OBLIQUE NOISE BANDS ABOVE LOCAL LHR FREQUENCY

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ABSTRACT

The noise bands at lower hybrid resonance (LHR) frequency at a satellite position have already been observed and described. Observations onboard the MAGION 5 satellite revealed oblique noise bands above the local LHR frequency. Examples of such oblique bands, both in review (large time-scale) spectrograms, and in detailed (small time-scale) spectrograms are presented. Based on ray-tracing simulations, an explanation of these oblique bands is suggested. We show that they are formed due to the separation of nonducted whistler mode waves of different frequencies propagating near the so-called resonance cone. The influence of plasmaspheric disturbances upon these emissions is also discussed. We suggest that oblique noise bands are mainly formed under quiet conditions, when indistinct plasmapause is situated at higher L shells. © 2003 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

We would like to begin with a very short account of some features of whistler wave propagation in the magnetosphere, which is necessary for understanding the results of simulations and suggested explanation of oblique noise bands formation. To take into account the magnetospheric reflection of nonducted whistler mode waves, we have to consider the effect of ions on whistler mode wave propagation. So we use the dispersion relation in the following form:

\[ \omega^2 = \omega_{LH}^2 + \frac{\omega_p^2 \cdot \cos^2 \theta}{1 + \frac{\omega_p^2}{c^2 \cdot k^2} \left(1 + \frac{\omega_p^2}{c^2 \cdot k^2}\right)^2} \]  

Here \( \omega_e \) is electron cyclotron frequency, \( \theta \) is the angle between the wave normal vector \( k \) and the ambient magnetic field, and \( \omega_{LH} \) is the lower hybrid resonance (LHR) frequency. For the definition of LHR frequency, see for example Smith and Brice (1964). We want to stress that this dispersion relation is a good approximation for frequency, which is higher than cyclotron frequencies of ion species.

As follows from Eq. 1, for whistler mode waves the following inequality is always valid:

\[ \omega^2 - \omega_{LH}^2 \leq \omega_p^2 \cdot \cos^2 \theta \]  

The equality sign in Eq. 2 corresponds to the so-called resonance cone \( (\omega_p^2/c^2k^2 << 1 \text{ in the dispersion relation}) \), which obviously exists only for waves with \( \omega > \omega_{LH} \). So, the case when \( \omega_p^2/c^2k^2 << 1 \) corresponds to quasi-resonance mode of propagation, and the wave is a quasi-electrostatic one (Smith and Brice 1964). As follows from Eq. 2, for such waves \( \omega^2 = \omega_{LH}^2 + \omega_p^2 \cdot \cos^2 \theta \), thus these waves always propagate along the resonance cone. If such a wave approaches the region where \( \omega^2 = \omega_{LH}^2 \), the wave normal angle tends to 90 degrees, thus \( k_k \cdot v_{nk} \rightarrow 0 \), and the wave reflection in longitudinal direction takes place (Kimura, 1966).

In the review spectrograms, which visualise the spectral intensity of electric component of the waves, the LHR frequency is usually very distinct (Brice and Smith, 1965). It corresponds to an abrupt low frequency cut off of the noise spectrum. The LHR frequency along MAGION 5 orbits is of the order of kHz, and it generally increases smoothly when the satellite is moving towards lower altitudes, and decreases in the opposite case.
Under quiet geomagnetic conditions, so far unnoted oblique noise-like bands above the local LHR frequency have been observed in review spectrograms recorded by MAGION 5. An example is given in Figure 1. As will be shown later, the waves, which form those bands, propagate near the so-called resonance cone (Kimura, 1966; Walker, 1976). That means that they are of the quasi-electrostatic nature. They merge into the LHR noise band as the satellite moves to higher altitudes. These bands have not been observed below the LHR frequency. The formation of these emissions observed as oblique bands above the LHR frequency is the subject of the present paper.

EXPERIMENTAL DATA

The space region from which satellite data are collected is determined by the satellite orbital parameters and by the position of a telemetry station. The orbital parameters and the basic characteristics of the data are as follows:

Data source: Magion 5 satellite, measurements in electric and magnetic component from June 1998 to July 2001

Analogue transmission to the ground receiving station

MAGION 5 orbital parameters: Apogee ~19000 km, Perigee ~1200 km (S. hemisphere), Inclination= 63.3°

Telemetry station: Panska Ves (Latitude =53.53°N, Longitude=14.57°E)

Frequency range: After digitalization (sampling frequency $f_s = 44.1$ kHz) on the ground the band is from $-10$ Hz to $22$ kHz

Data processing, resolution: Short Time Fourier Transform, the time (frequency) resolution $\Delta t (\Delta f)$ depends on the number of samples (N) used for FFT calculation, $\Delta f = N / f_s$ ($\Delta t = f_s / N$)

Visualisation: Different types of spectrograms. The spectral intensity is depicted by the darkness in the case of black and white spectrograms or by rainbow colour map in the case of colour ones (red for the highest intensity, blue for the low one)

Region of measurement: Data from equatorial latitudes, starting from about 3000 km altitudes, up to the latitudes of about 63° in the whole range of altitudes.

Region of observation of oblique noise bands: L=1.8-3.7, Altitude=4300-8000 km, (MLT=17-21)

Conditions of observation: Local evening (mostly between MLT=17-21), low geomagnetic activity ($Kp_24 < 3$; $Dst_{24} >-28$, both are mean values for 24 hours preceding the observation), and lightning activity in “proper region”. Occurrence is quite rare (~10 observation per year). Actually we did not perform any real statistics, because it is always a matter of subjective assessment, whether to count or not, if the oblique noise are poorly formed.

Fig. 1 Oblique noise bands and LHR noise along the trajectory of Magion 5 on Aug. 17th 2000. The LHR frequency can be seen as an abrupt low frequency cut off of the noise.
OBLIQUE NOISE BANDS ABOVE LHR FREQUENCY AND THEIR EXPLANATION BY MEANS OF NUMERICAL SIMULATION

Below, we suggest an explanation of the oblique noise bands observed above local LHR frequency and presented in review spectrogram in Figure 1. Note that $K_p24 = 1.89$, $Dst24 = -13.2$ in these cases. It is also instructive to take a careful look at Figures 2 and 3, which show detailed spectrograms (two time intervals of 9 seconds) of the mentioned review spectrogram. The arrows indicate the Universal Time UT. One can notice that the upper frequency parts of magnetospherically reflected (MR) whistlers in Figure 2 transform gradually into the oblique noise band. This oblique noise band can be clearly seen as the upper noise band in Figure 3. The bottom band is associated with LHR noise.

Fig. 2 Detailed spectrogram recorded onboard of Magion 5 on Aug. 17th 2000, showing a part of the review spectrogram in Figure 1. MR whistlers prove that the waves propagate near the resonance cone.

Fig. 3 Detailed spectrogram recorded onboard of Magion 5 on Aug. 17th 2000, showing a part of the review spectrogram in Figure 1. The upper part of MR whistlers transform into oblique noise band.
To clear up the formation of oblique bands, we turn to the results of computer simulations (based on the solution of Hamiltonian equations of geometrical optics) of the ray trajectories presented in Figure 4, which shows the wave ray paths in the plane of local magnetic meridian for different frequencies from 3 kHz to 7 kHz. Some details concerning the simulations could be found in Shklyar and Jiricek (2000). The satellite trajectory shown in the Figure 4 is that on which the record presented in Figure 1 has been obtained. The asterisk on the satellite trajectory corresponds to the beginning of data acquisition. The rays corresponding to different frequencies are discerned by the darkness (the higher frequency, the darker the grey scale color). The region from which the ray tracing starts is spread over L-shells from 2.4 to 3.4, with initial height of 1000 km for all waves. In our simulation model, this starting area, which we further call the illuminating region, corresponds to the surface at which we set the initial conditions (the wave normal vector \( \mathbf{k} \) and the corresponding wave frequency \( \omega \)) for whistler mode waves. We assume that these waves are induced by lightning discharges and start propagating in the magnetosphere after some part of the lightning energy has penetrated through the ionosphere.

Analyzing the result of the simulation, first of all, we notice a significant focusing of the trajectories corresponding to the same frequency, but different initial latitudes. For frequencies shown in the Figure 4 the focusing is accomplished before the first magnetospheric reflection, and after it, all waves corresponding to the same frequency propagate in the wave tubes with a small transversal dimension. The wave tubes corresponding to higher frequencies are shifted towards lower L-shells as compared to the wave tubes corresponding to lower frequencies. Those tubes themselves move towards lower L-shells with the increasing number of reflections. This fact (which finally is connected with the wave transition to quasi-resonance regime of propagation) is far from being trivial, because all these waves start from different latitudes and have essentially different wave normal vectors. At the same time, the reflection points for higher frequency waves are situated at lower altitudes and lower L-shells as compared to lower frequency waves. Consequently, the wave spectrum observed by a satellite on a large time scale depends essentially on the satellite trajectory. Thus, for the orbit shown in Figure 4, the satellite should cross the bunches of tubes with decreasing frequencies, until it leaves the region filled by the wave trajectories. On review spectrograms, this will be revealed as oblique bands of decreasing frequencies. (Obviously, if the satellite moves towards decreasing L-shells, the variation of frequency in the band will be opposite.) After the satellite has left the region filled by the wave trajectories, it detects no quasi-resonance waves any more. For example, in the Figure 4, it cannot detect the quasi-resonance waves at frequencies which are lower than \( \sim 3 \) kHz, because the reflection points for those frequencies lie at higher altitudes, and the tubes of quasi-resonance waves of such frequencies do not reach the satellite trajectory. In other words, the satellite cannot detect quasi-resonance waves at frequencies, which are lower than the local LHR frequency.

![Fig. 4](image) Simulated ray trajectories of the waves of frequencies 3 kHz, 4 kHz, 5 kHz, 6 kHz and 7 kHz. The higher is frequency, the darker is the grey scale colour. Separation of waves of different frequencies is clearly seen.
To prove this explanation, special software simulating review spectra has been developed. A 2D continuum of wave trajectories in the frequency band from 0.5 to 10 kHz and with initial latitudes from 5 to 60 degrees has been calculated, together with the variation of wave energy density along the trajectory, in frame of geometrical optics. The spectral intensity at a frequency $\omega$, which is supposed to be measured by a satellite at some point on its trajectory, is equated to the energy density associated with the waves of frequency $\omega$, which cross the unit volume around the satellite position. This consideration assumes, of course, that the spectral intensity distribution is stationary in time, and does not change significantly over a space region crossed by the satellite during the calculation of elementary spectrum on review spectrogram. Thus, in this model, the time variation of the review spectra is attributed completely to the variation of the spectra in space along the given satellite orbit. First results of the simulation gave higher intensities at higher frequencies. So we decided, to take into account the change of the spectral intensity of the wave, due to the change of group velocity ($v_g$) and the tube cross section. The ray tracing method was improved for that reason by the solution of energy conservation law in the form $\text{div} (v_g \times w) = 0$, where $w$ is the energy density of the wave related to the electric field. The agreement with real spectrograms was much better now; despite of that we did not consider damping or amplification (the energy density $w$ does not depend explicitly on time).

Since each wave trajectory includes the initial latitude as one of the characteristics, it is possible to choose the illuminating region when calculating the review spectra. This database permits to simulate review spectrograms along given satellite trajectories when they are in the region $1.5 < L < 6.5$ and $0^\circ < \lambda < 60^\circ$. Figure 5 provides an example of simulated spectrogram corresponding to MAGION 5 trajectory, on which the spectrogram presented in Figure 1 was recorded. The simulated spectrogram was calculated for illuminating region from 42 to 46 degrees of Northern latitudes. We should stress that choosing this illuminating region leads to the best agreement between real and simulated spectrogram. We can see that simulated spectrogram is similar to the real one; in particular, it reproduces the bands of wave activity above LHR frequency, with about the same obliquity, perhaps with a little bit higher spectral intensity at high frequencies than on real spectrogram. A similar result was achieved for other orbits. The noise generated near the local LHR frequency is not seen on the simulated spectrograms, of course, since the only source of whistler-mode waves in simulations is the lightning activity, thus, resonant wave excitation is not included into simulations.

![Simulated oblique noise bands along the satellite trajectory.](image-url)
INFLUENCES ON OBLIQUE NOISE BANDS FORMATION

By varying the illuminating region, we can draw a conclusion that the simulation matches best with the observation when illuminating region is not very large and is situated in middle latitudes. Wave tubes of different frequencies are well separated in that case.

We further performed simulations under different plasmapause condition. The results of these simulations could be shortly summarized as follows. Distinct plasmapause inhibits separation of wave tubes of different frequencies and the transition to quasi-resonance regime of wave propagation. Under the influence of the plasmapause, the wave propagation is more of the longitudinal type, which is typical for ducted propagation, and the crossing of the ray trajectories is more likely, than in the absence of the plasmapause. Certain wave packets are ducted along the plasmapause so well that they do not enter the quasi-resonance regime of propagation and cannot be magnetospherically reflected. Thus in the presence of distinct plasmapause, the ray bunches of particular frequencies are not formed. These results agree well with the fact that the oblique bands have mainly been observed under quiet geomagnetic conditions and in the local evening times, when the plasmapause is not pronounced and is situated at higher altitudes.

The simulations give slightly higher intensities at higher frequencies, even if the wave intensity along the ray trajectory is considered. This shows that other mechanisms play a role in oblique noise bands formation - probably resonance processes near the LHR frequency. A stronger damping of high frequencies may also be important.

CONCLUSIONS

Oblique noise bands are mainly observed mostly under quiet geomagnetic conditions and in the local evening times, when plasmasphere is undisturbed and indistinct plasmapause is situated at higher altitudes.

The occurrence of the oblique noise bands corresponds to the “tubes” of quasi-resonance whistler mode waves near the point of their reflection. The wave tubes corresponding to higher frequencies are shifted towards lower L-shells as compared to the wave tubes corresponding to lower frequencies. At the same time, the reflection points for higher frequency waves are situated at lower altitudes and lower L-shells as compared to lower frequency waves. These characteristics of the whistler mode propagation in the Earth’s magnetosphere are important for the oblique noise bands formation.

Simulations give the best results (matching with observations) when not a very large illuminating region (supposed region of lightning activity) is situated in middle latitudes. The illuminating region from 42 to 46° (or very close region) gives the best agreement for the most observations, if comparing to the real spectrogram.

A certain discrepancy in the intensity between the observations and simulations at higher frequencies is probably due to resonance processes near the LHR frequency and stronger damping of high frequency waves, which are not taken into account in simulations.

The propagation of quasi-resonance whistler mode waves in the undisturbed Earth’s plasmasphere is important, but not the only mechanism which plays a part in oblique noise bands formation.

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