Reports

Satellite Ionosonde Records: Resonances Below the Cyclotron Frequency

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

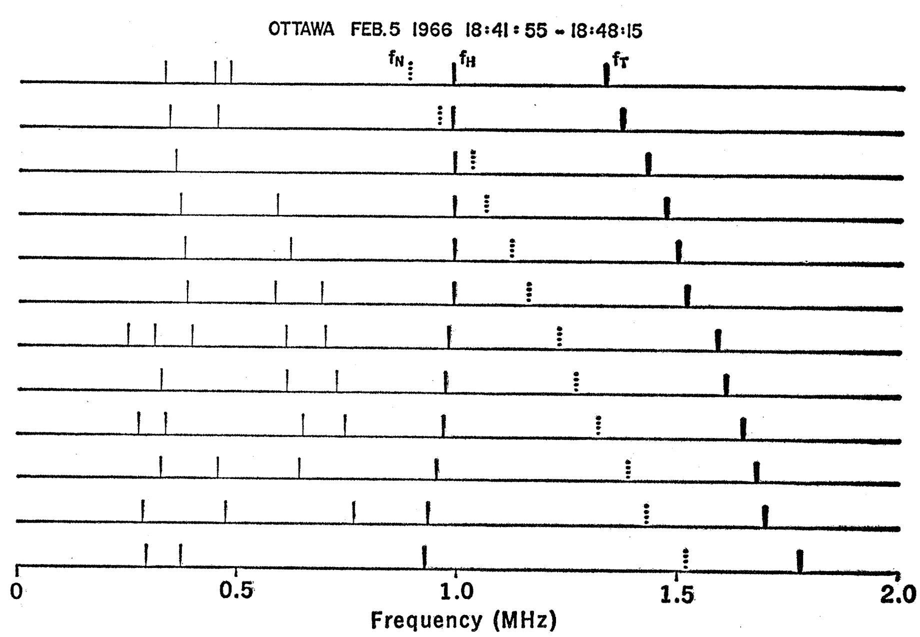


Fig. 1. Ionosonde data obtained on a pass by Alouette II over Ottawa. The resonances observed on the successive frequency sweeps are identified as the plasma frequency f_N, the electron gyrofrequency f_H, and the upper-hybrid frequency f_T. Additional resonances indicated in the left-hand portion of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

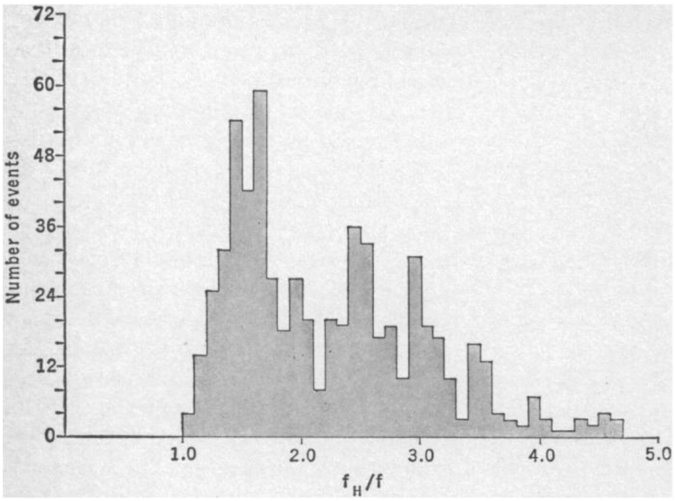
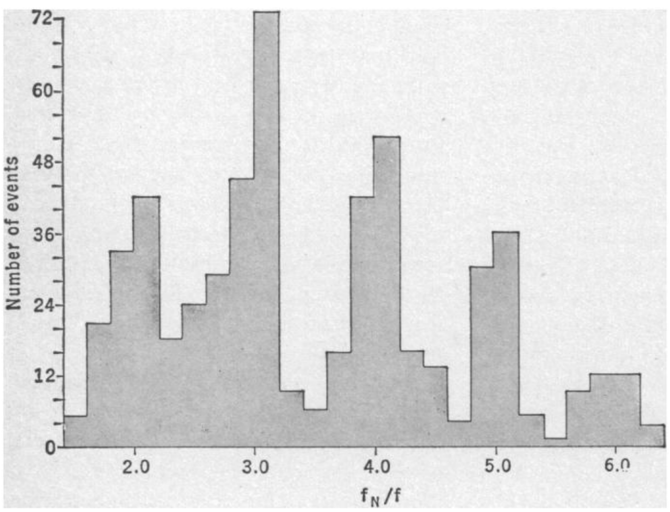
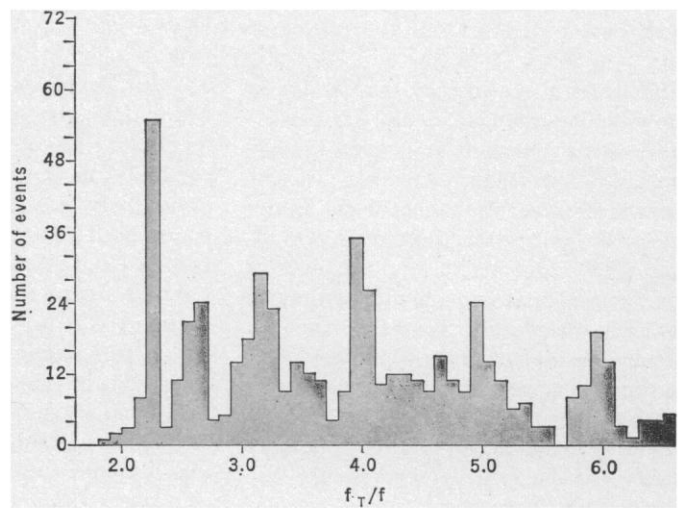


Fig. 2 (left). Distribution of the subsidiary resonance occurrence as a function of f_H/f.

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.





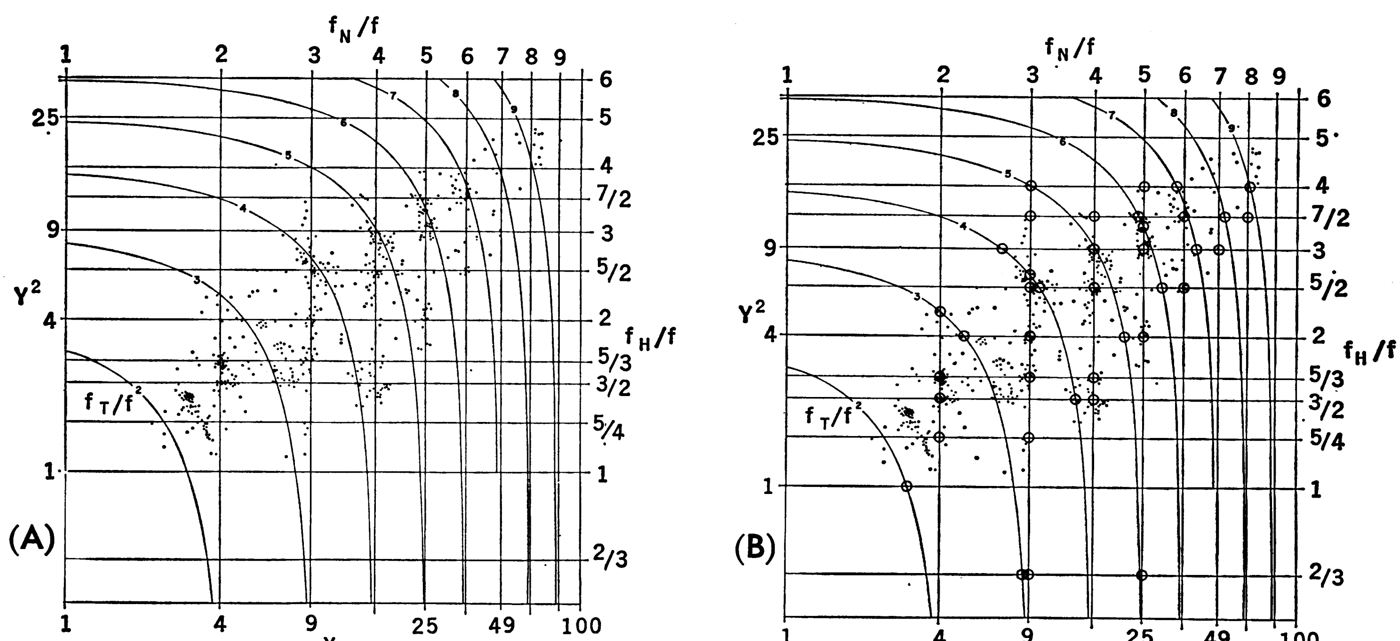


Fig. 5. (A) Distribution of the subsidiary resonances on a C.M.A. diagram; for easy reference, lines have been indicated for particular values of f_T/f, f_N/f, and f_H/f, as indicated. (B) The circles mark locations in the C.M.A. diagram at which subsidiary resonances are expected on the basis of the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

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. 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 ⅔, ½, ⅖, ⅓, 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 ½, ⅓, ¼, and ⅕ 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 5½, 7½, and 10½ (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 $[= (f_N^2 + f_H^2)^{½}]$ 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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Mummy Cave: Prehistoric Record from Rocky Mountains of Wyoming

Abstract. *Archeological materials from 8.5 meters of deposits in a stratified rock shelter in the Absaroka Mountains near Yellowstone National Park provide a projectile point sequence and cultural record beginning more than 9000 years ago, and include evidence of human occupation during the Altithermal period.*

Mummy Cave is located on a bend of the North Fork of the Shoshone River in the Absaroka Mountains of northwestern Wyoming. The cave (altitude, 1922 m) is cut into the northeast wall of the valley near the mouth of Blackwater Creek and is immediately adjacent to U.S. Route 20, 54.7 km west of Cody, Wyoming, and 19 km east of Yellowstone Park.

The mountains, which are the eastern extension of the Tertiary volcanic rocks of the Yellowstone Plateau, are deeply dissected in the area of the site, with relief up to 1220 m. The North Fork valley, in which the site lies, is the only passageway in the area leading from the Big Horn Basin around Cody (altitude, 1525 m) to the plateau to the west (altitude, 2440 m).

The cave is a large alcove in a cliff of south-dipping beds of volcanic breccia and tuff. Because of its similarity to an alcove being cut in similar rocks now at river level near Clocktower Creek, the cave is believed to have been formed largely by the erosive action of the North Fork as it cut downward through the volcanic strata. After cutting the alcove, the river shifted its course slightly, and a thick pile of talus and colluvium from the roof and walls of the alcove and from the cliff above gradually accumulated in the cave. In this fill the artifacts and bones were found.

Of special geological interest is the evidence from carbon-14 dating, from the lower part of the fill, that shows that the river must have been at its present level approximately 10,000 years ago and that it has done little downcutting since. According to radiocarbon dates, in general, the rate of accumulation of sediment declines from approximately 2.4 m per thousand years near the base to approximately 0.22 m per thousand years near the top. The rate varies considerably in between.

Significant to the remarkable preservation of bones and perishable cultural materials is the dryness of the cave and its fill. This dryness is due to the low permeability of the overlying rocks, the wide spacing of joints in the immediate vicinity of the cave, and the small catchment area for precipitation provided by the knifelike summit of the ridge containing the cave.

The cave fill, as cross-sectioned by the excavations, consisted of 38 distinct layers with evidence of human occupation contained within 8.5 m of detrital sediment. Radiocarbon dates derived from charcoal (available for about half the layers) start about 7280 B.C. for culture layer 4, and end at A.D. 1580 for culture layer 38 (Fig. 1). The occupied layers consist of gray sandy silt mixed with ashes, charcoal, angular rockfall fragments, animal bones, plant remains, and artifacts. Ash-filled hearths, sometimes containing stones but never lined, are present in several levels. Culturally sterile strata (2 to 30 cm thick) consisting of colluvium and interbedded, thin silt layers separate the occupation layers from one another.

The lower and middle layers of the fill, below about 2.7 m from the surface, generally produced few artifacts, and these were principally chipped stone projectile points. In the upper layers, artifacts occurred in much greater numbers and variety; and layers 30 to 36 (Fig. 1) yielded, in addition to 300 or more points, other objects of stone, bone, wood, animal skin, and plant fiber. Pottery fragments were found only in the uppermost culture layer, within 20 to 30 cm of the surface. The identifiable animal bone shows a surprising range of forms, including at least five bird species, 30 or more mammal species, a very heavy incidence of mountain sheep, but few deer, and almost no bison. The plant remains have not been identified. Pollen was poorly preserved and for the most part could not be identified.

Projectile points were found in 22 levels. They appeared first at a depth of 8 m in layer 4 and continued upward with notable changes in form, size, and other particulars through time (Fig. 1). Medium to large leaf-shaped points with narrow bases occurred exclusively in layers 4 through 15, from about 7280 to 6000 (carbon-14) years B.C. They then give way in layers 16 through 19 (5600 to 5200 B.C.) to side-notched points that suggest eastern plains forms. Stemmed and shouldered types follow; and by about 2500 B.C. points of the well-known McKean type and its variants (*1*) appear in some numbers. Along with these in layer 30 (about 2470 ± 150 B.C.), there were tubular bone pipes, coiled basketry fragments, bits of vegetable fiber cordage and netting, wood trimmings, leather scraps, many flint chips, and animal bones, and other perishable and imperishable materials. Grinding stones that were probably used by inhabitants who relied somewhat on the gathering and crushing of seeds also appear at this level and again in layer 36, dated at about A.D. 720; but these stones are much less common than in Archaic stations on the Great Plains or in the Great Basin. They are associated in the later level with small corner-notched points that have finely serrate edges, and with steatite, basketry, worked wood and leather, abundant bone scrap and flint chips, and various other articles. The dessicated body of an adult male wearing a mountain sheepskin garment, interred from layer 36 about 1230 years ago as judged by radiocarbon dating, gives the site its name.

It is abundantly clear that during the last 9000 years or more the cave was occupied, abandoned, and reoccupied many times, probably by people coming into the locality from widely different directions, but all of whom tended to adjust their lifeways to a mountain-adapted subsistence economy. The leaf-shaped points from the lower levels are similar to forms that are widely distributed throughout the montane regions of Idaho, Montana, and Wyoming, and are found also on the plains to the east. The side-notched points resemble those found with *Bison occidentalis* at the Simonsen site (*2*) in northwestern Iowa and also at Logan Creek in eastern Nebraska, and they suggest that peoples or cultural influences from east of the Rocky Mountains arrived in the locality. Points from layers 21 through 28 are of types apparently found only in