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Lower Hybrid Resonance Emissions

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Abstract. Examination of very low frequency records of the Alouette 1 satellite has revealed the presence of an unusual band of noise. This band shows several features that distinguish it from other VLF emissions which are observed both in the satellite and on the ground. It is suggested that this noise is generated in the immediate vicinity of the satellite as a result of a resonance in the plasma surrounding the satellite. From a knowledge of the resonance frequency and the ambient plasma and gyrofrequencies, an inverse mean of the ionic mass can be determined.

Introduction. An unusual band of noise observed at midlatitudes in the VLF recordings of the Alouette satellite has been reported by *Barrington and Belrose* [1963] who noted that this hiss band had a sharp lower frequency cutoff which increased in frequency with decreasing latitude of the satellite. *Brice et al.* [1964] reported that the generation of this noise could be enhanced or triggered by whistlers and atmospherics. *Brice and Smith* [1964] noted that since the lower frequency cutoff of this hiss band varied consistently with latitude of the satellite the variation must be spatial rather than temporal. They also suggested that these emissions were related to the lower hybrid resonance for propagation transverse to the earth's magnetic field.

A noise band with characteristics similar to those described above was found in the Injun 3 VLF recordings by *Gurnett* [1964]. Subsequently other examples of this noise band have been found in the Injun 3 data (Gurnett, private communication). Thus the name 'Alouette hiss band' tentatively suggested by *Brice et al.* [1964] and *Brice and Smith* [1964] seems somewhat inappropriate. Further, as is shown below, there is much evidence to support the suggestion of *Brice and Smith* [1964] that this band is related to the lower hybrid resonance, and therefore this noise will be referred to as the LHR hiss band.

Observations. The LHR hiss band is more commonly observed in the Alouette 1 VLF recordings than in those of Injun 3; all the examples of this noise band shown below were obtained from Alouette.

The example of the spectrums of the LHR hiss band shown in the top of Figure 1 was recorded during a north to south pass of Alouette over the South Atlantic.[2] Shown in the bottom of Figure 1 are spectrums of simultaneous ground-based recordings made at Eights Station, Antarctica. The LHR hiss band in the Alouette spectrums shows the characteristic sharp lower frequency cutoff and decrease of frequency (from about 10 to about 5 kc/s in this example) as the satellite moves to higher latitudes. Also seen in Figure 1 are two rising frequency bands of emissions recorded by both the satellite and the ground station. This figure illustrates the conclusion drawn after examination of many simultaneous satellite and ground-based recordings that the LHR hiss band has never been observed on the ground. Because of the A.G.C. action of the Alouette receiver, the noise bands shown on the Alouette spectrums must be of comparable amplitude at the satellite. Obviously the same cannot be said of the ground-based recordings. It is apparent that the frequency variation of the individual rising bands must be a temporal effect, whereas, as noted above, the variation in LHR hiss band frequency must be spatial. On this occasion the

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[2] This spectrogram was obtained from tape recordings kindly loaned by J. S. Belrose of the Defence Research Telecommunications Establishment in Ottawa, Ontario, Canada.

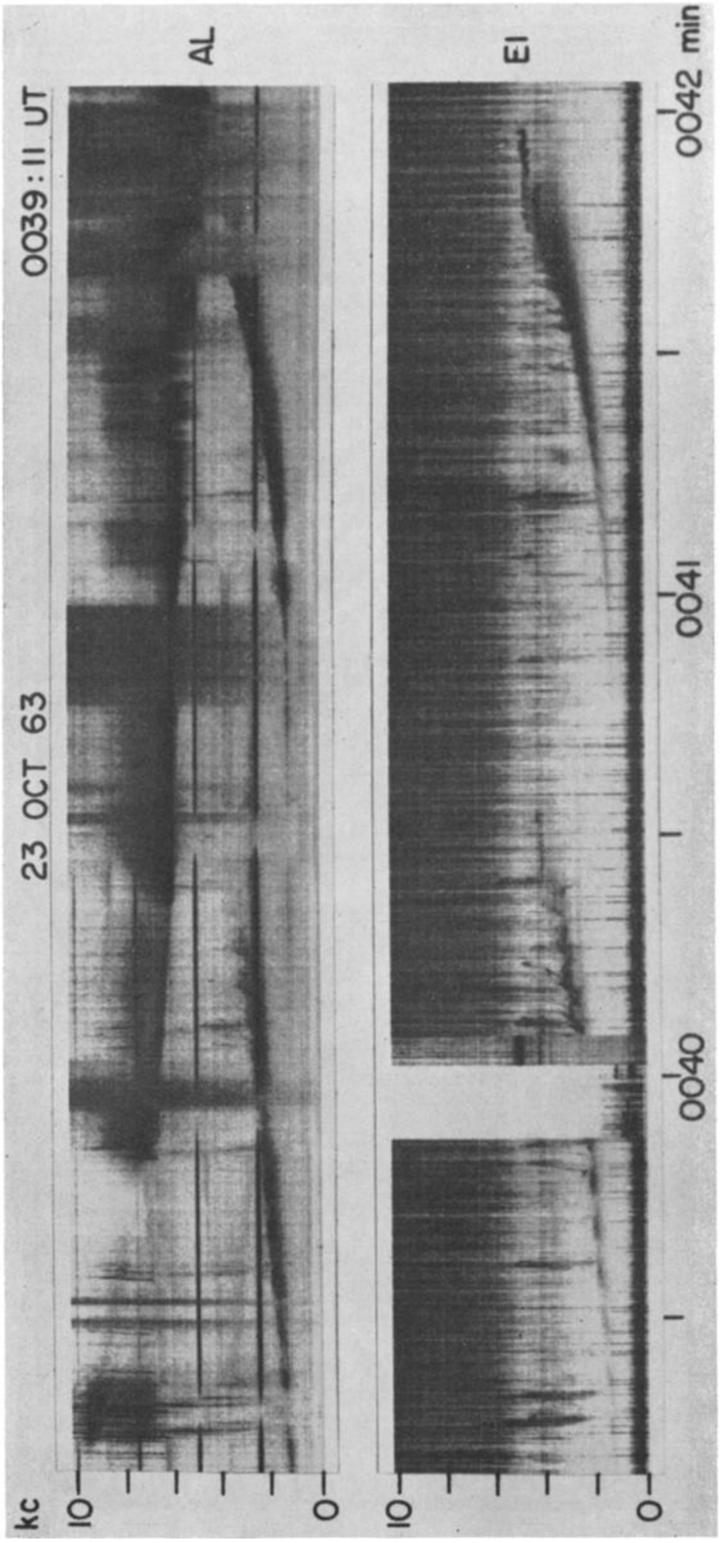

Fig. 1. Simultaneous VLF record from Alouette satellite and Eights Station, Antarctica, showing LHR emission in satellite.

satellite passed close to Eights Station, and rising bands of emissions similar to those shown in Figure 1 were observed at Eights before, during, and after the satellite pass. Only three such bands were observed by the satellite over a period of about 3½ minutes, the latter two bands appearing in Figure 1. If these rising bands consist of a number of overlapping periodic emissions (and there is evidence to support this in Figure 1), then it can be deduced that these emissions were propagating along a single whistler-mode path in the outer magnetosphere [*Helliwell,* 1963*b*; *Helliwell and Brice,* 1964]. This point will be further discussed below.

Triggering of the LHR hiss band by atmospherics and whistlers as reported by *Brice et al.* [1964] is illustrated in Figure 2. This figure shows spectrums recorded during a north-south pass over Stanford, California. The lower record is the section of the upper record from 17 to 33 seconds shown on an expanded time scale. The emission triggered by the first atmospheric shows initially a rapid decrease in lower cutoff frequency; this frequency then becomes nearly constant. The emissions triggered by whistlers indicate that frequencies near the low frequency cutoff are enhanced for longer periods than the higher frequencies. Also, the sharp lower frequency cutoff increases measurably within these emissions. The whistler triggered emissions have durations of the order of a few seconds. Such triggering of LHR emissions by atmospherics and/or whistlers is relatively common in Alouette recordings.

Of 94 ten-minute recordings examined, 18 showed triggering of the hiss band by atmospherics, and 20 showed triggering by whistlers. As was noted above, this hiss band, triggered or otherwise, has never been observed on ground-based recordings. The LHR emissions, either continuous or triggered, were observed in 55% of the recordings examined. The seasonal-diurnal occurrence data are given in Table 1. It is seen that the nighttime occurrence was significantly more frequent than daytime. Furthermore, almost all daytime observations of the hiss band were recorded either before 8 A.M. or after 4 P.M.

In Figure 3, also recorded during a north-south pass over Stanford, weak triggering of the LHR band by whistlers can be seen between 40 and 80 sec. Also apparent at the beginning of the upper record of Figure 3 is a whistler echo train. Whistlers with echoes showing the same echo delay can be seen throughout most of the period illustrated. In addition, from 225 to 260 sec, a periodic emission is observed, the period being the same as the echo delay of the preceding whistlers. It is apparent that the whistlers with echoes and the periodic emissions propagated over the same outer magnetospheric path. From this we conclude that, during this pass, signals propagating along the same path in the outer magnetosphere were observed by the satellite for more than four minutes. It will be remembered that a similar conclusion was drawn from examination of the rising bands of emissions shown in Figure 1. From the satellite speed of approximately seven kilometers per second, it is found that the satellite travels more than 1700 kilometers or more than 15 degrees of latitude during a four-minute interval. During this time the LHR emission frequency changes markedly and, in fact, measurable changes in the low frequency cutoff may occur in a very few seconds.

Another feature of the LHR emissions is illustrated by Figure 4, which shows a section of the Alouette spectrums of Figure 3 together with simultaneous ground-based recordings from Stanford. On the Stanford record a very weak whistler appears just before 3 seconds and other whistlers at 4, 6, 8½, and 11 seconds. For each of these Stanford whistlers, a corresponding whistler is seen in the satellite. None of these whistlers triggers LHR emission. Other whistlers recorded by the satellite during this interval trigger LHR emissions, but no whistlers corresponding to them were observed on the ground at Stanford. Furthermore, a careful examination of the whistlers in Figure 3 shows that none of the whistlers with echoes trigger LHR emissions. The observations that the whistlers which do not trigger tend to have echoes and that these are observed on simultaneous ground recordings both indicate that these whistlers are ducted [*Helliwell,* 1963*a*], whereas the whistlers which trigger LHR emissions are nonducted. It should be pointed out that on one or two occasions the data indicate that whistlers which triggered LHR emissions were also observed on the ground. On these occasions only the triggering whistlers were observed on the ground, not the triggered emissions. A number

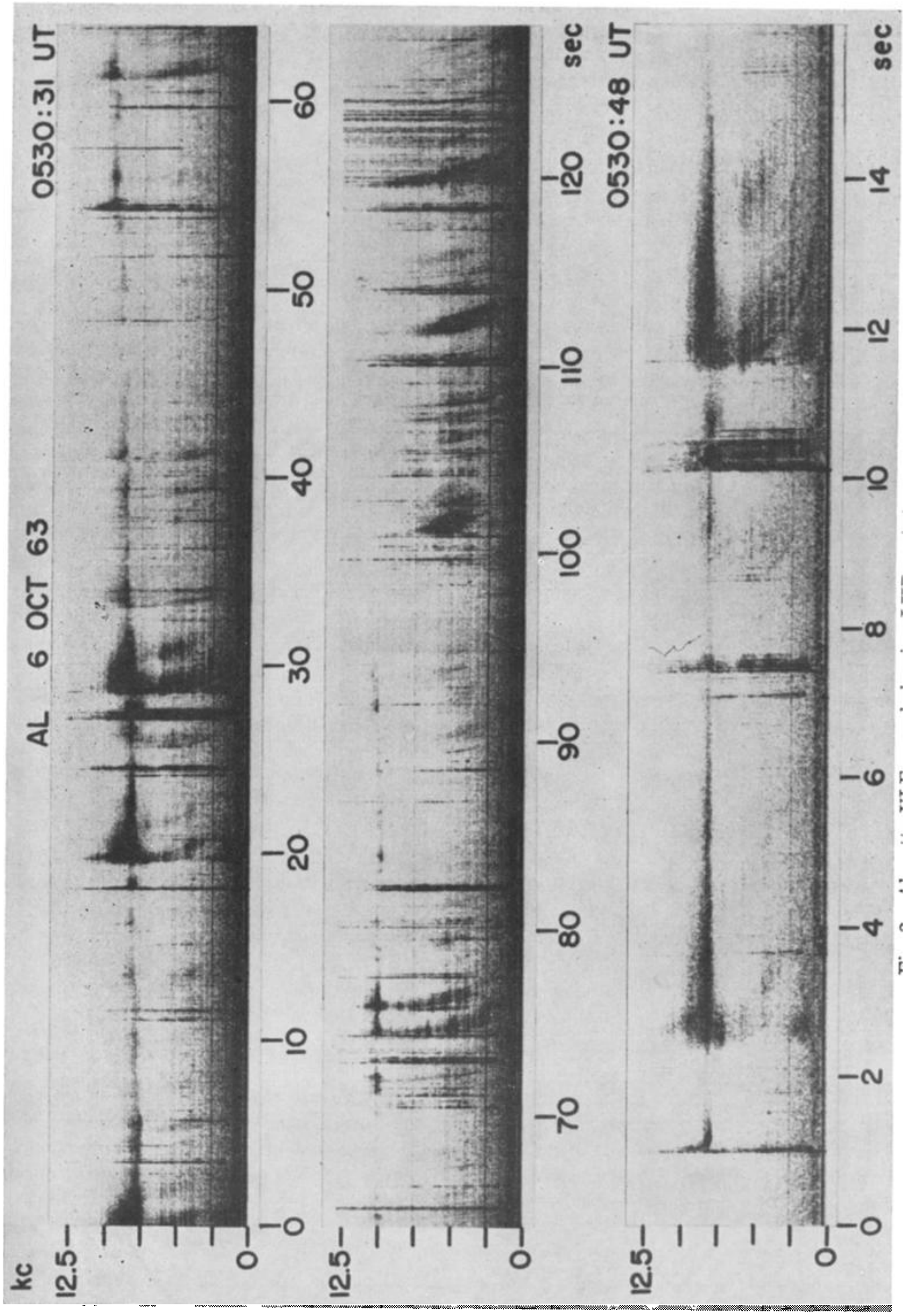

Fig. 2. Alouette VLF record showing LHR emissions and whistlers.

TABLE 1. Occurrences of LHR Emissions on Alouette 1 from February 2, 1963, to April 20, 1964

	1963			1964		
	Spring Night	Summer Day	Fall Night	Winter Day	Spring Night	Total
Present	15	11	13	2	11	52
Absent	7	6	4	19	6	42

Day 34%
Night 67%
Total 55%

Summer day occurrences were morning and evening, absent near noon; 'present' is observation of steady *or* spheric triggered *or* whistler triggered LHR emissions.

of the unusual features of the LHR hiss band described above were brought to the attention of the authors by John Katsufrakis (private communication).

Interpretation. It is apparent from the above observations that the LHR hiss band has a number of features which distinguish it from other VLF emissions. For these other emissions, and for whistlers, the frequency-time spectrums observed simultaneously in the satellite and on the ground are essentially the same, indicating that the spectral variations are temporal rather than spatial.

The LHR hiss band almost invariably shows a general increase in the lower cutoff frequency with decrease in the latitude of the satellite. Because of this latitude dependence, we deduce that the general increase in frequency must be a spatial effect. It may be suggested that the short-term variations as seen in Figure 1 are also spatial, but the possibility of temporal variation cannot be ruled out. However, the long-term change in frequency is certainly spatial. Given that the lower frequency cutoff is very sharp, that it is a function of the location of the satellite, and that it changes measurably in a few seconds, we can deduce that at any given instant the LHR emissions observed by the satellite are different from those observed a few seconds previously. Since at least some of the frequency variation must be spatial, the horizontal field of view of the satellite must be limited to less than a few tens of kilometers.

One possibility is that the noise is generated near the top of the magnetic field line path and propagates strictly along the field lines from the region of generation to the satellite. However, as was observed in Figures 1 and 3, signals propagating in the whistler mode over a single path in the outer magnetosphere can be observed in the satellite for well over a thousand kilometers. It appears unlikely then that this hiss band is generated at great heights in the magnetosphere. Furthermore, the observation of triggering of the hiss by atmospherics indicates that the generation region is at or below the satellite, while triggering by whistlers indicates generation at or above the satellite [*Brice et al.,* 1964]. Since the region in which the observed hiss is generated is also limited in horizontal extent, it is apparent that the observed hiss band is generated in the immediate vicinity of the satellite.

The observation that whistlers with echoes (which are also observed on the ground) do not trigger the hiss and that whistlers without echoes (which are not observed on the ground) do trigger the hiss can be interpreted as follows. It was suggested above that the whistlers with echoes are ducted whistlers, whereas those without echoes are not ducted [*Helliwell,* 1963*a*]. For this interpretation, the nonducted would be expected to have larger wave normal angles than the ducted whistlers [*Yabroff,* 1961], suggesting that triggering is more likely for signals propagating with large wave normal angles.

From considerations of amplitude alone, it would be expected that triggering of this hiss band by atmospherics would be observed far more frequently than triggering by whistlers. Since it is expected that whistlers generally have larger wave normal angles than atmospherics, the observation that triggering by whistlers and atmospherics occurs with almost equal frequency may also indicate that triggering is more favorable at larger wave normal angles. Further support for this suggestion is also found in Figure 2, where very weak whistlers produced longer enhancements of the LHR hiss band than atmospherics.

Possible origin. In considering possible origins for the LHR hiss band, it should be borne in mind that the observed noise is generated in the immediate vicinity of the satellite, that the

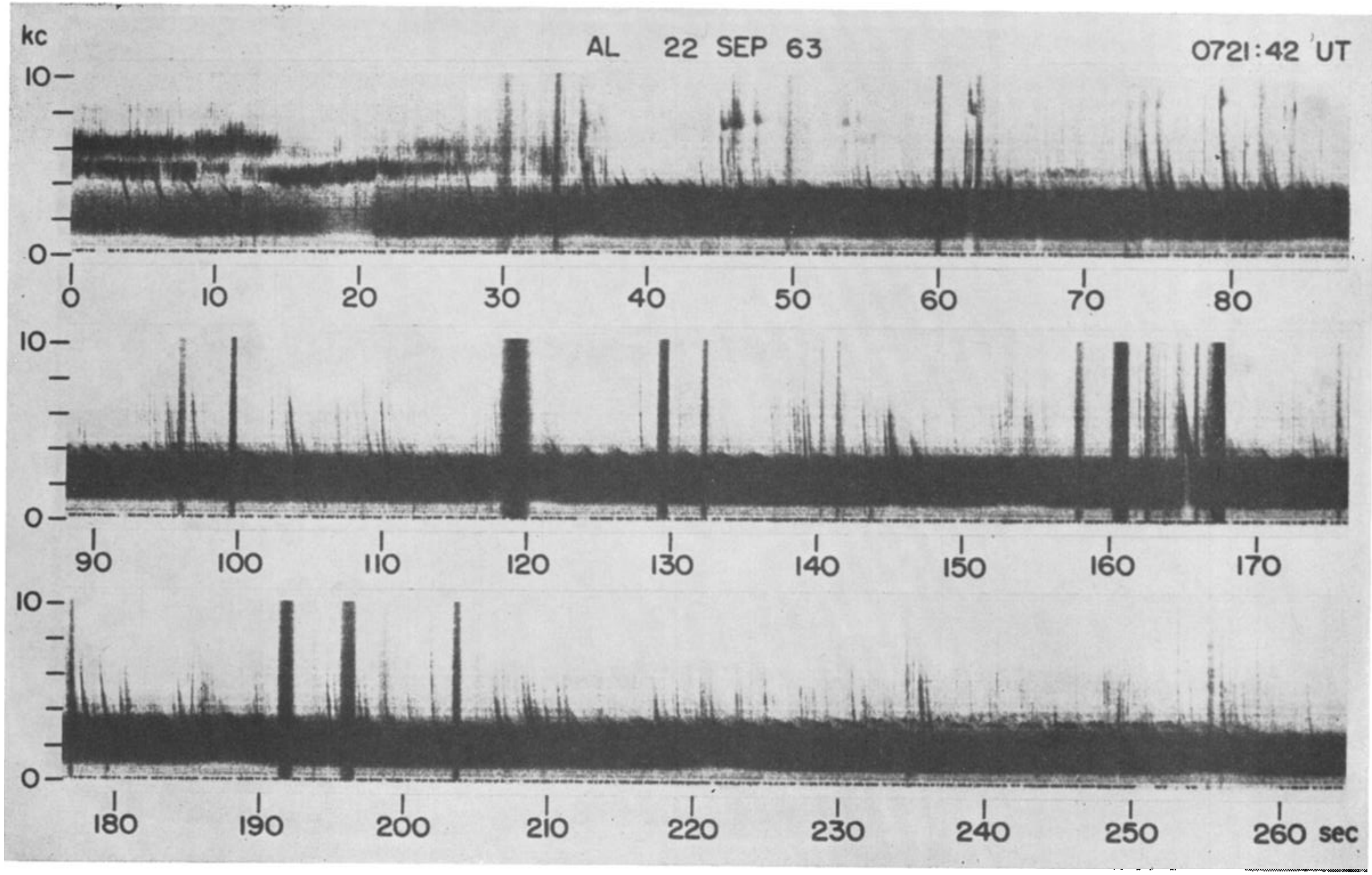

Fig. 3. Alouette VLF record showing LHR emissions triggered by atmospherics and whistlers.

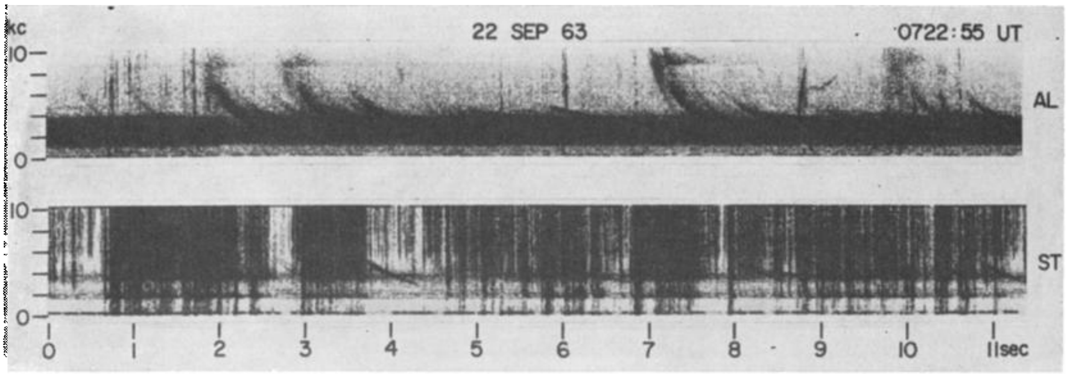

Fig. 4. Simultaneous VLF records from the Alouette satellite and ground station (Stanford) showing LHR emissions triggered by whistlers seen only in satellite.

noise may be triggered, and that triggering appears to be enhanced for waves propagating with large wave normal angles. Also all the mechanisms suggested for the generation of VLF emissions observed on the ground invoke resonances between particles and whistler mode waves propagating quasi-longitudinally [*Brice,* 1964*a*]. Further, it has been suggested by *Calvert and Goe* [1963] that the high frequency 'spikes' observed in the Alouette topside sounder records are related to the resonances in the plasma surrounding the satellite. Since the LHR emissions are a function of the location of the satellite (as are the high frequency spikes), it appears likely that these emissions also arise from a resonance between electromagnetic waves and the ambient plasma in the vicinity of the satellite. The frequency of LHR emissions lies above the proton gyrofrequency and below the electron gyrofrequency. The only resonance in this frequency range is the lower hybrid resonance.

The lower hybrid resonance defines a cutoff frequency for propagation transverse to the ambient magnetic field. For a plasma consisting of electrons and one ion species and for which the ion plasma frequency (F_0) is much larger than the ion gyrofrequency (F_H), the resonance frequency (f_r) is given by [*Stix,* 1962]:

$$\frac{1}{f_r^2} = \frac{1}{F_0^2} + \frac{1}{f_H F_H} \qquad (1)$$

where f_H is the electron gyrofrequency.

It is apparent that the resonance frequency will be of the order of the ion plasma frequency or the geometric mean of the electron and ion gyrofrequencies, whichever is the less. The geometric mean gyrofrequency for protons in the ionosphere is always less than 40 kc/s.

Theory of the lower hybrid resonance. Equation 1 can be rewritten in terms of the electron plasma frequency f_0 as

$$\frac{1}{M f_r^2} = \frac{1}{f_0^2} + \frac{1}{f_H^2} \qquad (2)$$

where M is the mass to charge ratio of the ions relative to electrons. As is seen in Table 1, the LHR emissions are observed in Alouette predominately at night. At this time and at the height of the satellite (1000 km), the electron plasma frequency is usually less than the electron gyrofrequency for latitudes of interest here (roughly, $L = 2.5$ to 5). In this situation the lower hybrid resonance is approximately the ion plasma frequency. For this case, a simple physical picture of the resonance can be given. The resonance frequency is much less than the electron gyrofrequency, so that the electrons can be considered as tightly bound by the earth's magnetic field. The ion gyrofrequency is much less than the resonance frequency, so that the ions are considerably more mobile. Thus if the ions are displaced across the static magnetic field, the tightly bound electrons form a fixed negatively charged background and the ions oscillate at their plasma frequency in a manner similar to electrons in the absence of a magnetic field.

Since the ionosphere contains in general more than one ion constituent, it is of interest to derive the resonance frequency for plasmas with multiple ion species. *Smith and Brice* [1964] have shown that for propagation transverse to the earth's magnetic field a resonance occurs when

$$1 + \sum_r X_r/(Y_r^2 - 1) = 0 \qquad (3)$$

where the X_r are the ratios of plasma frequency squared to wave frequency squared and the Y_r are the ratios of gyrofrequency to wave frequency for the various constituents (electrons and ions) present.

In the ionosphere, ion plasma frequencies are typically much greater than ion gyrofrequencies and the lower hybrid resonance is much less than the electron gyrofrequency, so that we can assume

$$Y_e^2 \gg 1 \qquad Y_i^2 \ll 1$$

where subscript e refers to electrons and i to ions. Using these approximations, we find that (3) becomes

$$1 + \frac{X_e}{Y_e^2} - X_e \sum_i \frac{\alpha_i}{M_i} = 0 \qquad (4)$$

where the fraction of the positive charge density due to the ith ion is α_i, and M_i is the mass to charge ratio of the ith ion with respect to that of the electron.

We define the effective mass M_{eff} as

$$\frac{1}{M_{\mathrm{eff}}} = \sum_i \frac{\alpha_i}{M_i} \qquad (5)$$

and find

$$\left(\frac{1}{M_{\mathrm{eff}}}\right)\left(\frac{1}{f_r^2}\right) = \frac{1}{f_0^2} + \frac{1}{f_H^2} \qquad (6)$$

Note that for a single ion species the resonance frequency from (6) is the same as that given by (1) taken from *Stix* [1962].

The term 'lower hybrid resonance frequency' is used here to denote the frequency of resonance for propagation strictly perpendicular to the earth's magnetic field. It can be shown that for wave normal angles less than 90° the frequency of resonance is higher than the lower hybrid resonance frequency. Thus the frequencies at which a resonance can occur have a natural lower frequency cutoff.

In view of the observation that LHR emissions are observed more frequently in Alouette than in Injun, it is of interest to consider the polarization at the lower hybrid resonance, since the Alouette receiver is fed from an electric dipole antenna while the Injun 3 receiver uses a magnetic loop antenna. It can be shown [e.g., *Smith and Brice,* 1964] that for frequencies near the lower hybrid resonance the polarization for transverse propagation is approximately linear and that the dominant wave field component is the wave electric field in the wave normal direction. Given this information and that a resonance is found for higher frequencies for other angles, we can anticipate that the impedance of an electric dipole in the medium would show zero reactance and very large resistance at the lower hybrid resonance frequency and that the resistance would decrease very rapidly for lower frequencies and much more slowly for higher frequencies. These factors do indeed appear in calculations of impedance for a dipole antenna in a plasma (W. Blair, private communication). The antenna used for the Alouette VLF receiver is a 150-foot dipole. For a typical frequency of 6 kc/s, the free space wavelength is 50 km. However, near resonance the refractive becomes extremely large and the wavelength in the medium relatively small, so that the antenna may not be small compared with a wavelength.

Discussion. It has been shown that the LHR hiss band is a highly localized phenomenon, suggesting a resonance in the ambient plasma. It has been noted that the frequencies observed in the hiss band are between the electron and proton gyrofrequencies, and that the only resonance in this frequency range is the lower hybrid resonance.

In addition, several of the properties of this resonance may be related to characteristics of the hiss band.

The frequencies at which a resonance may occur have a sharp lower frequency limit; the LHR hiss band has a sharp lower frequency cutoff. The resonance is characterized by large electric fields; the hiss band is found more often on a receiver fed from an electric or dipole antenna (Alouette 1) than a receiver fed from a magnetic or loop antenna (Injun 3). The lower hybrid resonance occurs for a wave normal angle of ninety degrees; triggering of the hiss band appears to be enhanced for signals propagating with large wave normal angles.

Though the hiss band and the lower hybrid resonance are both at frequencies intermediate between the electron and ion gyrofrequencies, it is necessary to determine whether the postulated association between them requires unreasonable values of effective mass. By taking typical values of electron plasma frequency of 600 kc/s and electron gyrofrequency of 1 Mc/s, we find that the range 5 to 10 kc/s of hiss frequencies would require effective masses in the range 2.1 to 8.3 times the proton mass. Since these are by no means unreasonable values, it can be said that the lower cutoff frequencies of the LHR hiss band are of the order of those expected for the lower hybrid resonance.

From the LHR postulate, it is seen that the resonance frequency increases with the electron plasma frequency. It may be suggested then that the high electron densities (and hence plasma frequencies) found near local noon usually give lower hybrid resonance frequencies above 10 kc/s (the upper frequency cutoff of the Alouette VLF receiver). This suggestion provides a plausible explanation of the infrequent observation of the hiss band in the hours near local noon.

With regard to the variation in low frequency cutoff of the hiss band with latitude, *Brice* [1964*b*] has suggested that this is typically somewhat greater than the typical variation in electron plasma frequency at 1000 km. Thus from the LHR postulate it would be deduced that the effective mass at 1000-km height usually increases with increasing latitude. This deduction agrees with that made from predictions of *Angerami and Thomas* [1964] and on the basis of satellite measurements [*Bowen et al.,* 1964].

Summary. The local generation of the LHR hiss band and the range of frequencies observed suggest that the hiss is directly related to the lower hybrid resonance. Further support for this hypothesis is found in the sharp low frequency cutoff of the band, the more frequent occurrence in the receiver fed from an electric antenna, and the enhanced triggering at large wave normal angles. This postulate provides an explanation of the absence of the hiss band in the hours around local noon; it requires a variation of effective mass with latitude which agrees qualitatively with that found by other workers.

Thus the properties of the band found to date are all consistent with the lower hybrid resonance hypothesis.

Application. In view of this evidence, it is of interest to assume that knowledge of the lower hybrid resonance frequency can be obtained (from hiss or from antenna impedance measurements) and to consider the applications of this knowledge in ionospheric research. As was shown above, the lower hybrid resonance frequency is directly related to the effective mass of the ionic constituents and thus provides a useful diagnostic tool. Since the weighting factor is the inverse ionic mass, the effective mass will be largely determined by the lighter ions. In the protonosphere, where the ionic mass is known, a measurement of the lower hybrid resonance frequency and the earth's magnetic field strength will in principle yield the electron density. This method of measuring electron density would be useful in the height range above Alouette (1000 km) and below that at which whistler measurements are available.

If the short term fluctuations in the hiss band noted earlier are in fact spatial rather than temporal, then it may be suggested that they are the result of small fluctuations in the ambient electron density. These fluctuations could be related to the field-aligned ducts of ionization postulated for whistlers by *Smith* [1961].

Suggested experiments. The work above suggests a number of interesting experiments for rockets and satellites. In addition, the search for noise at the lower hybrid resonance in a laboratory plasma might prove instructive (this resonance has apparently been recently found in a laboratory plasma by Von H. Schlüter [private communication]).

Following the suggestion above that noise is observed near a resonance at very low frequencies, it would be of interest to examine the output of a very high sensitivity swept frequency HF receiver to determine whether ambient noise is enhanced at the resonant frequencies already found by the topside ionosonde.

Simultaneous or alternate topside ionosonde and VLF recordings would be extremely useful. From the high frequency spikes the electron plasma and gyrofrequency can be found. This information in conjunction with the VLF spectrums would then yield the effective ion mass. Since the Alouette hiss band is not always observed, antenna impedance measurements at very low frequencies would be preferred. The frequency range of the VLF receiver or impedance measurement should cover from the highest possible hybrid resonance frequency of 40 kc/s to at least the lowest ion gyrofrequency expected for the height range covered.

A VLF ionosonde or separated transmitter-receiver pair could be used to study resonance frequencies, and, in addition, artificial stimulation of VLF emissions [*Helliwell et al.*, 1964].

Observation of the LHR hiss together with independent measurements of ionic constituents and antenna impedance would provide a test of the hypothesis suggested above.

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