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A NOVEL IONOSPHERIC CYCLOTRON RESONANCE PHENOMENON OBSERVED ON ALOUETTE I DATA

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A NOVEL IONOSPHERIC CYCLOTRON RESONANCE PHENOMENON OBSERVED ON ALOUETTE I DATA

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ABSTRACT

Characteristics of an extraordinary wave trace recently identified on Alouette I topside ionograms, and called the remote resonance trace by Hagg (1966), are discussed in detail. From the observations it has been deduced that the radio energy associated with the production of this trace propagates along an ionospheric magnetic field-aligned wave guide. The electric field of an h.f. wave propagating along such a guide would have a gradient normal to the earth's magnetic field, and because of this gradient the wave could excite an electron-cyclotron resonance in a region of the ionosphere that includes the height where the wave frequency is equal to twice the electron gyrofrequency. At some time delay after the wave has passed through the resonant region, the resonating electrons generate an extraordinary wave, which propagates upward along the guide and is subsequently received by the satellite. This wave is responsible for the production of the remote resonance trace. The equation for the time delay is given and the resonance trace computed, using this equation, is shown to be in good agreement with the observed resonance trace for a specific ionogram.

INTRODUCTION

Ionospheric plasma resonances have been observed in both rocket and satellite experiments, and these resonances have been discussed by many authors (Knecht *et al.* 1961; Knecht and Russell 1962; Lockwood 1963; Calvert and Goe 1963; Johnston and Nuttall 1964; Lockwood 1965; Barrington *et al.* 1965). Fejer and Calvert (1964) have given an explanation of the various resonances observed with the Alouette topside sounder (at the plasma frequency f_N, the electron gyrofrequency f_H, the hybrid frequency $f_T = \sqrt{(f_N^2 + f_H^2)}$, and the multiples of the gyrofrequency) in terms of electrostatic oscillations of the ionospheric electrons in the vicinity of the satellite. Shkarofsky and Johnston (1965) give an explanation of the cyclotron harmonic resonances observed by satellites in terms of plasma waves whose group velocity at the resonant frequency is equal to the velocity of the satellite. The resonances discussed above are excited in the vicinity of the satellite. Hagg (1966) demonstrated that a resonance occurs in the ionosphere, remote from the satellite, at the height at which the frequency of the extraordinary wave is equal to $2f_H$. Further characteristics of this resonance (called the "remote resonance") are discussed here, and a model explaining the observations is indicated.

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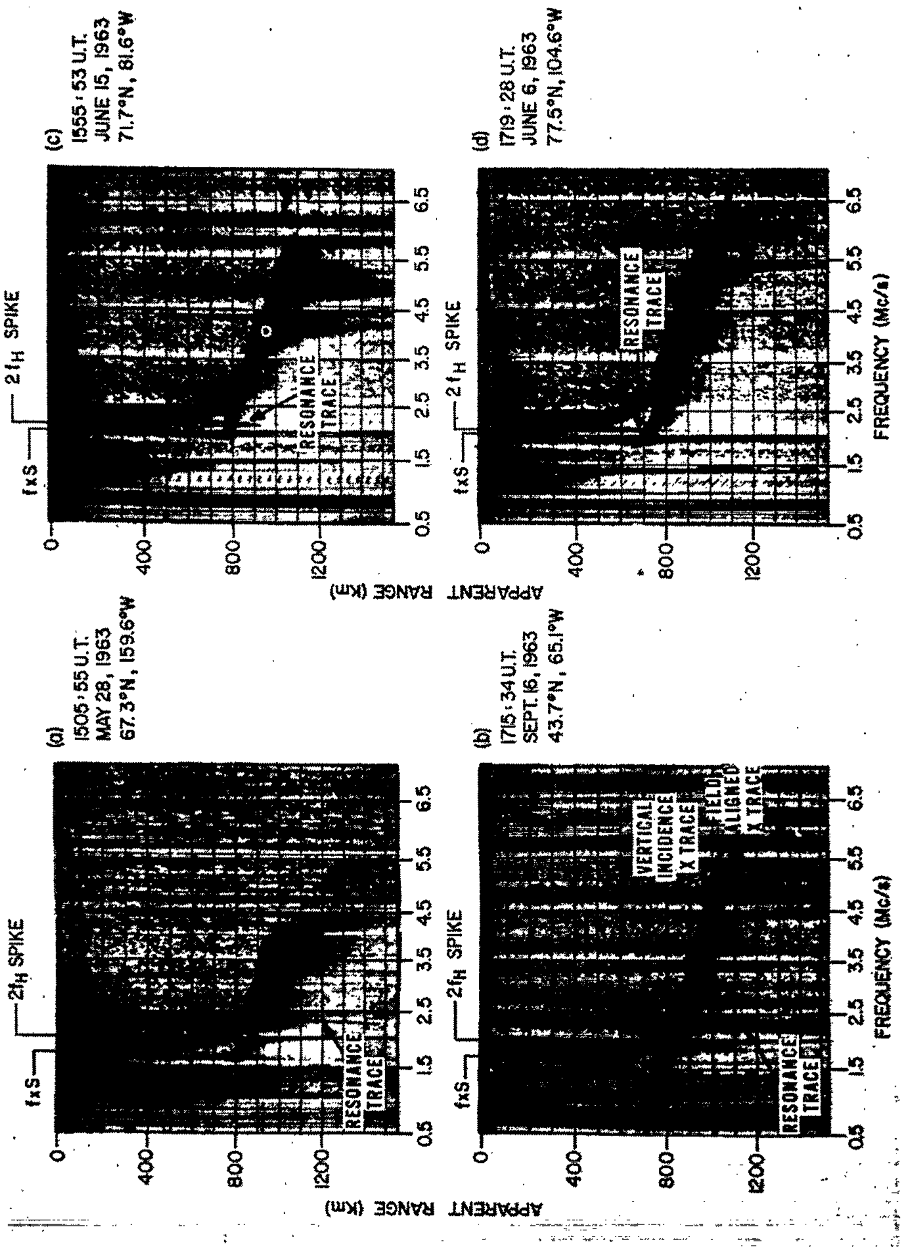
(a)
1505:55 U.T.
MAY 28, 1963
67.3°N, 159.6°W
(b)
1715:34 U.T.
SEPT. 16, 1963
43.7°N, 65.1°W
(c)
1555:53 U.T.
JUNE 15, 1963
71.7°N, 81.6°W
(d)
1719:28 U.T.
JUNE 6, 1963
77.5°N, 104.6°W
fxS
2fH SPIKE
RESONANCE TRACE
VERTICAL INCIDENCE X TRACE
FIELD ALIGNED X TRACE
APPARENT RANGE (Km)
0
400
800
1200
FREQUENCY (Mc/s)
0.5
1.5
2.5
3.5
4.5
5.5
6.5

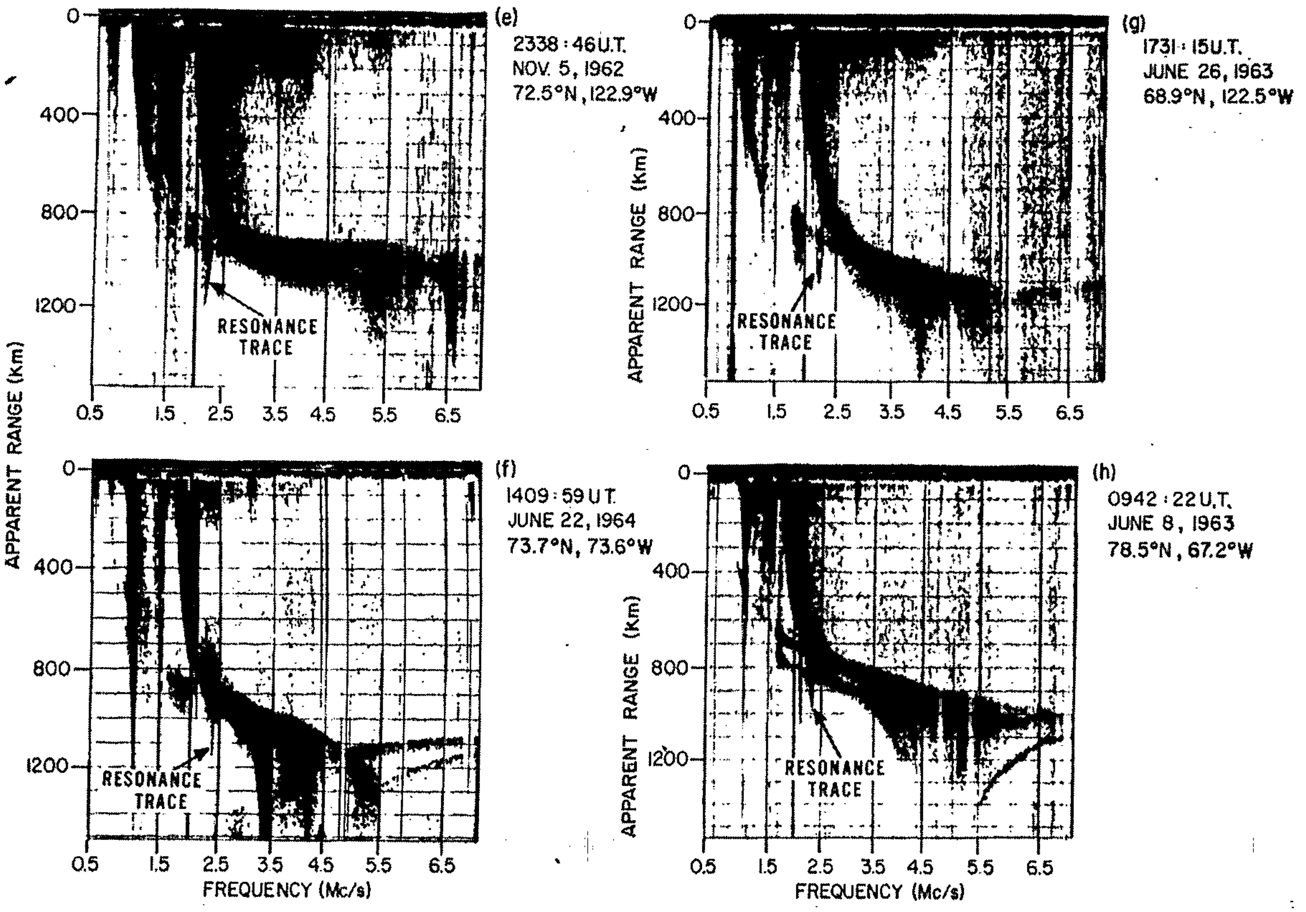

FIG. 1. Ionograms, recorded by the Alouette I topside sounder, illustrating the resonance trace.

CHARACTERISTICS OF THE REMOTE RESONANCE

Topside ionograms showing the trace produced by the remote resonance (resonance trace) are presented in Fig. 1. A schematic diagram of the resonance trace in Fig. 1(*a*) is presented in Fig. 2(*a*). In Fig. 1(*a*) the lowest observed frequency of the resonance trace occurs at a delay time corresponding to an apparent range of about 1 450 km. At slightly higher frequencies it appears at rapidly decreasing range and subsequently joins the extraordinary wave trace. The frequency at which the resonance trace meets the extraordinary reflection trace will be called the "cutoff frequency" f_c (see Fig. 2(*a*)). The second harmonic cyclotron spike ($2f_H$ spike) caused by a local resonance at the satellite is also indicated on the ionogram.

In the majority of cases, the resonance trace is similar to that shown in Fig. 1(*f*); it appears as a short vertical trace (about 200 km in apparent range) protruding from the spread *F* of the extraordinary wave trace. The other ionograms in Fig. 1 were selected to illustrate some of the outstanding features of the resonance trace.

Figure 1(*b*) shows a resonance trace that is particularly well defined; it occurs on an ionogram recorded at 54° N. geomagnetic latitude. Resonance traces are very seldom observed on ionograms recorded at latitudes as low as this. Figure 1(*c*) shows a resonance trace with a low-frequency limit equal to that of the $2f_H$

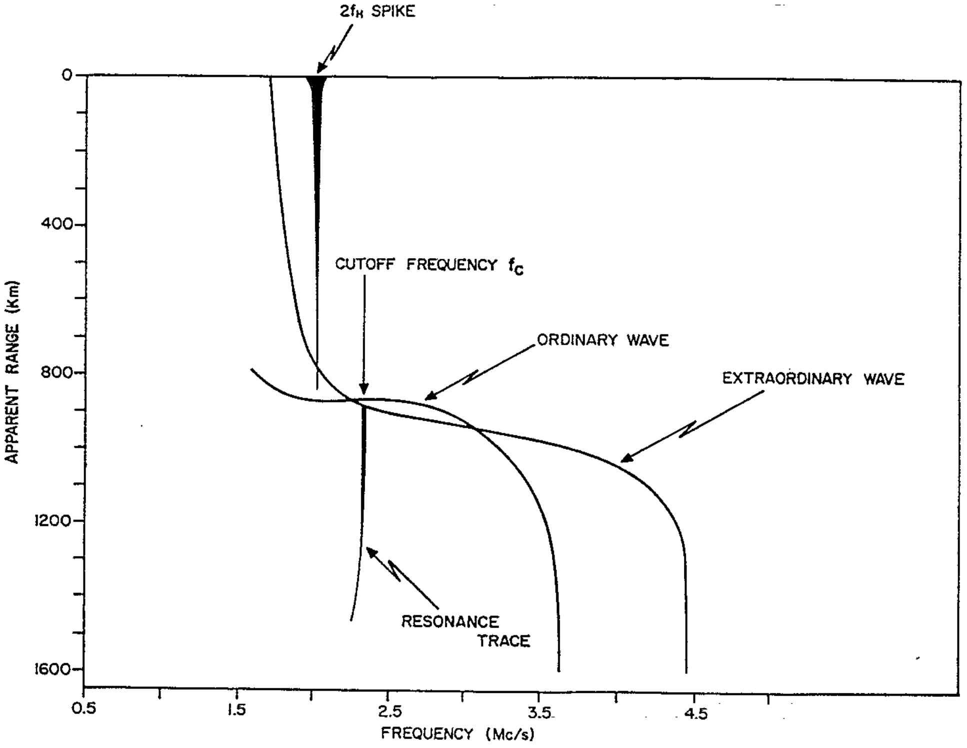

Fig. 2(*a*). A schematic diagram of the ionogram in Fig. 1(*a*) (after Hagg 1966).

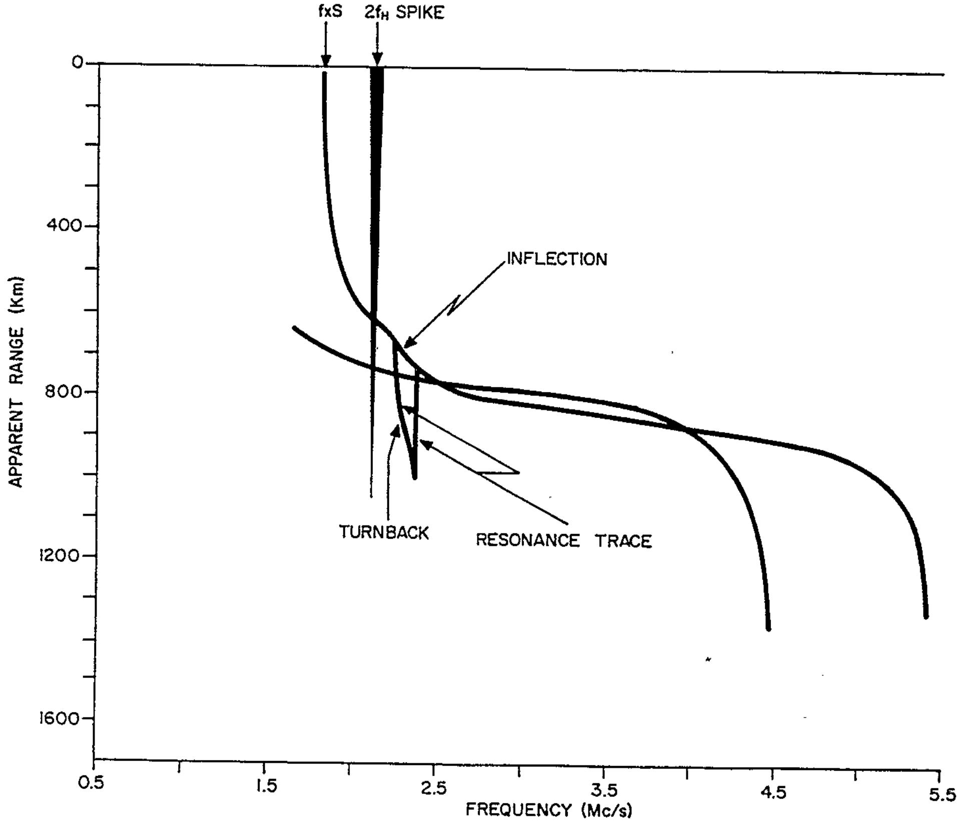

FIG. 2(*b*). A schematic diagram of the ionogram in Fig. 1(*h*).

spike; this has been observed on a few occasions. The resonance trace has never been found to extend below the frequency of the $2f_H$ spike. Figure 1(*d*) shows a resonance trace that was recorded when the $2f_H$ spike was at a frequency only slightly greater than f_xS (the frequency of the extraordinary wave reflected at the height of the satellite). If the $2f_H$ spike is at a frequency less than f_xS, no resonance trace is observed. Figure 1 (*c*), (*d*), and (*e*) illustrate that the resonance trace is associated with the extraordinary wave and not with the ordinary wave. Figure 1(*e*) demonstrates that if the resonance trace shows spread *F*, then this spread *F* occurs between the trace and the $2f_H$ spike. Figure 1 (*g*) and (*h*) show a reversal in apparent range (turnback) of the resonance trace (see Fig. 2(*b*), that is, as the frequency decreases from f_0 the apparent range increases to some maximum and then decreases. This is related to the inflection (see Fig. 2(*b*)) that can be seen in the extraordinary wave trace. This turnback in the apparent range will be discussed in more detail later in this paper. It should be stated that the resonance traces in Figs. 1(*g*) and 1(*h*) showing reversal in apparent range are exceptional. In fact, only these two were observed in a study of several thousand ionograms on which resonance traces could be identified.

The remote resonance trace is only observed on ionograms that show moderate to extreme spread F and the spread echoes must occur to the height of the satellite.

The series of amplitude recordings (A-scans) in Fig. 3 for the ionogram of Fig. 1(*b*) show the echoes resulting from the remote resonance. At frequencies near 1.96 Mc/s, the maximum amplitude of the local $2f_H$ resonance ($2f_H$ spike) can be observed. At 2.12 Mc/s the remote resonance echo is first seen on the record. As the frequency increases, the signal strength of the remote resonance echo increases until it reaches a maximum at the resonance cutoff frequency (2.23 Mc/s). The received signal strength of the remote resonance echo at the cutoff frequency is still somewhat below the received signal strength of the regular extraordinary wave echo.

No resonance traces have been found to be associated with the third or higher harmonics of the cyclotron frequency.

MAGNETIC FIELD-ALIGNED PROPAGATION

The observation that the resonance trace occurs only when spread F extends to the height of the satellite indicates that ionization irregularities (causing spread F) existing only at the height at which the remote resonance occurs are not a sufficient condition for the observation of the remote resonance. Apparently these irregularities must exist from the height at which the remote resonance occurs right up to the satellite. If spread echoes occur up to the height of the satellite, then field-aligned sheets of ionization or field-aligned ionization irregularities probably extend up to the height of the satellite. Field-aligned propagation could thus occur at all heights from the satellite to the height at which $f = 2f_H$. Since spread F extending up to the height of the satellite is a special requirement for the observation of the resonance trace, in order that the remote resonance trace be observed on Alouette ionograms it may be that the energy associated with the production of the trace must propagate along field-aligned irregularities or sheets of ionization.

Field-aligned propagation may occur along field-aligned sheets of ionization (Muldrew 1963) or along field-aligned ducts (Knecht *et al.* 1961; Calvert *et al.* 1963). In particular examples Muldrew found sheets to be of the order of 1 km thick. A sheet implies a large extension in the east–west direction; in principle, propagation may occur along a sheet with an electron density that is either greater or less than the background electron density. A duct implies a tube of ionization. In order that a tube of ionization may guide a wave propagating as an extraordinary wave (upper-frequency branch), the index of refraction of the tube must be greater than the ambient index of refraction, since the wave is refracted away from regions of decreased index of refraction. For convenience the phrase "ionospheric wave guide" will be used here to mean either sheets or ducts of ionization.

The ionogram of Fig. 1(*b*) contains an additional extraordinary wave trace with an apparent range about 50 km greater than the vertical incidence extraordinary wave trace. Some of the ionograms recorded preceding and following this ionogram have similar traces. The difference in apparent range

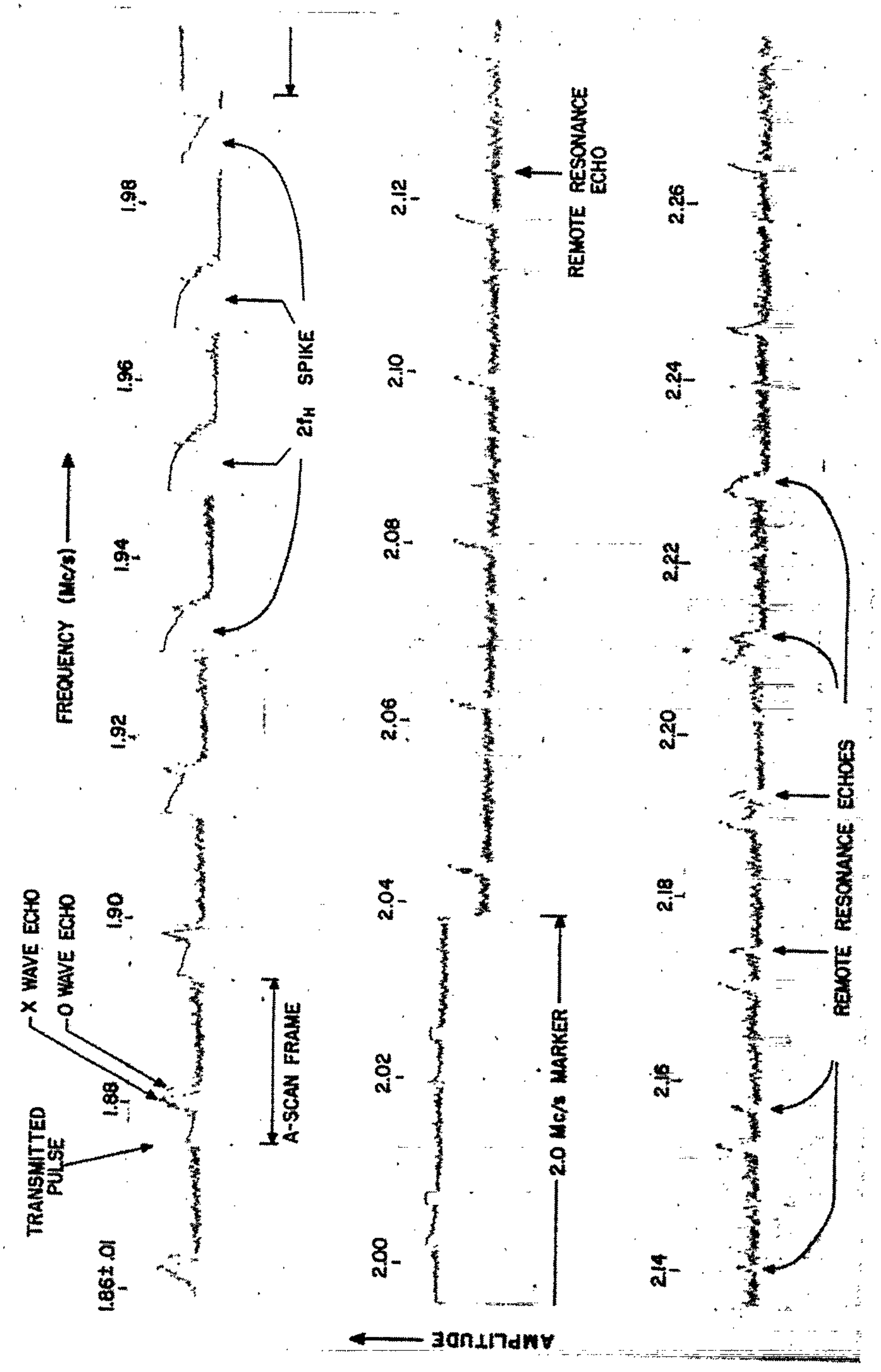

FIG. 3. *A* (amplitude) scans for the frequency range from 1.86 to 2.28 Mc/s for the ionograms of Fig. 1(*b*).

$\Delta h'$ at 5.0 Mc/s between this additional trace and the vertical incidence trace is plotted (with an "X") as a function of time (and latitude) for these ionograms in Fig. 4. On the assumption that the additional trace is caused by propagation along ionospheric wave guides, $\Delta h'$ can be calculated as a function of latitude. Muldrew (1963) indicates that the height of reflection of a wave propagating along a field-aligned wave guide in the topside ionosphere is very nearly the same (within one or two kilometers) as the vertical-incidence reflection height. Thus if the apparent range of the extraordinary wave reflection trace at 5.0 Mc/s is h' and I is the magnetic dip at the satellite, then, (1) assuming no horizontal gradient of electron density, and (2) neglecting the dependence of index of refraction on the angle ν between the wave normal and the direction of the earth's magnetic field, the apparent range of the field-aligned trace can be approximated by $h' \csc I$. Thus $\Delta h'$ is given approximately by

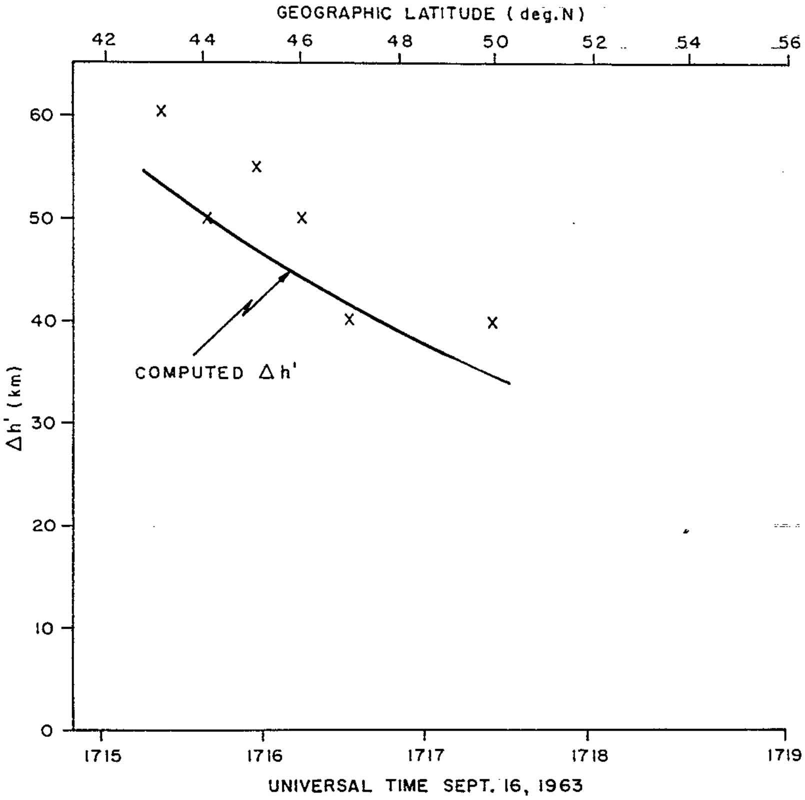

FIG. 4. The difference in apparent range at 5.0 Mc/s between the two extraordinary wave traces of six ionograms preceding, including, and following the ionogram of Fig. 1(*b*).

$$\Delta h' = h'(\csc I - 1). \tag{1}$$

The position of the satellite and hence the magnetic dip at the location of the satellite at the times when the echoes near 5.0 Mc/s were recorded on the ionograms is known quite accurately (Jensen and Cain 1962), and thus $\Delta h'$ can be plotted as a function of time as shown by the smooth curve of Fig. 4. The effect of the dependence of the index of refraction on ν was calculated by ray tracing for one of the ionograms (given in Fig. 1(*b*)). It was found that this effect increased the apparent range of the field-aligned trace by about 3 km. If this effect were the same for all of the ionograms used in the construction of Fig. 4, the smooth curve in the figure could be shifted upward by about 3 km.

There is an estimated error of 5 to 10 km in determining the observed value of $\Delta h'$ from the ionograms. Neglecting the horizontal gradient in the electron-density distribution could cause an appreciable error in the computed value of $\Delta h'$ near the extraordinary wave critical frequency; however, at 5.0 Mc/s the error is probably no more than 5 km.

It can be seen in Fig. 4 that the computed curve and the observed values of $\Delta h'$ are in good agreement. The rate of change of $\Delta h'$ with the latitude of the points agrees with the smooth curve. This indicates that the additional trace in the ionogram of Fig. 1(*b*) is a field-aligned extraordinary wave trace. (Field-aligned traces occurring at the latitude at which this ionogram was recorded are not common.) Thus at the time the resonance trace of the ionogram of Fig. 1(*b*) was recorded, field-aligned propagation occurred. This is consistent with the suggestion made above that the energy associated with the production of the resonance trace propagates along the earth's magnetic field. At higher latitudes than that at which the ionogram of Fig. 1(*b*) was recorded, the dip is greater and the separation between the vertical incidence trace and the field-aligned trace becomes less; consequently, it becomes more difficult or even impossible to observe two separate traces.

Propagation along field-aligned ionospheric wave guides would result in a considerable gain in the energy arriving in the height region at which $f \simeq 2f_H$ over the energy that would arrive if the propagation were not confined to a wave guide. This gain is undoubtedly an important factor in determining the strength of the remote resonance echoes.

THE MODE OF PROPAGATION

An explanation of the remote resonance must account for the following experimental observations:

1. When the resonance trace is observed, spread *F* occurs from the height at which $f = 2f_H$ right up to the height of the satellite.
2. A gyroresonance is generated at the height at which $f = 2f_H$ (Hagg 1966).
3. Remote resonance traces are associated with extraordinary and not ordinary wave traces.
4. The apparent range of the remote resonance trace decreases rapidly with increasing frequency.
5. On rare occasions a turnback in apparent range of the remote resonance trace is observed.
6. The lowest observed frequency of the remote resonance trace is always equal to or greater than the frequency of the $2f_H$ spike (that is, the remote resonance trace is only observed when the height at which $f = 2f_H$ is below the height of the satellite).

A number of models of the mode of propagation responsible for the remote resonance trace have been conceived, but each of them was found to be unsatisfactory because it did not explain one or more of the above experimental facts. In particular, the requirement that the remote resonance occur only when the height at which $f = 2f_H$ is below the satellite eliminates most of the simple models. Therefore, an investigation was undertaken of the motion of the electrons, in the height region at which $f \simeq 2f_H$, under the influence of an electromagnetic pulse propagating along an ionospheric wave guide. The following is a qualitative description of the major features of the model; the derivation of the equations describing the motion and energy of the electron is lengthy and will be presented in detail in two papers by Muldrew (1966*a*, *b*). An electromagnetic pulse propagating along an ionospheric wave guide is confined to a region that is about a kilometer thick. Thus a relatively large gradient in the electric field of the pulse would occur in a direction perpendicular to the direction of the earth's magnetic field. Because of this gradient, an extraordinary wave pulse can cause electrons oscillating about the field at the gyrofrequency to become energy bunched (i.e., electrons with certain phases gain energy from the pulse, whereas electrons with other phases lose energy to the pulse). In the height region of the ionosphere where $f \simeq 2f_H$ there are two energy bunches and initially, that is at the time the pulse passes through the region, the phase of the energy-bunched electrons will have a variation with height determined by the wave length. It was found that if the initial phase of the energy-bunched electrons, in the height region of the ionosphere where $f \simeq 2f_H$, is produced by an extraordinary wave pulse propagating in the direction of increasing magnetic field, then at some time delay after the passage of the pulse the variation of the phase with height becomes identical with the phase that would be caused by an extraordinary wave pulse propagating in the opposite direction. This phase variation apparently produces an extraordinary wave pulse of frequency f propagating in the direction of decreasing magnetic field. On the other hand, if the initial phase is set up by a pulse traveling in the direction of decreasing magnetic field, no pulse is generated at any time. The time delay τ, to a good approximation for $I > 70°$, is found (Muldrew 1966) to be

$$\tau = \frac{2}{3}\frac{r}{c}n = \frac{2}{3}\frac{r}{c}\sqrt{1 - \frac{2f_N{}^2}{f^2}}, \tag{2}$$

where τ is in seconds, c is the velocity of light, n is the index of refraction for the extraordinary wave of frequency f, and f_N is the plasma frequency at the height r (measured from the earth's center) in the ionosphere at which $f = 2f_H$.

The mode of propagation (i.e., the path taken by the radio energy) involved in the generation of the resonance trace is then as illustrated in Fig. 5. A pulse of frequency f transmitted from the satellite propagates downward, along an ionospheric wave guide, through the height A in the ionosphere where $f = 2f_H$. After a time delay τ, the distribution of the phase with height of the energy-bunched electrons at A becomes identical with the distribution that would be produced by an upward-propagating extraordinary wave pulse of frequency f. A pulse is apparently generated which propagates upward along the ionospheric

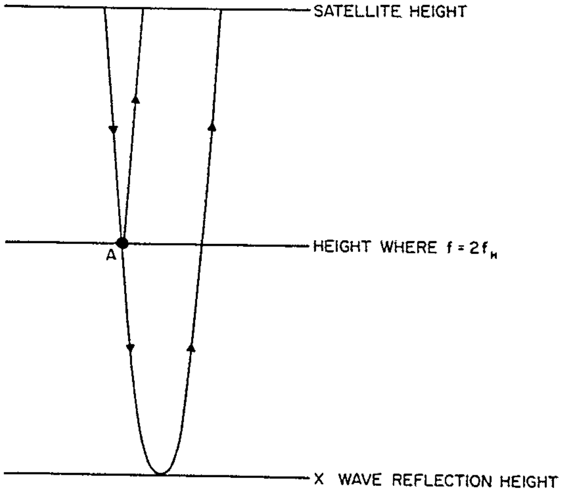

FIG. 5. Mode of propagation of the radio energy associated with the production of the resonance trace.

wave guide to the satellite, and is responsible for producing the resonance trace on the ionogram. The total time delay of the generated pulse may be calculated by adding to τ twice the time required by the extraordinary wave to propagate from the satellite to height A.

Time delays calculated on the basis of the above propagation mode were compared with those observed experimentally for the remote resonance trace of Fig. 1(*b*). The time required by the extraordinary wave to propagate from the satellite to the height A was determined by means of a ray-tracing computer program; some of the properties of this program are discussed by Muldrew* (1963). To perform the ray tracing it was necessary to obtain a plasma-frequency profile (curve of plasma frequency vs. height) from the field-aligned reflection trace of the ionogram (Lockwood and Nelms 1964). To facilitate the ray tracing, a parabolic curve was fitted to this plasma-frequency profile and the resulting profile is shown in Fig. 6. The time required for the extraordinary wave to propagate from the satellite to the height at which $f = 2f_H$ was determined from this profile, and the time τ was determined from equation (2). The calculated apparent range of the remote resonance echoes is shown as a function of frequency by the continuous curve in Fig. 7. The experimental resonance trace in the ionogram of Fig. 1(*b*) was scaled from the A scans and is drawn in the figure as a series of vertical lines. These lines give the apparent range over which the resonance trace is observed for each sweep line (or each A-scan frame) on the ionogram.

In calculating the smooth curve of the resonance trace in Fig. 7 there are two main sources of error. The maximum estimated error in the Jensen and Cain value of the gyrofrequency is about ±10 kc/s. The maximum estimated error in

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*The term $1 - n^2$ in equation (5) of Muldrew (1963) should be $(1 - n^2)^2$. The correct form of the equation was used in the calculations made in the paper.

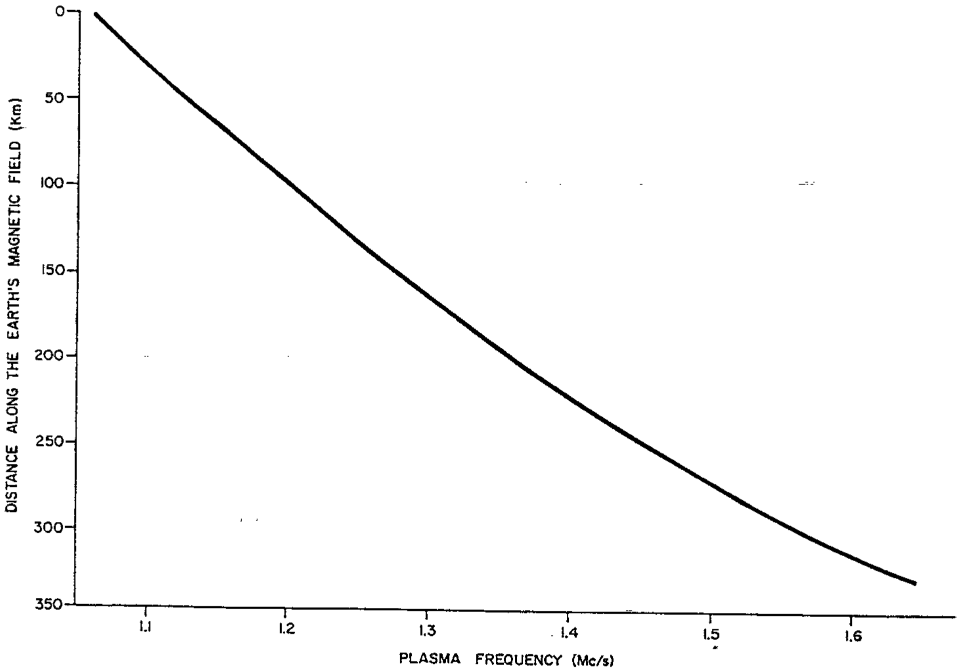

FIG. 6. The distribution of plasma frequency with distance along the magnetic field.

the profile of plasma frequency as a function of height is also about ±10 kc/s in the plasma frequency at a given height. The frequency of the individual remote resonance echoes can be determined from the *A* scans to within about ±6 kc/s. If the continuous curve of the remote resonance trace in Fig. 7 (calculated from the above model using (2)) were shifted about 12 kc/s towards lower frequencies, it would very nearly pass through the center of the observed remote resonance echoes. A shift of 12 kc/s is within the limits of accuracy; the calculated resonance trace is thus in good agreement with the observed resonance trace.

The reversal in apparent range (turnback) of the resonance traces of Fig. 1(*g*) and (*h*) can now be explained in terms of the above model. In the frequency interval in which the range reversal occurs, there is an inflection in the extraordinary wave trace (see Fig. 2(*b*)). In Fig. 1(*h*) (see Fig. 2(*b*)) the resonance trace actually returns to the extraordinary wave trace at a lower frequency than the cutoff frequency. Figure 8 shows qualitatively the extraordinary wave reflection height and the height where $f = 2f_H$ over a series of decreasing frequencies. Above the cutoff frequency (f_1) the resonance mode cannot occur. At the cutoff frequency (f_2) the heights coincide. At a lower frequency (f_3) the separation between the heights increases to a maximum, and at a still lower frequency (f_4) the distance between the heights begins to converge. At some frequency (f_5) they again coincide. From (2), the index of refraction and hence τ increases from zero (at f_2) to some maximum (at f_3) and then decreases again to zero (at f_5). Under these conditions, as the frequency decreases, the resonance

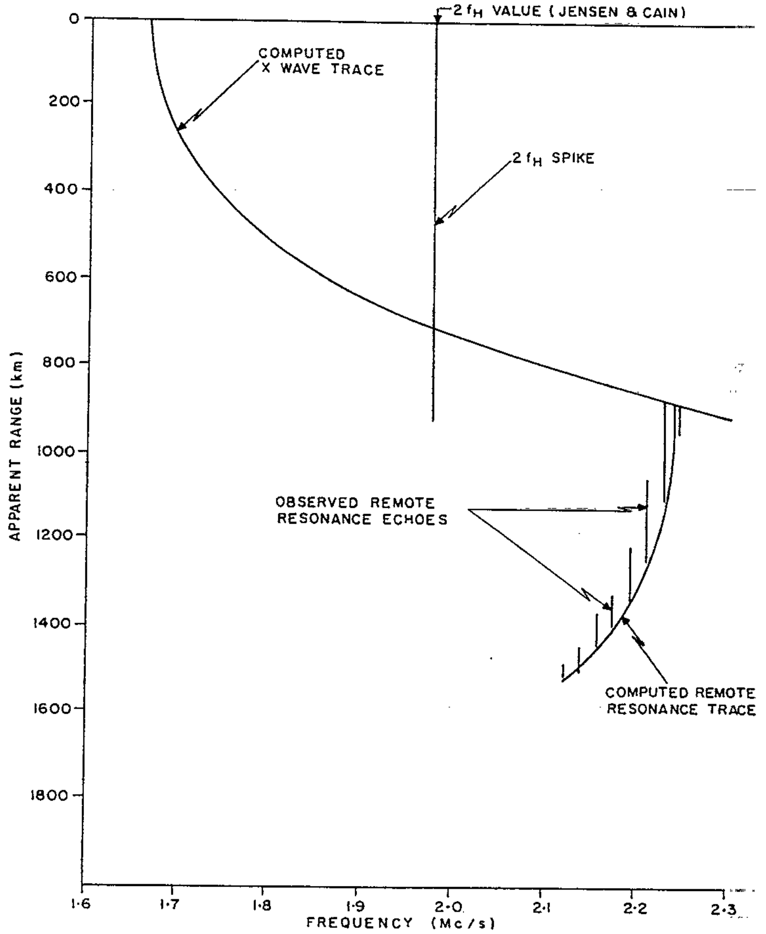

FIG. 7. The extraordinary wave reflection trace computed from the plasma-frequency profile of Fig. 6 and the remote resonance trace computed from the same plasma-frequency profile and equation (2). The observed remote resonance echoes are also shown; the vertical lines give the increment of apparent range for each individual transmitted pulse.

trace increases in apparent range to some maximum and then decreases until it joins the normal extraordinary wave trace. If the heights again separate with the extraordinary wave reflection height below the height where $f = 2f_H$, a secondary or subordinate remote resonance could occur and this could result in an additional remote resonance trace on the ionogram.

If the height where $f = 2f_H$ is above the satellite (f_6 of Fig. 8), energy transmitted by the satellite would propagate upward (i.e., in the direction of decreasing magnetic field) to reach this height and, as mentioned previously, the theory (Muldrew 1966) predicts that no pulse would subsequently be generated at this height. Thus, as observed (see Fig. 1(*c*)), the resonance trace cannot occur on ionograms at frequencies below the local $2f_H$ spike.

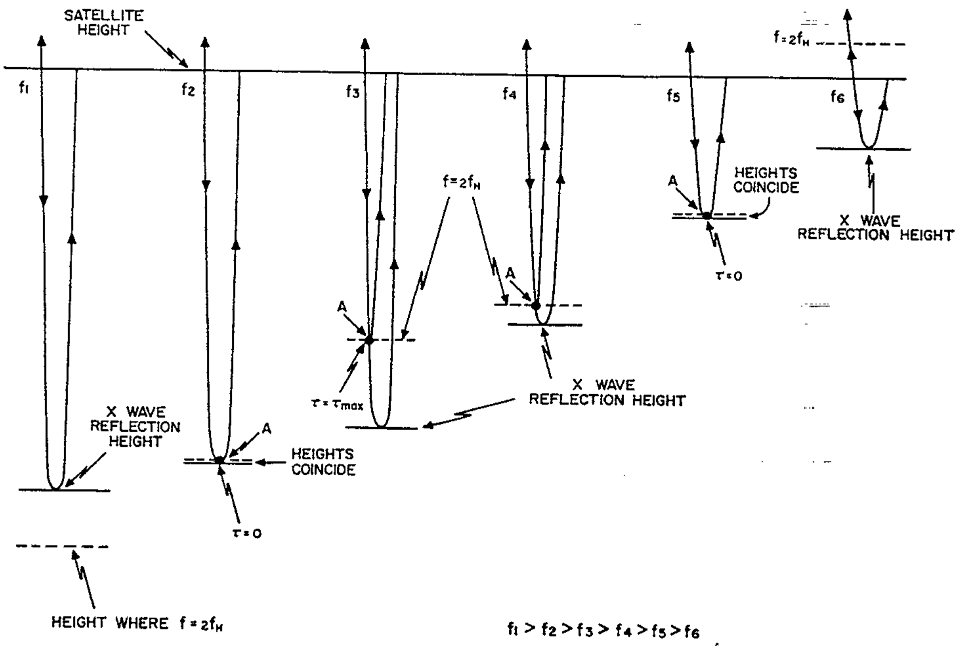

FIG. 8. Qualitative model for the observed turnback in apparent range of the resonance trace for the ionogram in Fig. 1(*h*).

CONCLUSIONS

Examples of some of the characteristics of the remote resonance traces have been presented and discussed. The resonance trace normally appears as a short vertical trace protruding from the spread *F* of the extraordinary wave trace. The $2f_H$ cyclotron spike is the low-frequency limit for the resonance trace; the resonance trace is never observed below this frequency limit. The signal strength of the remote resonance echoes increases with increasing frequency and reaches a maximum at the resonance cutoff frequency. It is shown that remote resonance traces are recorded at times when field-aligned propagation occurs, and it is concluded that the energy associated with the production of the remote resonance trace propagates along field-aligned ionospheric wave guides.

The characteristics of remote resonance traces on Alouette ionograms are consistent with the following physical model. A transmitted extraordinary wave pulse travels down an ionospheric field-aligned wave guide through the region in the ionosphere where $f \simeq 2f_H$ and a cyclotron resonance is excited in this region. At some later time τ the phase distribution of the electrons as a function of height is such that an extraordinary wave pulse of frequency f is generated in the region, and this pulse propagates upward along the guide to the satellite. This generated pulse produced the resonance trace on the ionograms. The equation for the time delay τ is given, and for a specific ionogram it is shown to be in good agreement with the observed time delays.

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