harvard University Press, Oxford, 1956.

563. Hallen, E., Electromagnetic Theory, Chapman and Hall, Ltd., London, 1962.

564. Deschamps, G. A., "Angular dependence of the refractive index in the ionosphere," J. Res. NBS, 69D, 3, March 1965, 395-400.

565. Deschamps, G. A., "Dispersion surfaces and characteristic plane waves in a gyrotropic medium," in Proceedings of the Application Forum on Antenna Research, ed. P. E. Mayes, University of Illinois, Urbana, 1964.

566. Chen, Y. M., and J. B. Keller, "Current on and input impedance of a cylindrical antenna," J. Res. NBS, 66D, 4, April 1963, 417-431.

567. Wu, T. T., and R. W. P. King, "Driving point and input admittance of linear antennas," J. Appl. Phys., 30, 1, Jan. 1959, 74-76.

568. Duncan, R. H., "Theory of the infinite cylindrical antenna including the feedpoint singularity in antenna current," J. Res. NBS, 66D, 2, March-April 1962, 181-188.

569. Fante, R. L., "On the admittance of the infinite cylindrical antenna," Radio Science, 1, 9, Sept. 1966, 1041-1044.

570. Miller, E. K., "Admittance dependence of the infinite cylindrical antenna upon exciting gap thickness," Radio Science, 2, 12, Dec. 1967, 1431-1436.

571. Lee, S. W., and R. Mittra, "Admittance of solid cylindrical antenna," Can. J. Phys., to be published, 1969.

572. Alpert, Y. L., A. V. Gurevich and L. P. Pitaevski, "Effects produced by an artificial satellite rapidly moving in the ionosphere or in an interplanetary medium," Sov. Phys. Uspekhi, 6, 1, Jan. 1963, 13-46.

573. Osborne, F. J. F., and M. A. Kasha, "The $\vec{v} \times \vec{B}$ interaction of a satellite with its environment," Can. J. Phys., 45, 2, Feb. 1967, 263-277.

574. Heald, M. A., and C. B. Wharton, Plasma Diagnostics with Microwaves, John Wiley and Sons, Inc., New York, N. Y., 1965.

575. Huddlestone, R., and S. Leonard, Plasma Diagnostic Techniques, Academic Press, New York, N. Y., 1965.

576. Leob, L. B., Basic Processes of Gaseous Electronics, University of California Press, Berkeley, 1960, 332-370.

577. Shkarofsky, I. P., T. W. Johnson and M. P. Bachynski, The Particle Kinetics of Plasmas, Addison-Wesley Publishing Co., Inc., Reading, Mass., 1966.

578. Dyson, J. D., "The design of conical log-spiral antennas," IEEE Int. Convention Record, 1964, 259-273.