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Letters

Lower Hybrid Resonance Noise and a New Ionospheric Duct

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It has been suggested by *Brice and Smith* [1964, 1965] that a type of noise observed in the VLF range in satellites is related to an ion-electron resonance called the lower hybrid resonance (LHR). Further support for this hypothesis was published by *Barrington et al.* [1965]. Although the evidence is quite convincing that the noise (called LHR emissions or LHR noise) is related to the lower hybrid resonance, the mechanism of the noise generation has not been adequately explained. Also, there has been no attempt to explain the upper frequency cutoff of LHR noise or the variation of occurrence of LHR noise as a function of latitude and time of the year.

We wish to suggest here that the LHR noise may be essentially a propagation rather than an emission effect and that it results from the trapping of electromagnetic waves propagating nearly transverse to the magnetic field in what amounts to an ionospheric duct or cavity.

The lower hybrid resonance frequency is determined principally by three factors: the electron gyrofrequency, the electron plasma frequency, and the effective ion mass. An approximate formula was given by *Brice and Smith* [1965] as:

$$\left(\frac{1}{M_{eff}}\right)\frac{1}{f_r^2} = \frac{1}{f_0^2} + \frac{1}{f_H^2}$$

$$\frac{1}{M_{eff}} = \sum \frac{\alpha_i}{M_i}$$

where f_r is the lower hybrid resonance frequency, f_0 is the electron plasma frequency, f_H is the electron gyrofrequency, α_i is the fractional amount of the ith ion, M_i is the mass of the ith ion, and M_{eff} is the effective mass.

The variation of the lower hybrid frequency with altitude for a typical ionospheric model is shown in Figure 1, left [*Kimura*, 1966]. The lower maximum results from the maximum of plasma frequency in the *F* layer. The increase of f_r with altitude at about 500 km results mainly from the rapid decrease in effective mass in the transition from oxygen to hydrogen ions. The final decrease with altitude above 1000 km results from a decrease of both plasma frequency and gyrofrequency with altitude.

Consider now the variation of refractive index with height for a wave of frequency 5.25 khz with a wave normal transverse to the earth's magnetic field shown in Figure 1, right. In some regions the transverse refractive index is infinite or imaginary, but propagation is still possible for wave normal angles somewhat less than 90°. For simplicity assume that the earth's magnetic field is vertical and that stratification is horizontal. Assume that a wave in region II is nearly transverse with a horizontal component of refractive index greater than 700. By simple application of Snell's law (i.e., that the component of refractive index in the planes of stratification is constant) we see that the wave will be completely trapped in region II between approximately 500 and 785 km. Thus we can demonstrate the existence of a heretofore unexpected duct or trapping region in the ionosphere. The minimum in refractive index with altitude occurs only for nearly transverse propagation, and only when more than one ion constituent is included. No ionization minimum is required. Thus this new duct is not predictable from measurements of electron density only.

Further study of Figure 1 indicates that this

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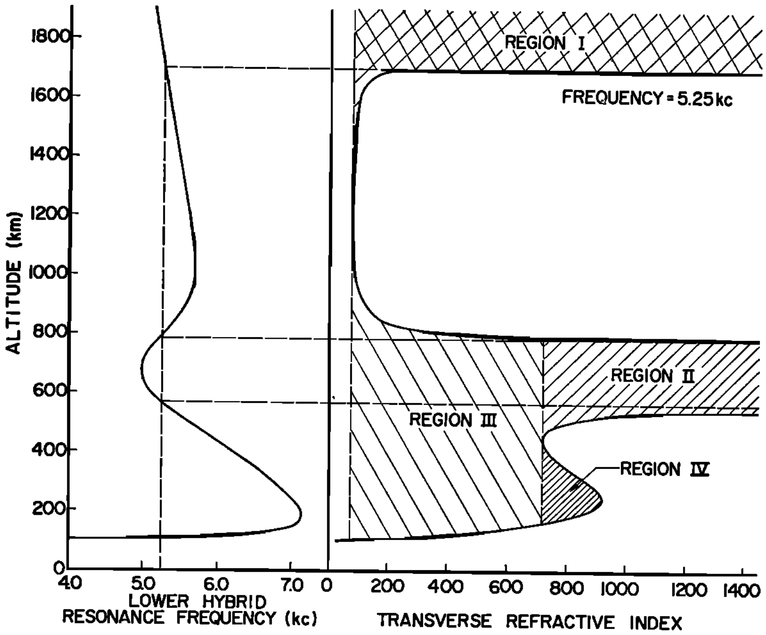

Fig. 1. Left: variation of the lower hybrid frequency with altitude for a typical ionospheric model [*Kimura*, 1966]; right: variation of refractive index with altitude for a wave of frequency 5.25 khz with wave normal transverse to the earth's magnetic field. The numbered regions represent various possibilities for trapping of waves with wave normals that are nearly transverse (see text).

type of trapping is not possible for frequencies greater than the lower of the maximum of the LHR frequency (5.7 khz). Furthermore, trapping is not likely for frequencies much less than the minimum LHR frequency. The altitude range between which energy of a given frequency is trapped can be approximately determined from Figure 1, left. Consider now an observer (i.e., a satellite) at a fixed altitude. The approximate frequency range of trapped energy that would be observed is slightly below the local LHR frequency that is the lower of the two maximums of LHR with height. Thus our hypothesis leads readily to an explanation of not only the lower frequency limit of LHR noise but also the upper frequency limit. To observe the LHR trapping we require first the existence of an LHR frequency minimum with height and second that the satellite must be in the proper height range between the two LHR maximums. Thus a variation of temperature and ion constituents with latitude and season could be expected to produce changes in occurrence rates and observable bandwidths of LHR noise.

A partial test of the above hypothesis is to trace the rays in the ionosphere under the appropriate initial conditions. These calculations have been made and have not only verified the possibility of trapping but have resulted in even more remarkable conclusions: (1) there may be not just one trapping region but three (regions II, III, and IV), but the one described above (II) shows the least attenuation; (2) the attenuation in this trapping region is remarkably low, considering the large wave normal angles involved; (3) the rays are confined principally to travel back and forth along the magnetic field lines with very little transverse motion. Thus this trapping region closely resembles a cavity resonator.

Since we have now described a mechanism that can completely trap nearly transverse waves in a limited frequency range, the next problem is to explain the excitation of the mode. We suggest that nearly longitudinal waves above the LHR frequency can be partially converted to nearly transverse waves upon encountering field-aligned irregularities. This possibility is readily demonstrated by considering reflection and transmission at a field-aligned discontinuity, using the refractive-index surface technique (see, for example, *Smith et al.* [1960]). Some experimental support for a mechanism of this kind is shown by another phenomenon, the LHR whistler. This is a whistler (or atmospheric) that exhibits added dispersion near the LHR frequency, thus strongly suggesting nearly transverse propagation.

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