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FREQUENCY VARIATION IN IONOSPHERIC CYCLOTRON HARMONIC SERIES OBTAINED BY THE ALOUETTE I SATELLITE

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ABSTRACT

Ionograms produced by the Alouette I topside sounder frequently show well-developed series of cyclotron harmonics. Their frequencies have been determined from *A* (amplitude) scans with an accuracy of ~0.02 Mc/s for the sweep range of 1 to 6 Mc/s. In all cases examined, the frequencies of all of the members of the harmonic series are, within the experimental accuracy, integral multiples of the cyclotron frequency derived from the best present estimates of the earth's magnetic field strength at the satellite height. This result is discussed in the light of recent laboratory results and theoretical studies.

I. INTRODUCTION

The ionospheric topside sounder of the Alouette I satellite records, under certain conditions, series of long-enduring signals that are evenly spaced in frequency. These have been identified by Lockwood (1963) as harmonics of the electron cyclotron frequency $\omega_H = eB/(2\pi cm)$ (ω_H is the frequency in radians per second; e and m are the charge and mass of the electron; B is the magnetic field strength) that are excited in the earth's magnetic field at the satellite.

Electron cyclotron harmonic resonance is of considerable general importance. Much of the interest in this field arises from work on thermonuclear fusion where emission at the electron gyrofrequency harmonics, if it occurs, will lead to considerable loss of energy (Bekefi and Brown 1961).

Radiation emitted by a magnetically confined hot plasma was first observed by Wharton (1960), who obtained the second and third, and possibly the fourth, harmonic. Shortly after, the phenomenon was observed also in cold, or in any case subrelativistic, plasmas produced in gas discharges. These experiments are essentially of two types. On the one hand there are Landauer's (1962) emission experiments in which more than 20 harmonics have been observed. On the other hand, there are a number of transmission experiments in which an external signal is imposed on the plasma by one probe and the resonance observed by another probe. An experiment of the latter type has been performed by Crawford, Kino, and Weiss (1964). This specific investigation was stimulated by the artificial earth-satellite experiment which is the subject of this paper.

The observation of electron cyclotron frequency harmonics in the ionosphere constitutes a welcome addition to the comparably few instances in which the phenomenon has been observed in the laboratory. Therefore the results will be discussed here in detail. They ought to provide some additional information on a process that is only partially understood so far. It must be remembered, however, that the satellite experiment has been undertaken for a different purpose and that, as a consequence, not all features of the cyclotron harmonic resonance phenomenon can be determined satisfactorily from it.

2. EXPERIMENTAL RESULTS

The Alouette I satellite is in a near polar, almost circular orbit at an altitude of approximately 1 000 km. It is equipped with a radio-frequency transmitter–receiver system that sweeps, at a rate of 1 Mc/s^2, through the frequency range from 0.5 to 11.5 Mc/s. This range covers the electron cyclotron fundamental frequency and a number of its harmonics for all values of the earth's magnetic field encountered in the orbit.

Ideally one would like to determine the mean frequency, the spectral distribution of the signal amplitude, and its form of decay for the individual resonances in a series. These features are obscured, in part, by the experimental technique. Since the satellite was intended primarily as a topside sounder, it uses short-duration (100-μsec) radio-frequency pulses to provide good altitude resolution of the echoes. The spectrum of these pulses is wider than that of the resonances, as shown by the fact that all the resonances are observed to have approximately the same spectral width as the transmitted pulses. Information on the width of the resonances is confined, therefore, to an upper limit of 15 kc/s, the width of the transmitted pulses.

The fact that the observations are made from a platform that moves with a velocity of about 7 km per second makes the interpretation of the observed duration and frequency dependence of the pulses uncertain. Any conclusions as to the corresponding parameters in a stationary experiment depend on the assumptions made as to the type of resonance process and consequent propagation velocity of the disturbance (see, for example, Shkarofsky and Johnston 1965).

Difficulties in the interpretation of the relative amplitudes in a gyroharmonic series arise from the rotational motion of the satellite, since the amplitudes of the cyclotron resonances are sensitive to the aspect of the antenna with respect to the earth's magnetic field (Lockwood 1965). The different harmonics are registered in sequence and 5 seconds or more may elapse betweeen the recording of the lowest and the highest member of the series. During this time the satellite rotates sufficiently to change the antenna aspect in certain cases. Further, the antenna system consists of two crossed dipoles, one of which is preferentially sensitive to the lower, the other to the higher harmonics. Thus, even if the effects of rotation are absent, the antenna aspect is not the same for the lower and higher harmonics. The automatic gain control of the sounder–receiver may also influence the amplitudes in a way that is difficult to assess for different frequencies. Amplitudes in a harmonic series are therefore not immediately comparable.

The situation is much more favorable with respect to the determination of the frequencies of the resonances. Although the signal observed by the sounder–receiver is rectified and only the pulse envelope is telemetered to the ground, considerable accuracy (see below) can be attained in determining the resonance frequencies on the basis of frequency markers provided by the satellite instrumentation. Any effect that a change of satellite position may have on the frequency of the gyroharmonics in the earth's magnetic field is small, and can, if necessary, be eliminated by comparing satellite passes in opposite directions through the same magnetic latitude range.

Hagg (1963, 1965) has studied the frequencies of gyroharmonic resonances on ionograms obtained by Alouette I, using linear interpolation between the frequency markers. He found, from the higher cyclotron harmonics, values for the earth's magnetic field strength at the satellite which agree within 1% or better with values determined by extrapolation of the ground-level values (Jensen and Cain 1962). He also was able to show, for a carefully selected case where the gyroharmonics coincide with frequency markers on the ionogram, that the series of harmonics consisted of integral multiples of the fundamental ω_H within an accuracy of about 1%.

The present study is an extension of Hagg's work. It is based on the amplitude records of single pulses or *A* scans in contrast to the earlier work using ionograms. The main advantage of using *A* scans lies in the fact that full use can be made of the accuracy of the frequency markers, which is ± 1 kc/s. If, as was done here, successive overlapping third-order polynomials are used for interpolation, the accuracy of frequency determination is within ± 5 kc/s. This is well within the limit of resolution of the single pulses, which is approximately 15 kc/s.*

A source of error in the frequency determination which may well be equally serious whether *A* scans or ionograms are used is the lack of symmetry of the line profiles which makes it difficult to decide on the position of the "center" of the resonance. This asymmetry is, in part, due to the profile distortion brought about by the automatic gain control of the sounder–receiver. Although the momentary gain level can be recorded, the record is not designed for, and not suitable for, quantitative evaluation. Studying a number of resonances that extend over successive pulses, one has, however, the impression that the uncertainty in finding the center of the resonance is due less to distortion by the gain control than to the natural asymmetry of the profile. In practice, an effective center of the resonance was chosen by subjective judgment, taking into account both frequency range and relative amplitudes of the component pulses. Actually, the problem of deciding on the position of the center arises only for the first few harmonics, generally up to $n = 3$; usually the higher harmonics are recorded for a single pulse only.

Owing to the sensitivity to antenna aspect of the resonances, the cyclotron spikes on the ionograms do not always form long series. The records used for the present study were specially selected from among those that do form reasonably long series to cover a wide range of conditions. They comprise series with fundamental cyclotron frequencies ω_H from 0.5 to 0.9 Mc/s, and with plasma frequencies ω_N ranging from 1.2 to 1.9 Mc/s.

*A computing program for the interpolation was provided by Bradford (1964).

For different series of gyroharmonic frequencies, Fig. 1 shows the deviation from strict linearity

$$\omega_n = n\tilde{\omega}_H.$$

Here $\tilde{\omega}_H$ is the unweighted mean value

$$\tilde{\omega}_H = \sum\omega_n/\sum n$$

obtained from the different harmonics ω_n in the series.

As can be seen, the deviation of the observed from the computed frequency $(\omega_n - n\tilde{\omega}_H)$ is only rarely greater than 15 kc/s, the resolution of the single pulses. In considering this close agreement between observed and computed values, one must remember that the computed values are based on an $\tilde{\omega}_H$ which is an empirical mean value obtained from the observations.

3. INTERPRETATION

A number of authors have treated theoretically the excitation of cyclotron resonances in a cold plasma in a magnetic field, and have applied their results

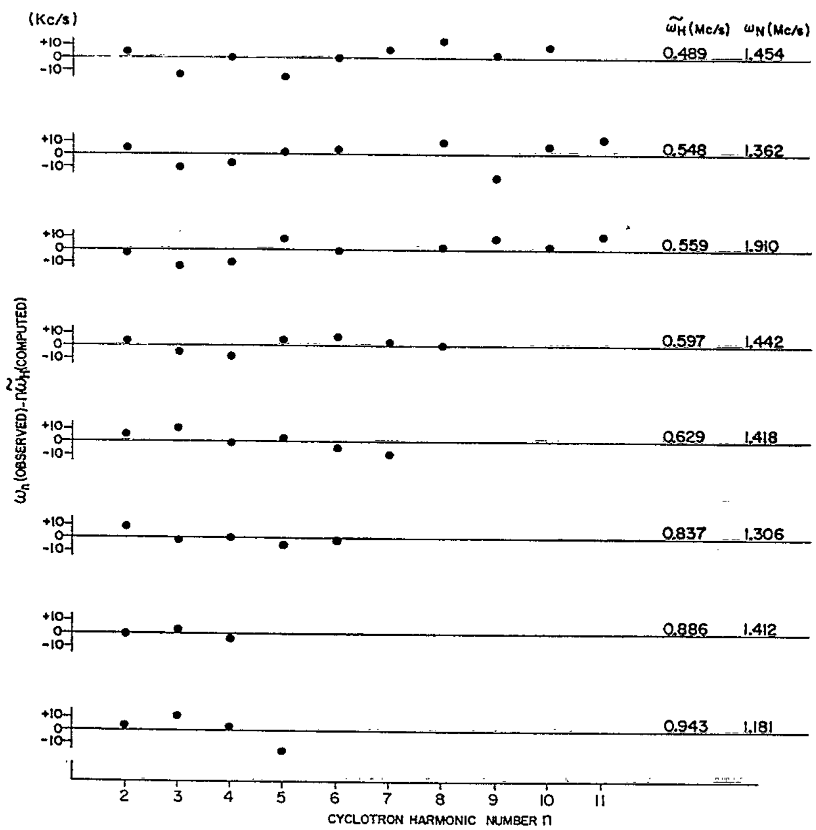

FIG. 1. Differences between the observed gyroharmonic frequencies ω_n(obs.) and the corresponding computed values $n[\sum\omega_n(\text{obs.})]/\sum n$, where the summation is taken over all observed harmonics in a series.

to the Alouette I observations. The earliest interpretation of the cyclotron harmonic resonances obtained in the satellite experiment has been given by Lockwood (1963) in terms of bunching of electrons in phase with the electric field of the transmitter. Johnston and Nuttall (1964) have suggested a similar mechanism of excitation depending on the presence of the electron sheath surrounding the antenna.

Both these processes involve a gradient in the electric field of the disturbances and, consequently, a nonlinearity of the frequency variation, the extent of which, however, has not as yet been determined. To be compatible with observation, the theoretical nonlinearity of the frequency variation would have to be less than one in 10^4.

More recently Sturrock (1965), Crawford, Kino, and Weiss (1964), and Fejer and Calvert (1964) have approached the problem in terms of quasi-electrostatic waves with the wave vector oriented approximately at a right angle to the direction of the steady magnetic field pervading the plasma. These workers have based their discussions essentially on the dispersion equation derived in various forms by Bernstein (1958), Gordeyev (1952), and other authors. It may be written

$$a = e^{-\lambda}\left\{I_0(\lambda) + 2\left(\frac{\omega}{\omega_H}\right)^2 \sum_{n=1}^{\infty} I_n(\lambda)\left[\left(\frac{\omega}{\omega_H}\right)^2 - n^2\right]^{-1}\right\} - 1. \qquad (1)$$

Here $a = (\omega_H/\omega_N)^2\,\lambda$ and $\lambda = k^2\rho^2$; ρ is the cyclotron radius $(2KT/m)^{\frac{1}{2}}/\omega_H$; k is the propagation constant; ω_H and ω_N are cyclotron frequency and plasma frequency, which are dependent, respectively, on magnetic field strength and number density of the electrons. The expressions $I_n(\lambda)$ are modified Bessel functions.

There is general agreement that the dispersion equation (1) is valid for λ values that are not very much less than one. However there are different points of view concerning the values of k and hence of ω that are relevant for the properties of the long-enduring signals observed by the satellite.

Sturrock (1965) analyzes the excitation by an infinitesimal dipole of cyclotron harmonics in a plasma pervaded by a magnetic field. He assumes that the resonance condition is

$$\partial\omega/\partial k = 0$$

(group velocity $v_g = 0$), since under this condition the disturbance transferred to the plasma does not propagate but remains confined to the volume in which it was originally set up until it is dissipated by some loss process such as collisions. Sturrock obtains an expression for the decay in time of signals excited at the resonance frequencies. For a plasma corresponding to the ionosphere at the height of the Alouette I orbit he finds a decay time of 10^3 seconds. Since the observed pulse length of the cyclotron harmonics obtained in the Alouette experiment is only of the order of 10^{-2} seconds, he concludes that in this case the decay process he has considered is not relevant. He suggests that the rapid motion of the receiver out of the region excited by the transmitter produces the observed decay of the resonances.

Shkarofsky and Johnston (1965) make the point that the cyclotron harmonic resonances are associated with k^{-1} values of the order of the free-space wavelength and that for very small λ equation (1) is inapplicable and the full electromagnetic equations must be used. They consider waves that travel at the satellite velocity and obtain the correct order of magnitude for the time decay.

Crawford, Kino, and Weiss (1964) have performed an experiment designed to obtain in the laboratory excitation of electron cyclotron resonances similar to those produced by Alouette I. The laboratory experiment consisted in the transmission of microwave signals between two probes embedded in a gas-discharge plasma in a magnetic field. The strong resonances observed are found to correspond to the solutions of the dispersion equation (1) for $\partial\omega/\partial k = 0$, that is for zero group velocity.

Figure 2 shows graphically the solutions of (1) for the condition $\partial\omega/\partial k = 0$, over the range of values for ω_H/ω_N that applies both to the laboratory and to

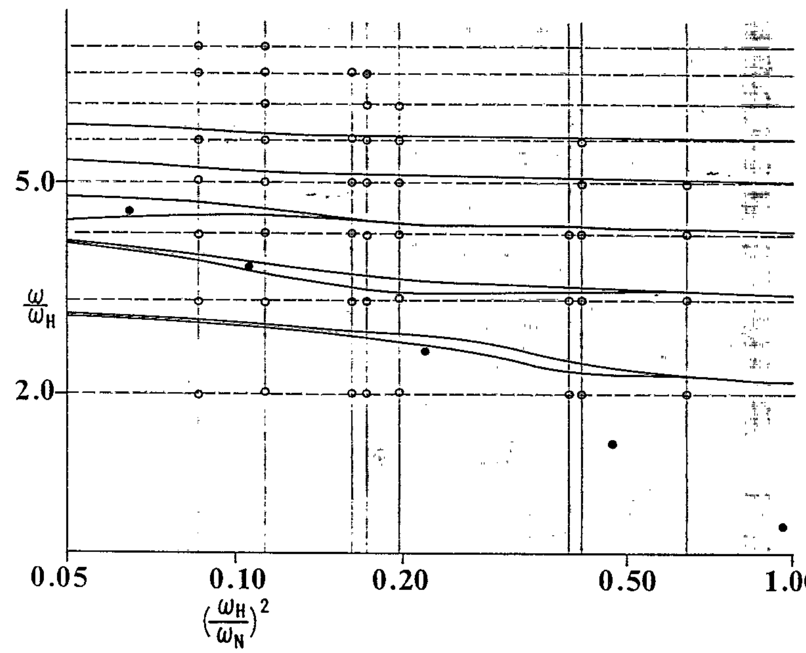

FIG. 2. Variation of ω/ω_H with $(\omega_H/\omega_N)^2$ according to the dispersion formula of Bernstein, for $\partial\omega/\partial k = 0$ (solid lines), according to the laboratory data of Crawford *et al.* (solid circles), and according to the Alouette I experiment (open circles).

the satellite experiment. As can be seen, the examples of laboratory results given fit the theoretical curves very satisfactorily. This is not the case for the resonances obtained with Alouette I. Obviously, in the relevant range of ω_H/ω_N values, the solutions of (1) for $\partial\omega/\partial k = 0$ and constant values of ω_H/ω_N do not follow the simple linear law $\omega_n = n\omega_H$. This discrepancy, it should be stressed, is not due to the difference of temperature, since temperature does not affect the solutions of (1) for $\partial\omega/\partial k = 0$.

The question arises whether the dispersion equation (1) is inapplicable to the Alouette I results, or whether it applies, but with a critical condition different from $\partial\omega/\partial k = 0$. The latter possibility has been explored by Fejer and Calvert (1964), who consider the pulse duration of the various resonances, and obtain satisfactory agreement between theory and observation.

Fejer and Calvert assume that the smallest appreciably excited value of k is determined by the length L of the antenna, according to the relation

$$k \leqslant 2\pi/L.$$

If this is taken into account, the dispersion relation (1), as it applies to the Alouette I experiment, can be simplified considerably. The length of the Alouette I antenna is $L \simeq 50$ m, the gyroradius at satellite altitude $\rho \simeq 10$ cm. The argument of the modified Bessel functions in (1) therefore becomes

$$\lambda = k\rho \leqslant 0.03$$

and

$$\frac{\omega}{\omega_H} = n + \left\{\frac{(k^2\rho^2)^{n-1}}{2^n(n-1)!}\left[\left(\frac{\omega_H}{\omega_N}\right)^2 - \frac{1}{n^2-1}\right]^{-1}\right\}. \tag{2}$$

For small values of $k\rho$, the second term in this equation is unimportant. Therefore

$$\omega/\omega_H \simeq n.$$

This means that only very narrow bands centered on the resonance frequencies $n\omega_H$ are observed for an appreciable time after the exciting pulse.

The approach of Shkarofsky and Johnston (1965), using the full electromagnetic equation and relativistic analysis, also indicates that the order of magnitude of k is $2\pi/L$ and the ω values satisfy $\omega = n\omega_H$ with a small relativistic correction. This result is in agreement with the Alouette I observations.

There are two ways in which the validity of equation (2) and the arguments leading to it might be tested further. One obvious way is to perform the experiment under identical conditions, alternately with a very long antenna and with a very short antenna. If this were done, the experiment with the long antenna should produce linear series of cyclotron harmonic frequencies according to (2); by contrast, the experiment with the short antenna should produce complicated series corresponding to the solutions of equation (1) for $\partial\omega/\partial k = 0$.

The second possibility is provided by the fact that, as the factor $[\omega_H^2/\omega_N^2 - 1/(n^2-1)]$ approaches zero, the second term in (2) becomes important and the cyclotron harmonic frequency concerned may deviate from the linear law $\omega_n = n\omega_H$ by a certain measurable amount.

Equation (2) is most sensitive for $n = 2$, that is for the second harmonic. Using Alouette I amplitude scans, the establishment of any deviation from linearity for $n = 2$ requires that $(\omega_H/\omega_N)^2$ approach $1/(n^2-1) = \frac{1}{3}$ within less than 1%. This in itself is a stringent condition. However, to be useful for the purpose the record in question will have to show a number of higher cyclotron harmonics and some other resonances, for instance ω_N, or $\omega_T = \sqrt{(\omega_N^2 + \omega_H^2)}$, in order to provide a reliable value for ω_H/ω_N.

We have carefully scaled the A scans of about 25 cases, which, judging from the values for ω_H and ω_N given in Alouette I Ionospheric Data ALOSYN (1965) and from the appearance of the ionograms, seemed to be promising test objects. However, it turned out that no case was sufficiently clear-cut to demonstrate or exclude any deviation from linearity. It appears, therefore, that this method is not practical for the Alouette I results. It might be useful, however, for sounding satellites with shorter antennas.

4. CONCLUSION

Careful analysis of Alouette I satellite records has shown that the observed gyroharmonic resonance frequencies follow a strictly linear law. Any deviation greater than 1% from such a law by individual members of the series, or a general nonlinear trend in the series, would have been detected. This result differs from certain laboratory observations. So far no definite choice can be made from the various ideas that have been developed to explain the satellite results.

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