SPECIAL ISSUE: PAPERS PRESENTED AT URSI-IUPAP SYMPOSIUM ON WAVES AND RESONANCES IN PLASMAS

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Contents

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Foreword

During the 1969 General Assembly of URSI at Ottawa, Canada, Commission III (Ionosphere) of URSI accepted a recommendation to cosponsor a symposium entitled, 'Waves and Resonances in Plasmas.' The symposium should have carefully controlled attendance and be organized in cooperation with URSI Commissions IV, VI, and VII and with the International Union on Pure and Applied Physics (IUPAP). On invitation of the Canadian URSI Committee this symposium was held from July 5 through 9 at St. John's, Newfoundland.

The following program committee was established by agreement between the participating commissions and IUPAP:

R. E. Barrington, Canada	Ionospheric resonances
S. C. Brown, USA	Artificial plasmas in laboratories
A. A. Rukhadze, USSR	Theory of resonances in plasmas
F. L. Scarf, USA	Magnetospheric plasma
K. Suchy, FRG	Theory of wave propagation and collisions in plasmas

The undersigned was chairman. The selection of specialists to be invited to attend the symposium was made by the committee. Every member made a list of colleagues from his speciality, and these lists were compared and combined by the chairman. It was found that there was almost no overlap in these lists. The chairman feels that this demonstrates one reason for holding the symposium, namely, a lack of contacts between different specialists dealing with plasma problems and a resulting need to provide an opportunity for these specialists to exchange ideas.

In fact, the main objective was to bring together representatives of groups interested in plasmas from different points of view: experimenters with plasmas in space and in the upper atmosphere, theoreticians, and laboratory scientists working mainly on hot plasmas. One of the principle aims was to stimulate contacts between these groups by discussing the plasma resonance phenomena discovered in recent years by space vehicles.

Even though final answers to the various open questions could not be found during the symposium, the participants often gained a new insight into their own problems as well as worth-while information on concurrent activities in related fields. It is hoped that the personal contacts established at the symposium will be maintained and even expanded in the future. The 51 scientists attending the meeting came from the following countries: Belgium, Canada, Denmark, France, Japan, UK, USA, USSR, and FRG.

The invited speakers and the chairman of the sessions were as follows:

Session	Chairman	Speaker	Subject
A1	M. P. Bachynski	K. G. Balmain	Frequency response (antennas in plasmas)
A2	M. Petit	D. B. Muldrew	Transient response (spikes in topside ionograms)
B1	T. Watanabe		Waves in laboratory plasmas
B2	P. E. Vandenplas	K. W. Gentle	Instabilities and turbulence in laboratory plasmas

Session	Chairman	Speaker	Subject
C	I. Kimura	M. J. Rycroft	VLF emissions in the magnetosphere
D1	A. A. Rukhadze	T. W. Johnston	Excitation
D2	L. B. Felsen	R. W. Larenz	Coupling
E1	R. W. Larenz	A. A. Rukhadze	Instability of inhomogeneous plasma streams
		K. Suchy	Attenuation
E2	K. Rawer		Summary, discussion

Grateful acknowledgment is made to the Canadian URSI Committee Chairman, Dr. R. E. Barrington, and the National Research Council for extending the invitation to hold the Symposium in Canada and for joining URSI in making travel grants to some of the speakers.

The Program Committee is grateful to the Editor of *Radio Science* for publishing the invited papers and summaries of the discussions and contributed papers.

K. Rawer
Chairman, URSI Commission III
Guest Editor, Radio Science

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Antennas in plasma: Characteristics as functions of frequency

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The literature on the subject is reviewed under the headings: anisotropic (cold) electron plasma, isotropic (warm) electron plasma, loop antennas, resonance rectification, and ion effects. Though the gap between theory and experiment has narrowed for most of these topics, understanding is still unsatisfactory at lower frequencies where ion motion cannot be neglected.

INTRODUCTION

The behaviour of antennas in plasma is characterized by primary dependence on the surrounding medium and secondary dependence on the detailed shape and size of the antenna structure itself, especially insofar as the resonances of the medium are concerned. The ionospheric plasma is well-known to be a complicated medium containing several species of charged particles and exhibiting such properties as anisotropy and inhomogeneity, the latter being especially pronounced in the immediate vicinity of a spacecraft antenna. These are just a few of the many complications, the end result of which is a shortage of research papers in which the theory of antennas in plasma is compared to experiments. Because of its importance to understanding, the relation of theory to experiment will be emphasized in this review. Such an approach, while useful, does lead inescapably to some over-emphasis on impedance properties simply because of their accessibility to direct measurement.

The time period covered by this review is three years, going back approximately to mid-1968; earlier papers will be mentioned only to illustrate a historical sequence or to make points that appear to have been overlooked. The main reason for the general three-year limit is the existence of considerable review material up to then, including *Bachynski* [1967], *Wait* [1968], and *Thomas and Landmark* [1969, 1970].

The review does not pretend to be all-inclusive and insofar as possible it will refer only to material readily available in the open literature. The antenna types considered will be those used to detect ionospheric resonances, such as dipoles, spheres, and loops. Problems related to reentry (horn antennas or slot antennas covered by plasma layers) will not be considered.

ANISOTROPIC ELECTRON PLASMA

The observation of resonance cones in the field of a small source in the laboratory by *Fisher and Gould* [1971] is particularly significant. These cones had been predicted earlier by a number of authors using several different theories, the simplest of which is the cold-plasma, quasi-static theory illustrated, for example, by the dipole field calculations of *Miyazaki* [1969]. The quasi-static, lossless differential equation under resonance conditions is of the hyperbolic form in space coordinates, and therefore the discontinuity represented by any small source will extend outward along the conical characteristic surface passing through the source. Under these resonance or hyperbolic conditions, lossless quasi-static impedance theory predicts an input resistance caused by whistler-mode radiation, the fields of which are approximately quasi-static. The relationship between quasi-static and full-wave theory has been studied extensively by *Wang and Bell* [1969a], *Lafon and Weil* [1971], and *Snyder and Weitzner* [1968].

The simple theories of dipole input impedance are supported by recent rocket measurements, such as those of *Ejiri et al.* [1968] and *Melzner and Rabben* [1970], the latter being especially precise because of the use of a guard ring. Both sets of measurments bear a strong resemblance to the quasi-static calculations of *Balmain* [1969], especially in the vicinity of the electron plasma frequency. In addition some fairly extensive calculations and rocket dipole measurements have been carried out by *Miller and Schulte* [1970] who consider the effects of plasma compressibility and sheath inhomogeneity. In all of these measurements and calculations the admittance magnitude is shown as a function of frequency, and the most prominent feature of the results is a sharp peak at the series resonance of the capacitive ion sheath and the surrounding inductive plasma. With no magnetic field the series resonance frequency is somewhat below the plasma frequency, and with a magnetic field it always lies somewhere between the gyrofrequency and the upper hybrid frequency which is also identifiable as a definite minimum in admittance magnitude. For plasma diagnostics, however, the plasma frequency itself is of greatest interest, and the above references demonstrate that the plasma frequency can be readily identified as a sharp dip in admittance magnitude in swept-frequency impedance measurements. However, it should be added that the variation of impedance with the angle between the dipole axis and the magnetic field is an area of study in which ionospheric measurements have not yet been compared to theory.

Some theoretical papers have confined their attention to particular dipole orientations in order to simplify their work to the point where it is possible to calculate the current distribution on the antenna. Examples of this are the cases of parallel orientation studied by *Lee* [1969] and perpendicular orientation dealt with by *Galejs* [1968]. Calculating the current distribution is important as can be seen from the measurements of *Ishizone et al.* [1969] but it is also clear that a good deal of work remains to be done in this area before a thorough comparison of theory and experiment can be made.

Some authors are of the belief that orientation effects can be done away with in impedance measurements by making use of a small spherical probe fed against a much larger electrode, such as a rocket body, immersed in the plasma; such a geometry would approximate an idealized, isolated sphere. Extensive ionospheric experiments with spherical probes have been reported by *Heikkila et al.* [1968], and comparison of theory with experiment has been done by *Balmain and Oksiutik* [1969], and *Holt and Trøim* [1969].

Cyclotron harmonic responses are readily seen in sounder-satellite ionograms but are not so frequently seen in impedance experiments, especially in the laboratory. This is why the work of *Downward and Harp* [1970] is especially noteworthy. Not only have the authors observed cyclotron harmonic responses in the input conductance of a wire probe, but they have also interpreted the fine structure in the responses in terms of the cyclotron harmonic wave passbands. In addition they have varied the dc bias on the probe (a procedure frequently overlooked in published papers) and have succeeded in interpreting the results qualitatively.

ISOTROPIC ELECTRON PLASMA

In the absence of a magnetic field the complications are fewer, and as a result a great deal of work has been done on the comparison of monopole impedance theory with laboratory experiments. Careful measurements have been carried out by *Scott and Rao* [1969] and *Uramoto* [1970] emphasizing the effects of collisions. *Ishizone et al.* [1969] made measurements of current distribution at frequencies below the electron plasma frequency. These measurements are particularly significant because they deal with the effect of the ion sheath and the dipolar resonance. *Jassby and Bachynski* [1969] have measured in the laboratory not only the input impedance of a dipole but its radiation pattern as well. Several papers by *Freeston* [1968, 1970a, b, c] serve to remind us that the measured impedance depends on signal level and bias and that the effects of electron depletion with positive bias are sometimes qualitatively similar to the effects of electron reflection with negative bias.

Theoretical calculations have been dominated by considerations of warm-plasma effects. Scalar-pressure theory has been employed by *Wunsch* [1968], *Galejs* [1969], and *Lin and Mei* [1970], all of whom were able to calculate the current distribution on a dipole and then calculate the input impedance. These authors have calculated results showing some fine structure in the vicinity of the plasma frequency, which should be watched for by laboratory experimenters. Kinetic theory is more difficult to use than scalar-pressure theory but it has been applied to a spherical probe by *Schiff and Fejer* [1970] and to a short dipole by *Schiff* [1970]. These papers contain interesting discussions of continuous-surface models of probes versus perforated-surface models, as well as dealing with collisionless loss phenomena. A thorough analysis of the plane-grid problem has been done by *Buckley* [1968].

LOOP ANTENNAS

Wire antennas of the dipole or monopole configuration and also spherical electrodes have been considered so far because of their frequent use on spacecraft to detect waves and resonances in the ionosphere. Loop antennas are also used occasionally, mainly to pick up VLF noise and discrete emissions. The behavior of a small-loop antenna in a plasma is not well understood at present except for the established fact that the plasma affects its impedance much less than it affects the impedance of a dipole. The laboratory experiments of *Duff and Mittra* [1970] show a measure of qualitative agreement between impedance measurements and cold-plasma theory in a magnetic field, but clearly much remains to be done to achieve good quantitative agreement. On the purely theoretical side, *Adachi et al.* [1969] have considered a loop in isotropic, compressible plasma and concluded that the power radiated in the plasma wave can be appreciably greater than that radiated in the electromagnetic wave. *Wang and Bell* [1969b] have calculated the VLF field radiated along the magnetic field for both loop and dipole antennas and have found their performance to be generally comparable. Corner-driven loops and Alford loops have been compared by *Gupta and Freeston* [1971].

RESONANCE RECTIFICATION

The phenomenon of resonance rectification (the detection of sharp variations in rectified probe current as an attached RF oscillator is swept through a resonance) has been used by *Heikkila et al.* [1968] as part of a multiple ionospheric probe experiment. The technique is awkward to use in the ionosphere where the experiment is inaccessible to the adjustments required to set correctly the steady bias potential and the proper RF level. A more fundamental objection is that the rather high RF voltage required, kT/e or a fraction of a volt, is enough to modify the plasma and make diagnostic conclusions questionable. These difficulties no doubt explain the shortage of papers on resonance rectification in recent years, one exception being the theoretical analysis of *Li and Gustafson* [1970].

ION EFFECTS

One of the most striking papers involving ions is that by *Shen et al.* [1970] who describes laboratory measurements and theory on longitudinal ion wave radiation patterns from dipole antennas, using a pulsed source. VLF electromagnetic-wave radiation (cold-plasma theory) has been studied in detail by *Wang and Bell* [1970] and *GiaRusso and Bergeson* [1970], with emphasis on the high-field cones extending outward from the source. The parallel-plate problem has been considered by *Vandenplas et al.* [1970] who make use of scalar-pressure theory and include a steady magnetic field. Parallel plates in a flowing ionospheric plasma have been studied theoretically by *Fiala* [1970] who raises the possibility of negative input resistance at around 20 kHz. *Shawhan and Gurnett* [1968] have measured the VLF impedance of a double-sphere dipole and noted variations with frequency which could be in fact variations with orientation due to wake or sheath effects. *Storey et al.* [1969] have described a quadripole mutual impedance probe, and it has been discussed by *Beghin and Renard* [1970] with respect to collisional damping and velocity damping.

CONCLUSIONS

The gap between theory and experiments on antennas in plasma has narrowed appreciably over the last three years, particularly at frequencies high enough to make ion motion insignificant. At lower frequencies where ion motion cannot be ignored, the gap remains very wide indeed with the few existing experiments serving to indicate that the task of achieving understanding is much more difficult than at higher frequencies [*Koons et al.*, 1970].

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The behavior of antennas in plasma as a function of the frequency of excitation: Summary report

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A feature of the session on the behavior of antennas in a plasma as a function of frequency of excitation was the variety of antenna configurations which was being investigated by various research groups.

The emphasis by the Groupe de Recherches Ionosphériques du Centre National d'Etudes de Télécommunications (France) was on quadrupole probes. *L. R. O. Storey* and *J.-M. Chasseriaux* reported on theoretical studies of plasma probes based on the mutual electrical coupling between pairs of dipole antennas. Two types of antennas were analysed, Hertzian dipoles which are short compared with the Debye-length and double-sphere dipoles which are long compared with the Debye-length. In both cases the complete probe is formed by two such antennas separated by a distance much larger than a Debye-length. The mode of operation of these quadrupole probes can be either active (by driving a current in one dipole and measuring the open circuit potential difference induced on the other) or passive (by measuring the cross-spectrum of the fluctuating potential differences induced on the two dipoles by the plasma microfield). The quadrupole probes can be applied to the measurement of plasma resonant frequencies, collision frequencies, and the velocity of motion with respect to the probes.

Experimental measurements using the quadripole impedance probe on a rocket flight where the lower hybrid resonance and the electron density profile were obtained in a range of 120 to 150 km altitude were discussed by *C. Beghin* (also of the Groupe de Recherches Ionosphériques). The technique was to measure the mutual impedance between two double-sphere dipoles with a swept frequency analyser. In this manner the local hybrid resonances appear as resonances to the probe while the gyroresonances are seen as antiresonances. This quadripole impedance probe is also being implemented in a laboratory-simulated plasma in argon operating at a pressure of 10^{-4} torr.

The theory of a single spherical admittance probe in a warm isotropic electron-ion plasma was described by *K. G. Balmain* (University of Toronto, Canada). A partially absorptive boundary condition was used to simulate a floating sheath condition. By determining the magnitude and phase of the admittance as a function of frequency, a broad resonance somewhat below the ion-plasma frequency can be identified. Increasing the ratio of the electron-to-ion temperatures increases the sharpness of the resonance. Admittance measurements in a laboratory plasma were found to be similar to those predicted by theory.

The behavior of various simple antennas in a laboratory magnetoplasma was described by *S. Y. K. Tam* (RCA Laboratories, Montreal, Canada). Using a half-wavelength dipole antenna in a large (ten-free-space wavelength by seven free-space wavelength) laboratory chamber, distinct increases in reflected signals from the plasma corresponding to the conditions for the upper hybrid resonance are observed when the dipole is perpendicular to the static magnetic field. No such phenomenon is observed when the half-wavelength dipole antenna is aligned parallel to the static magnetic field or when a short dipole ($<\lambda_o/4$) or small loop antenna (diameter: $\lambda_o/8$) is used. The 'strength' of the resonance reduces considerably as the electron cyclotron frequency is decreased below $f_N/(3)^{1/2}$ where f_N is the electron plasma frequency. This is in agreement with kinetic theory. The physical explanation for the observations is that the antenna in the magnetoplasma excites waves with a spectrum of propagation vectors. At the upper hybrid frequency a predominantly longitudinal plasma wave with propagation vector normal to the direction of the static magnetic field and with vanishing group velocity is excited. The energy carried by such a wave will be trapped in the vicinity of the antenna which picks it up resulting in a reflection back to the driving source. The plasma wave responsible for the upper hybrid resonance has an electric field normal to the static magnetic field and hence would couple more efficiently with an electric dipole perpendicular to the static magnetic field.

The radiation characteristics of a loop antenna transmitting in the VLF range and embedded in a warm magnetoplasma have been investigated by *T. N. C. Wang* (Stanford Research Institute, Menlo Park, California). The formal integral solution for the input impedance was derived for a circular loop antenna for two cases, the axis of symmetry oriented either parallel to or perpendicular to the static magnetic field. It is assumed that the current distribution is uniform over the loop and that the effects of finite temperature are included through a scalar-pressure term of the electrons while the ions are assumed to be cold. The integral solutions for the input impedance are valid for arbitrary values of driving frequency, static magnetic field, particle density, and plasma composition. Numerical plots were obtained of the radiation resistance both for orientations of the loop antenna for various loop radii and for typical magnetospheric plasma parameters. Estimates of the loop antenna radiation efficiency in the whistler mode indicates that it can, in general, be greater than 80%. For a small loop it can be shown (using the quasi-static approximation) that the leading term of the input reactance is identical to the self-inductive reactance of the loop in free space.

In summary this session highlighted the considerable progress made in theoretical analysis of antenna behavior in plasmas for a variety of antenna configurations. Meaningful laboratory measurements are just beginning to be achieved. Considerable opportunity still exists for detailed reliable antenna parameter measurements in space plasmas.

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Electron resonances observed with topside sounders

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Ionograms recorded with ionospheric sounders aboard rockets and satellites show signals (resonances) which can persist from a fraction of a millisecond to many milliseconds after the termination of the transmitted pulse. Many of the characteristics of the resonances at the plasma frequency f_N, the upper-hybrid frequency f_T, the harmonic gyrofrequencies nf_B, where $n \geq 2$, and the maximum frequencies of the Bernstein modes f_{Qn} can be explained by propagating electrostatic waves. At frequencies near f_N, f_T, and nf_B, electrostatic waves of slightly different frequencies generated by the transmitted pulse propagate in the ionospheric plasma, become reflected at distances up to several hundred meters away from the satellite, and return to the satellite, producing a continuous receiver response following the transmitted pulse. The resonance observed at the gyrofrequency f_B is not yet understood. Nonlinear properties of the receiving system and/or the plasma can result in resonances observed at the sum and difference frequencies of the principal resonances. Other resoncance phenomena are also discussed.

1. INTRODUCTION

In the last decade much has been learned about the propagation of plasma waves and about the physical properties of the ionosphere from the observation of electron-resonance phenomena using ionospheric sounders aboard rockets and satellites. The word *resonance* will be used here to denote a received signal which persists after the termination of the transmitter pulse of the sounder.

A brief history of the principal resonances observed with sounders aboard two rockets (launched 1961), Alouette 1 (1962), Explorer 20 (1964), Alouette 2 (1965), ISIS 1 (1969), and ISIS 2 (1971) will be given in section 2. The principal resonances (f_N, f_B, f_T, nf_B ($n \geq 2$), and f_{Qn}) will be discussed in section 3. In section 4 other resonance phenomena will be considered, such as the beating of principal resonances, the remote resonance, the diffuse resonance, the floating spike, ionospheric-resonance echoes, resonances at $2f_T$ and $2f_N$, and the proton gyroresonance. Although this paper is mainly a review, some of the author's recent work on the nf_B and f_{Qn} resonances is included. The list of references is representative rather than complete; additional references can be obtained in the reviews by *Chapman and Warren* [1968], *Calvert and McAfee* [1969], *Calvert* [1969], and *Muldrew* [1970].

2. HISTORY

The first observations of electron resonances in the ionosphere were made by two rocket-borne fixed-frequency sounders [*Knecht et al.*, 1961; *Knecht and Russell*, 1962]. In addition to some of the principal resonances, resonances were observed at the X and Z cutoff frequencies. These resonances, which are not observed with satellite sounders, might be caused by electromagnetic waves trapped in local minima of ionization [*Dougherty and Monaghan*, 1969] resulting from outgassing of the rocket.

Shortly after the launch of the Alouette 1 sweep-frequency sounder, the resonances at f_B and nf_B (Figure 1) were identified by *Lockwood* [1963]. It was proposed that these result from n electron bunches oscillating at f_B, with the bunches being caused either by the electric field gradient near the satellite [*Lockwood*, 1963] or by the nonuniform antenna sheath [*Johnston and Nuttall*, 1964]. In addition to the f_B and nf_B resonances, the resonances at f_N, f_T (Figure 1) and $2f_T$ (Figure 7) were identified by *Calvert and Goe* [1963]. They attribute the f_N and f_T resonances to the natural electron oscillations along and across the earth's magnetic field **B**. *Fejer and Calvert* [1964] attribute the principal electron resonances to electrostatic waves of near-zero group velocity. The energy in the waves tends to remain in the vicinity of the satellite with the decay of the resonance resulting from pulse spreading. The resonances at f_N and f_B

result from electrostatic waves with their wave normal **k** approximately parallel to **B**, and f_T and nf_B result from waves with **k** approximately perpendicular to **B**. The excitation mechanism, which was not considered by Fejer and Calvert, was studied by *Sturrock* [1965], *Nuttall* [1965], *Deering and Fejer* [1965], and by *Dougherty and Monaghan* [1966]. These authors determined the field in the vicinity of a short pulsed dipole in a homogeneous plasma. *Shkarofsky and Johnston* [1965] suggested that the motion of the satellite through the generated field should be considered in determining the characteristics of the resonance signals.

Figure 2 [*Calvert and VanZandt,* 1966] shows three Explorer-20 fixed-frequency ionograms illustrating the f_N, $2f_B$, and f_T resonances (the lowest Explorer-20 fixed frequency, 1.5 MHz, is too high for the observation of the f_B resonance). The interference-type fringes are modulated by the satellite spin.

McAfee [1968, 1969a, 1969b, 1970] discovered that the electrostatic waves which initially match the satellite velocity near f_N would quickly be refracted away from the satellite due to the electron-density gradient. By ray tracing he found that these waves could become reflected and return to the satellite. Interference of these rays explain some of the observed fringes. *Bitoun et al.* [1970] obtained similar results for the f_T resonance. *Fejer and Yu* [1970] using WKB solutions, justified the geometrical optics treatment of McAfee, and *Graff* [1970] justified the work of *Bitoun et al.* for delay times exceeding a millisecond. Some types of fringes may be explainable by surface waves on the antenna [*Fejer and Schiff,* 1969].

3. PRINCIPAL RESONANCES

The plasma-frequency resonance. The explanation of the f_N resonance given by *McAfee* [1968, 1969a, 1970] is now generally accepted. In his model, electrostatic waves of frequencies within a few kHz of f_N propagate up to several hundred meters from the satellite, where they are reflected, and return. These echoes can be received for many milliseconds after the transmitter pulse and produce the long duration of the f_N spike when $f_N > f_B$.

Ray paths obtained by *McAfee* [1968] for a horizontal magnetic field and a vertical electron-density gradient with a scale height 400 km are shown in Figure 3. These rays are determined for a given frequency and various angles of incidence. Similar curves could be obtained at different frequencies where the frequencies of interest all lie within the frequency spectrum of the transmitted pulse. If the satellite is moving to the right, after a given time a ray of the type 1, 2, or 3 (called the forward wave by McAfee) and a ray of type 5 or 6 (backward wave) will intercept the satellite. Ray paths 5 and 6 in Figure 3 can intercept the satellite since the direction of energy flow indicated in the figure can, of course, be reversed and these rays can be shifted to the right so that the points furthest to the left in the figure coincide with the starting points of rays 1, 2, and 3. At a given time the forward and backward waves arriving at the satellite will have slightly different frequencies and will interfere to produce a

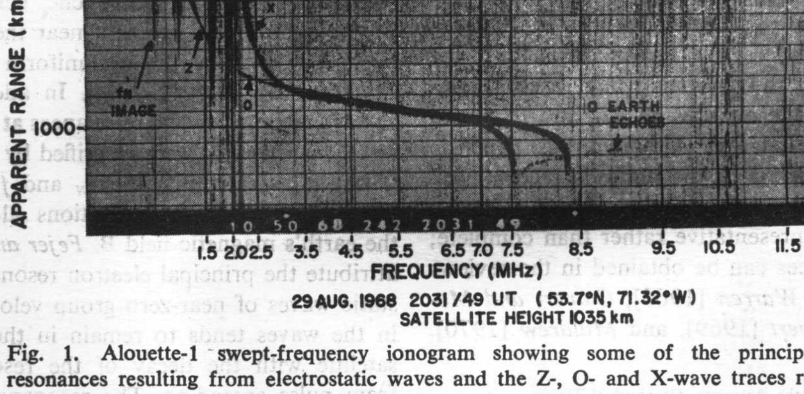

Fig. 1. Alouette-1 swept-frequency ionogram showing some of the principal resonances resulting from electrostatic waves and the Z-, O- and X-wave traces resulting from electromagnetic waves. After *Hagg et al.,* [1969].

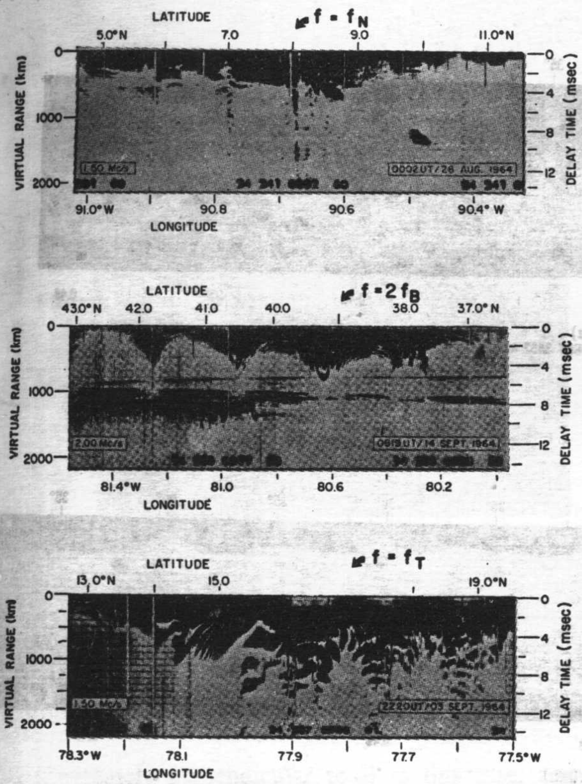

Fig. 2. Explorer-20 fixed-frequency ionograms showing fringe patterns and satellite-rotation effects near principal resonances. After *Calvert and VanZandt* [1966].

fringe pattern on the ionograms as can be seen in Figure 2 and Figure 4. The ray-tracing theory indicates that the interference frequency should increase with time, and it can be seen from Figures 2 and 4 that this is indeed the case. The interference frequency can be used to calculate electron temperature [*Warnock et al.*, 1970; *Feldstein and Graff*, 1972].

However, if $f_N < f_B$ [*McAfee*, 1970], backward waves are no longer possible, and the propagation time of the forward waves has a maximum value. This means that if $f_N < f_B$ fringes of the type mentioned above should not be observed and that the plasma resonance should not persistently ring as it does if $f_N > f_B$. *Benson* [1971a] has verified this experimentally. Figure 4 shows two ISIS 1 ionograms with the swept-frequency portion at the left and the fixed-frequency portion (0.48 MHz) at the right. On the top, $f_N > f_B$, and on the bottom $f_N < f_B$. In both cases, at the time the fixed-frequency ionogram was recorded, f_N was very close to 0.48 MHz. It can be seen that if $f_N > f_B$ the resonance duration or apparent range is large, and fringes of increasing frequency are observed, and if $f_N < f_B$ the duration is small, and no fringes are observed.

The angle between the antenna and **B** is given along the top of the fixed-frequency ionograms (Figure 4). Nulls occur in the signal if this angle is 90° and for $f_N > f_B$ the signal is of extra large duration at angles slightly off 90° [*Calvert and VanZandt*, 1966]. The nulls can be understood assuming the electric field of the transmitted wave is parallel to the antenna. For electrostatic waves, **k** is parallel to **E**. Hence, if the antenna is perpendicular to **B** there is no component of **k** parallel to **B**. Since it is the component of **k** approximately parallel to **B** which is responsible for the f_N resonance a null is to be expected. The signals of large duration on each side of 90° are not yet understood.

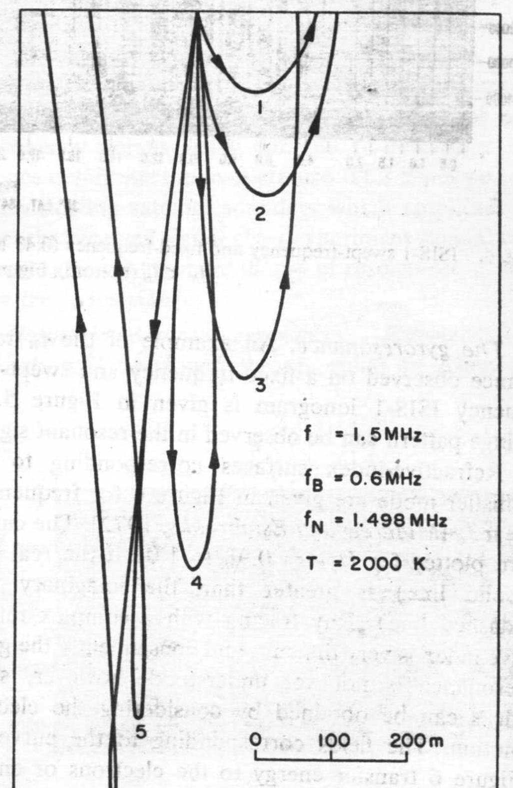

Fig. 3. Ray paths for electrostatic waves near the plasma frequency with a height scale of 4 × 10^5 m. The magnetic field is horizontal. After *McAfee* [1968].

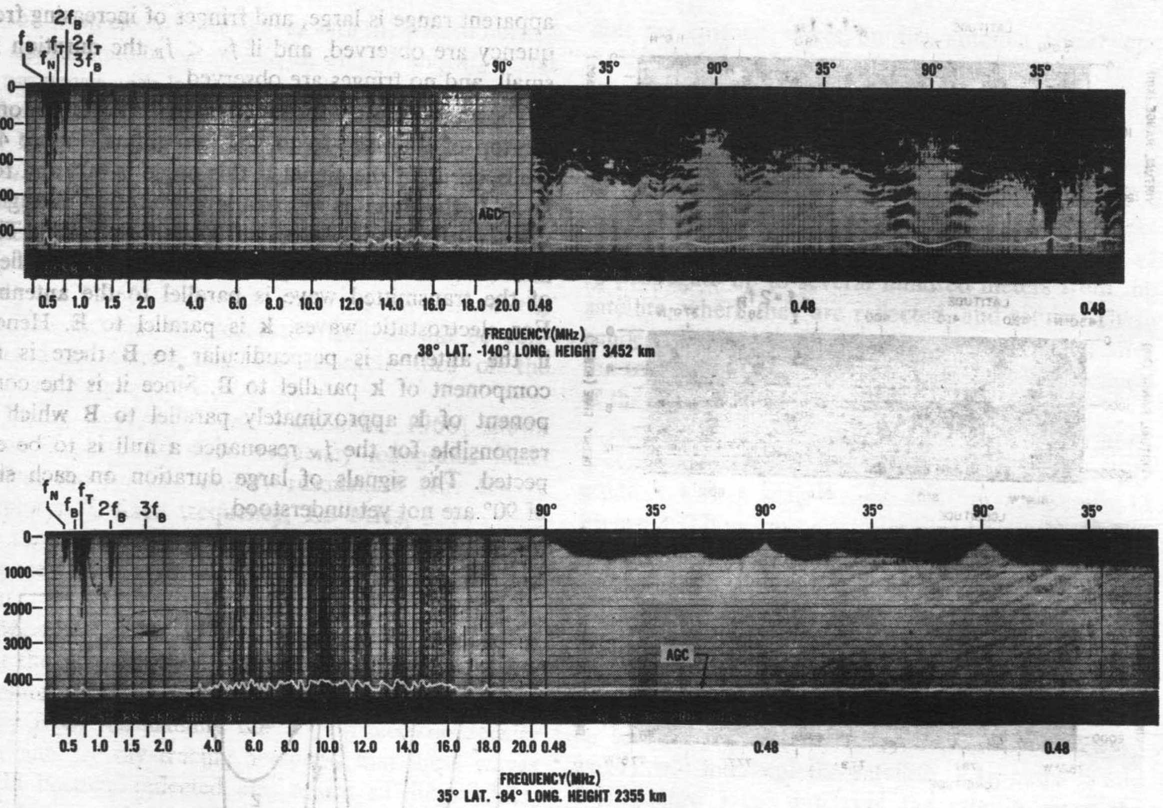

Fig. 4. ISIS-1 swept-frequency and fixed-frequency (0.48 MHz) ionograms illustrating the f_N resonance when $f_N > f_B$ (top), and $f_N < f_B$ (bottom). Figure prepared by G. E. K. Lockwood.

The gyroresonance. An example of the f_B resonance observed on a fixed-frequency and swept-frequency ISIS-1 ionogram is given in Figure 5. A fringe pattern can be observed in the resonant signal.

Refractive-index surfaces corresponding to the whistler mode are given in Figure 6 for frequencies near f_B [*Muldrew and Estabrooks*, 1972]. The curves are plotted for $f/f_B = 0.98$ to 1.01 if the real part (solid line) is greater than the imaginary part (dashed line). Ray tracing with a complex refractive index is very difficult, and consequently the gyroresonance is not yet understood; however, some ideas can be obtained by considering the electron motion. The fields corresponding to the curves of Figure 6 transfer energy to the electrons or energy bunch the electrons at the gyrofrequency [*Lockwood*, 1963; *Muldrew*, 1967]. Due to the large imaginary component of the refractive index, the bulk of the energy would likely be transferred within a few tens of meters of the antenna. The electric field associated with the energy-bunched electrons of frequency f_B could result in the observed resonance.

There are two other fields, besides the one corresponding to the whistler mode, which could contribute to the gyroresonance [*Muldrew and Estabrooks*, 1972]. First, there is the evanescent field at frequencies approximately between the upper-frequency limit of the whistler and the lower limit of the upper-frequency branch of the X wave for which the refractive index has a finite value at $f = f_B$ for $f_B < f_N$ in a hot plasma. Second, for a Vlasov plasma there is an infinite series of dispersion curves for $f \gtrsim f_B$ which correspond to a field which cannot easily be expressed in terms of exponential functions [*Derfler and Simonen*, 1969]. All these curves converge toward zero refractive index as f approaches f_B, and this property may in some way contribute to the observed resonance.

The upper-hybrid resonance. If $f_T < 2f_B$ the dispersion curves are somewhat similar to those for f_N when $f_N > f_B$ [*McAfee*, 1969b]. However, **k** is

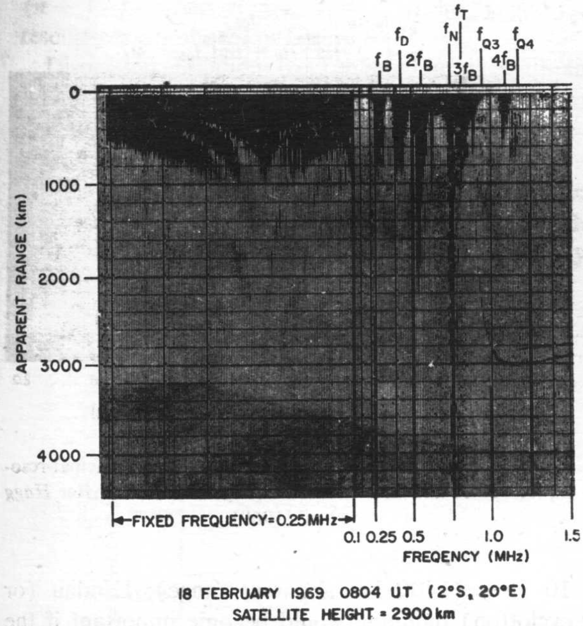

Fig. 5. ISIS-1 ionogram showing the cyclotron resonance on both fixed-frequency and swept-frequency ionograms.

approximately perpendicular to B in this case, and in addition to the forward and backward waves there is a slow electromagnetic wave (right-hand polarized Z wave) which can be reflected and return to the satellite. Dispersion curves have been calculated by *McAfee* [1969b] and by *Bitoun et al.* [1970]; the latter have calculated ray paths for the forward and backward waves. *Graff* [1970] verified the validity

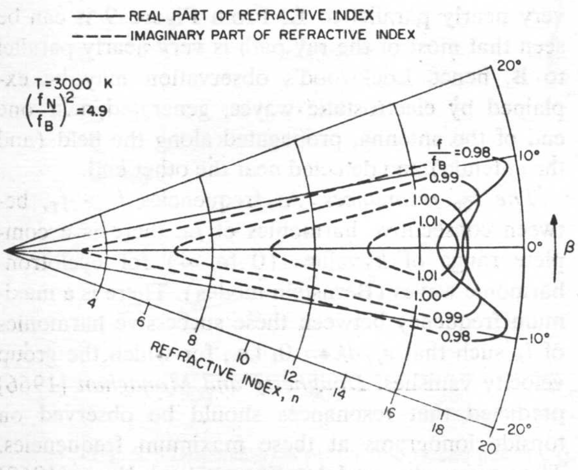

Fig. 6. Complex refractive index curves near the cyclotron frequency.

of this ray-tracing approximation for delays greater than about 1 msec. Beating between the forward and backward waves is only occasionally observed on ISIS-1 ionograms but an excellent example is shown in Figure 7. The beat frequency can be seen to increase with delay (or apparent range) as indicated by theory (Bitoun et al.). The beat frequency could be used to obtain electron temperature at the satellite [*Feldstein and Graff*, 1972].

If $f_T > 2f_B$ the dispersion curves for frequencies near f_T have a completely different character than when $f_T < 2f_B$, and no backward waves are possible. If f_T is only slightly greater than $2f_B$, the minimum group velocity possible is considerably greater than the satellite velocity, and the observed resonances are of much shorter duration than when $f_T > 2f_B$. The fact that a resonance is observed at all, presumably is due to the finite antenna size. If f_T is considerably greater than $2f_B$, minimum group velocities can be less than the satellite velocity, and resonances of long duration are observed again.

McAfee et al. (1972), in a recent rocket experiment, were able to measure the variation of echo frequency versus delay for the f_T resonance and hence determine the temperature. This is not possible with existing satellite sounders which amplitude-detect the received signal. This experiment thus directly verifies the electrostatic theory of resonances, at least for the f_T resonance.

Harmonic-cyclotron resonances. Barrington and Herzberg [1966] found the nf_B spike on Alouette 1

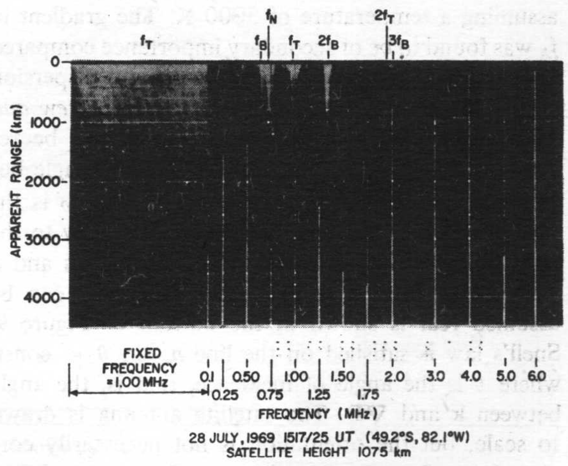

Fig. 7. ISIS-1 ionograms showing fringes on the f_T resonance resulting from interference between forward and backward electrostatic waves.