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TITLE

SATELLITE IONOSONDE RECORDS: RESONANCES BELOW THE CYCLOTRON FREQUENCY

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Satellite Ionosonde Records: Resonances Below the Cyclotron Frequency

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R. E. Barrington and T. R. Hartz

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Satellite Ionosonde Records:
Resonances Below the Cyclotron Frequency

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Abstract. *Resonant responses observed by the topside ionosonde in the Canadian satellite Alouette II are examined. In addition to the well-known plasma resonances, several subsidiary resonances are identified below the electron cyclotron frequency. Their patterns of occurrence are not consistent with a suggested explanation of induced magnetic dipole radiation; rather they appear to result from harmonic stimulation of the plasma resonances and beat-frequency generation.*

Data from the topside ionosondes in the satellites Alouette I and II consistently show resonant responses at several well-defined frequencies. The best known of these resonances occur at the cyclotron frequency (or electron gyrofrequency) and its harmonics, and at the fundamental and second harmonics of both the plasma frequency and the upper-hybrid frequency (*1*). Subsidiary resonances have been reported at lower frequencies (*2*, *3*). Barry *et al.* have suggested that some of those appearing below the electron gyrofrequency are attributable to radio reflection by free radicals in the atmosphere; they propose that the observed signals result from induced magnetic-dipole radiation from atmospheric constituents in the vicinity of the spacecraft.

We point out that these subsidiary resonances tend to occur at fractional multiples of the plasma frequency and of the upper-hybrid frequency, as well as of the electron gyrofrequency; consequently the explanation advanced by Barry *et al.* cannot apply in such instances. We propose a different explanation; it involves the nonlinear behavior of the plasma surrounding the spacecraft (and possibly the nonlinearities of the ionosonde system itself) in the generation of harmonics of the transmitted frequency, together with the production of beat frequencies such as have already been identified between the principal plasma resonances (*4*).

Alouette II (*5*) is in an orbit of 80-degree inclination, with apogee and perigee heights of about 3000 and 500 km, respectively. The ionosonde aboard consists of a pulse transmitter and receiver that together sweep from about 0.1 to 15 Mhz during each 30-second period. The pulse length is 100 μsec; the pulse repetition rate, 30 per second. The data received can be displayed as echo amplitude versus delay time relative to the transmitted pulse; these are the so-called A-scan data. The A-scan data are also a function of the frequency of the receiver, and the more conventional portrayal is by combination of A-scans in the form of an "ionogram" showing echo delay and intensity versus frequency.

In general one can identify the various resonances in the ionograms and in the A-scan data with little ambiguity. In this study we have used the A-scan data in order to benefit from a possible advantage in sensitivity. Moreover, as the receiver has an automatic-gain-control circuit, most of our data were selected under conditions of very low voltage of the automatic gain control, when the video sensitivity would be maximum.

Figure 1 shows the occurrence of resonances for a series of consecutive 30-second recordings, as a function of frequency. The principal plasma resonances at the electron gyrofrequency f_H, the plasma frequency f_N, and the upper-hybrid frequency f_T are identified in each frame, and the sequential variation of these resonances can be traced readily. The low-frequency end of each frame shows the additional or subsidiary resonances that are the subject of this report. Note that there is not the same sequential continuity here as for the principal resonances; the subsidiary resonances appear and disappear somewhat irregularly from frame to frame. Furthermore, the sequence of subsidiary resonances does not appear to vary directly with the f_H sequence; rather it seems to vary somewhat like the f_N or f_T sequences in this example; for instance, f_H decreases slightly from frame to frame, whereas the frequency of corresponding subsidiary resonances appears to increase—much as f_N is increasing.

Figure 1 does not include the higher harmonics of the principal plasma resonances. At least the second and third (and usually a number of higher) harmonics of f_H appear in each ionosonde record (*6*), as well as the second harmonic (and in a few instances the third harmonic) of f_N and f_T; thus the ionosphere in the vicinity of the spacecraft is resonant at frequencies of at least f_N, $2f_N$, f_T, $2f_T$, f_H, $2f_H$, and $3f_H$.

Recordings were selected from a number of satellite passes over three different geographic regions under conditions such that f_H and f_N were changing systematically throughout the pass.

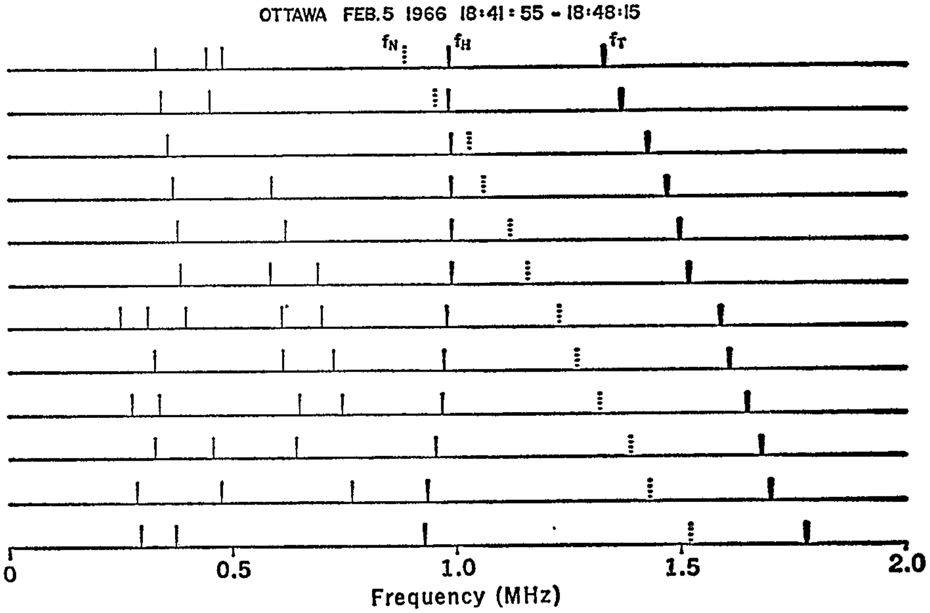


Fig. 1. Ionosonde data obtained on a pass by Alouette II over Ottawa. The resonances observed on the successive frequency sweeps are identified as the plasma frequency f_N, the electron gyrofrequency f_H, and the upper-hybrid frequency f_T. Additional resonances indicated in the left-hand portion of the diagram exemplify occurrence of the subsidiary resonances.

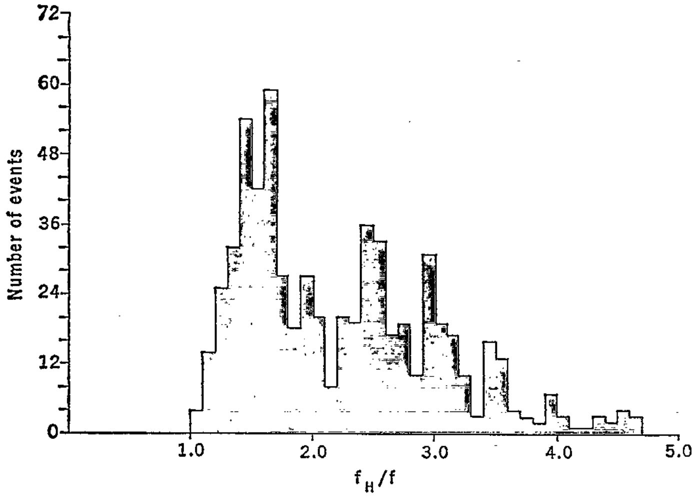
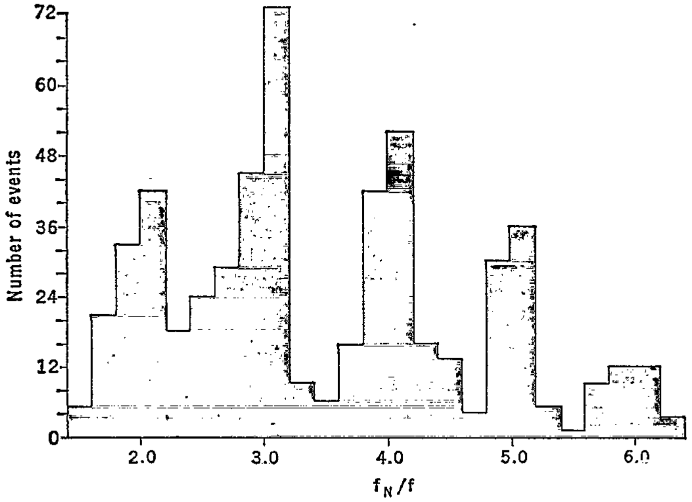
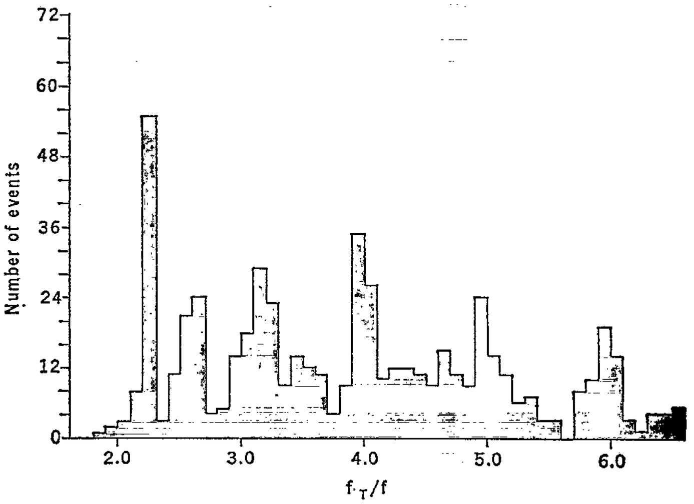


Fig. 2 (left). Distribution of the subsidiary resonance occurrence as a function of f_H/f.

Fig. 3 (below left). Distribution of the subsidiary resonance occurrence as a function of f_N/f.

Fig. 4 (below right). Distribution of the subsidiary resonance occurrence as a function of f_T/f.





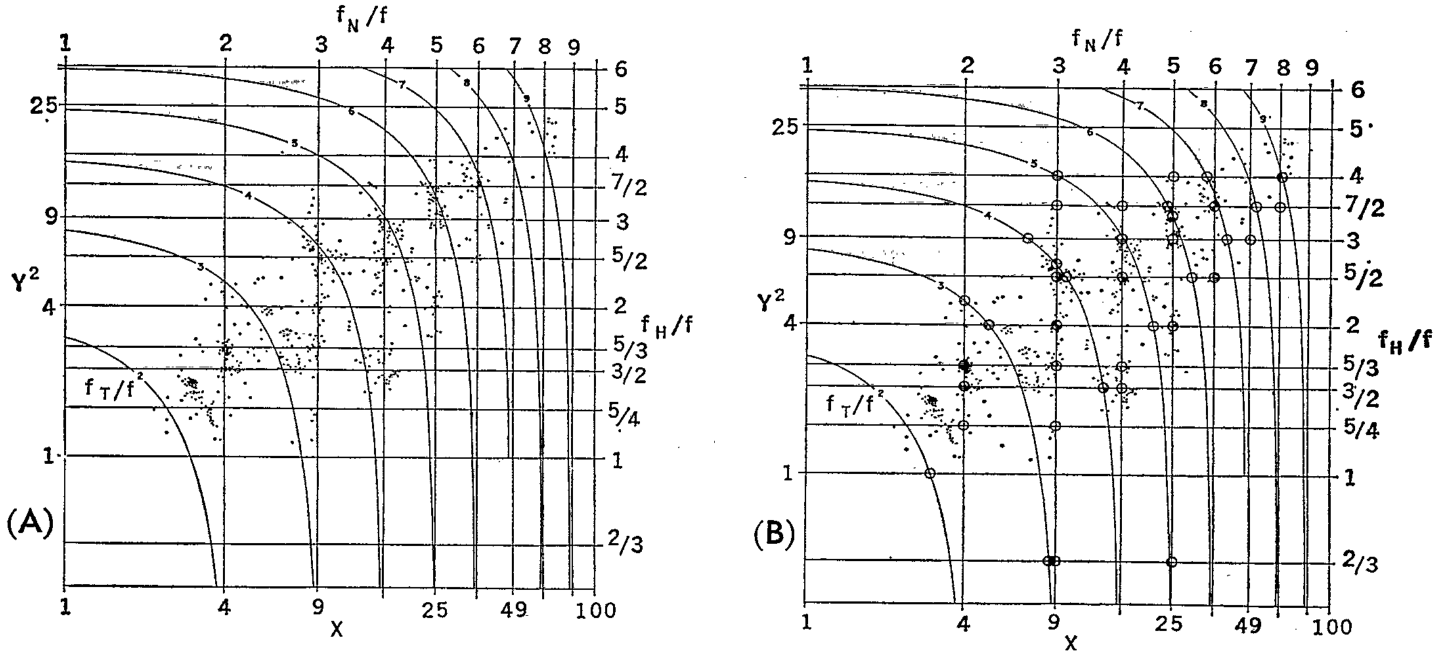


Fig. 5. (A) Distribution of the subsidiary resonances on a C.M.A. diagram; for easy reference, lines have been indicated for particular values of f_T/f, f_N/f, and f_H/f, as indicated. (B) The circles mark locations in the C.M.A. diagram at which subsidiary resonances are expected on the basis of the proposed process; for comparison, the true observations are also included.

Data similar to those of Fig. 1 were obtained for such passes, and from these the frequencies of the subsidiary resonances, relative to f_H, f_N, and f_T at the corresponding times, were determined; the resultant data appear in Figs. 2–4 in the form of histograms of occurrence as functions of f_H/f, f_N/f, and f_T/f. Because of the well-resolved peaks in these histograms and because the same data sample was used in each instance, it is immediately apparent that the subsidiary resonances are related to each of the electron gyrofrequency, the plasma frequency, and the upper-hybrid frequency. An acceptable explanation of the subsidiary resonances must satisfy this triple dependency.

In Fig. 2 the main peaks appear at f_H/f values of $^3/_2$, 2, $^5/_2$, 3, and $^7/_2$; thus a subsidiary resonance appears in the recordings when the ionosonde is at a frequency of $2/3$, $1/2$, $2/5$, $1/3$, and $2/7$ of the electron gyrofrequency. Similarly, the main peaks in Fig. 3 appear at f_N/f values of 2, 3, 4, and 5, the indication being that a subsidiary resonance appears when the ionosonde is at a frequency of $1/2$, $1/3$, $1/4$, and $1/5$ of the plasma frequency. The fact that the same data sample is included in these two histograms makes it appear that a simple fractional relation with f_H and f_N is satisfied simultaneously for production of a resonance.

This conclusion is also supported by the fact that on occasion clearly identifiable ionospheric echoes appear in the records at nonpropagating frequencies. These echoes can be explained as due to propagation of a pulse at an overtone of the transmitted frequency, which, on return to the vicinity of the spacecraft, beats with an ionospheric resonance stimulated by a different harmonic of the transmitter frequency; the beat frequency in such instances is also the receiver frequency.

On other occasions clearly recognizable transmissions from loran stations have appeared in the records at frequencies other than those used by loran transmitters; these signals can be similarly explained as a beat between the normal loran frequency and an ionospheric resonance that is harmonically related to the ionosonde transmitter.

An analogous line of reasoning applies to Fig. 4 also; as before, we can conclude that subsidiary resonances appear at particular subharmonics of f_T. Again the simultaneity argument suggests that a simple fractional relation exists between the subsidiary resonances and two, or perhaps all three, of f_H, f_N, and f_T. The nature of this relation is such as to produce resonant responses at specific subharmonics of the ionospheric resonances f_H, $2f_H$, f_N, and f_T, but this does not necessarily mean that the satellite receiver will observe these subsidiary resonances.

The additional and necessary condition for observation of a subsidiary resonance appears to be that the ionospheric resonances, that are excited as simple harmonics of the transmitter frequency, must differ by an amount that is the receiver frequency. For example, if the ionosonde happens to be tuned to a frequency f_1 under conditions such that, say, nf_1 equals $2f_H$ and $(n + 1)f_1$ equals f_N (n being an integer), we expect both the $2f_H$ and f_N resonances to be excited; then, in a manner similar to that demonstrated by Hagg (*4*), these two resonances may produce a beat frequency at f_1 to which the satellite receiver can then respond.

This situation can be demonstrated by replotting of the data on a graph in which Y^2 ($= f_H{}^2/f^2$) is the ordinate, and the abscissa is X ($= f_N{}^2/f^2$). Such graphs, termed C.M.A. diagrams, have already proved their usefulness in connection with wave phenomena in a plasma (*7*). Figure 5A shows the positions of the observed resonances as dots; the various lines in the graph are integral or simple fractional values of f_H/f, f_N/f, and f_T/f, as indicated. The data points clearly tend to cluster about certain preferred locations on this plane, corresponding to the peaks in the histograms (Figs. 2–4). Concentrations may be recognized, for instance, at $f_N/f = 3$, $f_H/f = 2$, and at $f_N/f = 4$, $f_H/f = 3$. On the other hand, no concentrations appear at $f_N/f = f_H/f = 3$, at $f_N/f = f_H/f = 4$, or at $f_N/f = 4$, $f_H/f = 2$.

We have identified on the C.M.A. diagram (Fig. 5B) by means of small circles some of the most propitious resonance conditions that would satisfy our explanation. Because of the demonstrated dependence (Fig. 4) on the upper-hybrid frequency, we expect subsidiary resonances to occur at the beat frequencies between all the harmonically excited ionospheric resonances, including the f_T and perhaps also the $2f_T$ resonance. We have included in this diagram the observations of the subsidiary resonances also; these data points should cluster preferentially in the vicinity of the small circles to justify our explanation.

Notably there is generally good agreement between the observations and the expected results. The spread of the points about the expected values can probably be attributed to a combination of the finite bandwidth of the receiver, and the changing ionospheric conditions during the frequency sweep of the ionosonde, and to the fact that the process itself must have a finite bandwidth since two ionospheric resonance conditions must be satisfied simultaneously.

We conclude, then, that, except for certain cases to be described later, we have identified the processes that produce the subsidiary resonances in the data from Alouette II's ionosonde. This explanation readily accounts for the observed dependence of such resonances on ionospheric electron density, which the explanation of Barry *et al.* does not do. We expect, moreover, that our explanation will explain the observations of the $\frac{3}{2}f_H$ resonance (*2*), but further data must be examined for clarification of some of the conditions set on the appearance of that resonance.

The exceptional cases involve certain fractions of the f_T resonance, and are contained in the left-hand portion of the histogram in Fig. 4 and in the bottom-left of Fig. 5. Contrary to our expectations, the data do not show a peak at an f_T/f value of 2, and give only a questionable response at a value of 3, although strong peaks appear at values of 4, 5, and 6. Prominent peaks do appear at the irrational values of $5\frac{1}{2}$, $7\frac{1}{2}$, and $10\frac{1}{2}$ (within the accuracy of measurement), and additional secondary peaks may be recognizable at other irrational values. The significance of these unexpected irrational values is not yet clear. We point out, however, that f_T [$= (f_N{}^2 + f_H{}^2)^{1/2}$] is not a linear function of the plasma frequency and the electron gyrofrequency, and our results on harmonic excitation may contain valuable clues as to the nature of this hybrid resonance. Further work is obviously required for clarification of these exceptional cases.

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