Proc. NIPR Symp. Upper Atmos. Phys., **1**, 168–172, 1988

DIRECTION FINDING OF HALF-GYROFREQUENCY VLF EMISSIONS IN THE OFF-EQUATORIAL REGION OF THE MAGNETOSPHERE

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Abstract: The GEOS 1 satellite observations of VLF/ELF waves in the off-equatorial region of the outer magnetosphere have indicated that the spectrum consists of upper and lower bands with a frequency gap between them. Based on the determination of wave normal directions of the upper band emissions in the off-equator and the subsequent inverse ray tracing toward the equator, it is found that the wave normal angles (θ) of the upper band emissions at the equator with respect to the magnetic field, are very close to the oblique resonance cone (θ_{res}) and that their normalized frequencies there are above 0.5. Hence, the upper band VLF emissions observed off the equator are identified as being "half-gyrofrequency" VLF emissions generated in the vicinity of the magnetic equator, with their wave normals close to θ_{res}, which lends further support to our previous equatorial conclusion. Also, their generation and propagation mechanisms are discussed.

1. Introduction

"Half-gyrofrequency" VLF emissions have been observed occasionally by satellites near the geomagnetic equator in the magnetosphere beyond the plasmapause, which are characterized by the wave frequency above one half the electron gyrofrequency. HAYAKAWA *et al.* (1984) have elucidated the detailed characteristics of those emissions by determining their wave normal directions in the vicinity of the equator based on the GEOS 2 satellite data and have found, for the first time, that they are quasi-electrostatic whistler-mode waves with wave normals close to θ_{res}. In order to make further studies of the generation and propagation of those waves, it is highly desirable to utilize the observations in the off-equatorial regions of the magnetosphere, which are to be compared with the previous equatorial observation. In this brief report, we describe only the essential points on the wave characteristics and wave normal directions of supposedly half-gyrofrequency VLF emissions observed off the equator by the GEOS 1 satellite. The inverse ray tracings are conducted from the off-equatorial observation points toward the equator so as to estimate the wave characteristics at the equator for the detailed study of the gneration mechanism of half-gyrofrequency VLF emissions.

2. Wave Characteristics and Wave Normal Directions in the Off-Equatorial Region

The field data are signals obtained by the S-300 experiment on board the GEOS 1 satellite, and by using the spectral matrices constructed by the three magnetic field components from the sweep frequency analyzers, we are able to determine the wave normal directions of VLF waves by means of the wave distribution function method.

Two events have been chosen and analyzed; (1) 12th October, 1977 and (2) 19th September, 1977. For the former event, the geomagnetic latitude of the satellite observation, Λ_m is 17.4°, while Λ_m for the latter event is considerably larger ($\Lambda_m=26.2°$) than the former event. Figure 1 illustrates an example of the sonagrams of VLF emissions observed in the off-equator for the latter event, and it is clear that the spectrogram is composed of upper and lower bands which are equally intense (more than $10^{-3}\ \gamma^2$/Hz). The frequency gap inferred from the spectrogram is around 1.3 kHz, which is much smaller than the half-gyrofrequency (1.745 kHz) at the observing point. The emissions in the lower band are found to be clearly structured such as chorus. The frequency spectrum of the upper band in Fig. 1 is quasi-continuous, more similar to hiss.

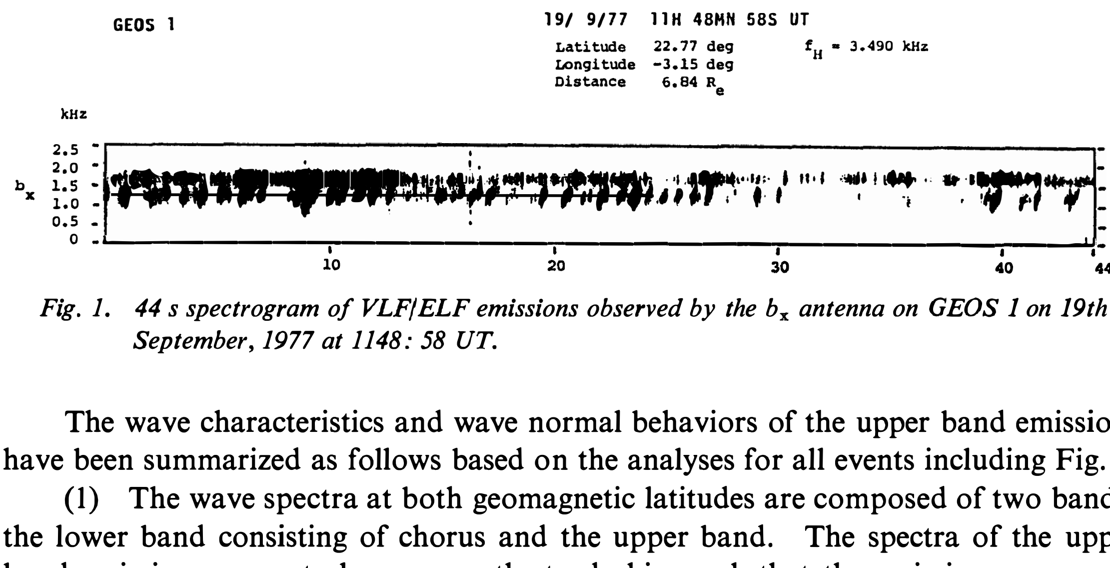

Fig. 1. 44 s spectrogram of VLF/ELF emissions observed by the b_x antenna on GEOS 1 on 19th September, 1977 at 1148: 58 UT.

The wave characteristics and wave normal behaviors of the upper band emissions have been summarized as follows based on the analyses for all events including Fig. 1.

(1) The wave spectra at both geomagnetic latitudes are composed of two bands; the lower band consisting of chorus and the upper band. The spectra of the upper band emissions are not always smooth steady hiss such that the emissions are sometimes of the hiss-type as in Fig. 1, but they are structured and impulsive on other occasions. The nature of such a variety of frequency spectra of the upper band emissions resembles very much that of odd half-harmonic electrostatic emissions.

(2) The bandwidth of the upper band is 300–500 Hz, which is nearly of the same magnitude as that observed previously at the equator (Hayakawa *et al.*, 1984) but is much larger than that observed off the equator ($\Lambda_m \sim 10°$) by Coroniti *et al.* (1971).

(3) The frequency gap between the two bands is found to be always much smaller than the local half-gyrofrequency, which is indicative of the source being located at a position with smaller geomagnetic field.

(4) The direction finding analyses have shown that the wave distribution functions are doubly peaked and that the wave energy tends to be mainly conveyed by

waves whose θ values are very close to θ_{res} at the smaller latitude ($\Lambda_m \sim 17°$), whereas the θ values are farther from θ_{res} (about 15°–20° inside θ_{res}) at the higher latitude ($\Lambda_m \sim 26°$). (An example of the wave distribution function at a frequency of 1510 Hz at the higher latitude, is given in Fig. 2, which is the result at 1148:58 711 ms UT in Fig. 1.) Then, both the main and secondary peaks are found to have propagated to the observing points from the direction of the equator.

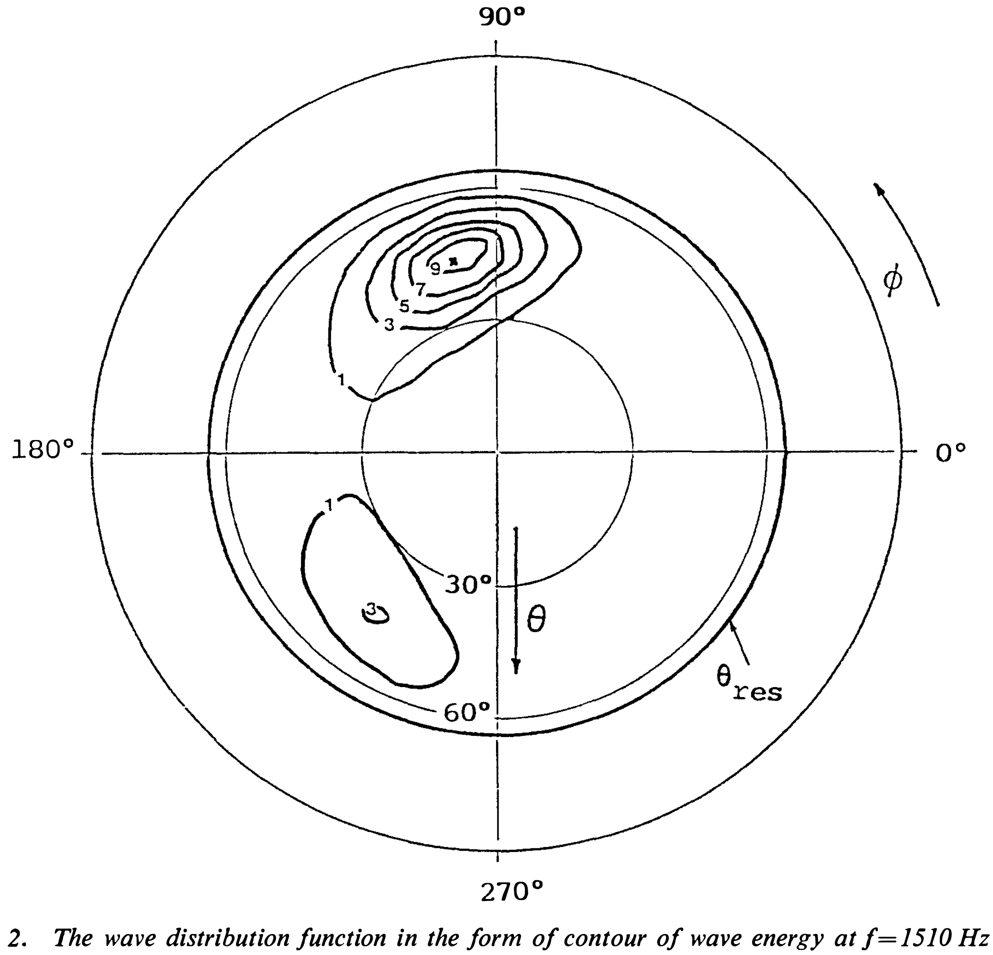

Fig. 2. The wave distribution function in the form of contour of wave energy at f=1510 Hz at 1148:58 711 ms UT on 19th September, 1977. The scale of wave distribution function is linear and runs from 0 to 10 indicated by a cross. We adopt a Cartesian coordinate system O_{xyz} where the z-axis is parallel to the Earth's magnetic field, the x-axis is in the magnetic meridian plane and is directed toward the Earth, while the y-axis completes the orthogonal set and is directed westward. The wave normal direction is characterized by the polar angle θ between the wave normal direction and the Earth's magnetic field and by the azimuthal angle ϕ with respect to O_x.

3. Inverse Ray Tracing and Wave Characteristics at the Equator

As mentioned at the end of Point (4) in the summary of Section 2, an additional use of one electric field component has enabled us to find that the upper band emissions had propagated from the equator to the observing points. So, we have performed inverse 3-dimensional ray tracing toward the equator which is considered to be the source region, by using the inverted observed wave normals at the observing points as the starting wave normals. The magnetospheric model for these ray-tracing studies, is very realistic in the L region we are interested in. The following facts have emerged from the inverse ray tracing studies.

(1) The wave normal direction (θ) of the upper band VLF emissions (both main and secondary peaks) traced backward to the equator, is found to be in the vicinity of θ_{res}. The normalized frequency, Λ_{eq} is always above 0.5.

(2) The inverse ray tracing results for the main and secondary peaks for all events have yielded that the difference in L_{eq} is relatively small, $\Delta L_{eq} \sim 0.3$, but the difference in longitude is rather larger, $\lesssim 20°$, suggesting a source region well elongated in longitude. Such source regions are located in two L regions, $L_{eq}=6.0$–6.4 and $L_{eq}=6.7$–7.2 for the events studied here.

4. Generation and Propagation of Half-Gyrofrequency VLF Emissions

The most important conclusions derived from the inverse ray tracing studies summarized in the previous section, are (1) the θ values are close to θ_{res}, and (2) Λ_{eq} is above 0.5. Point (2) is strongly indicative of a generation of the upper band VLF emissions in the vicinity of the equator. This result is consistent with our previous direction finding, made exactly at the equator (Hayakawa *et al.*, 1984), which indicated that upper band VLF emissions appear mainly above one half the equatorial gyrofrequency. Point (1) seems to lend further support to our model of wave generation in the quasi-electrostatic mode. As a result, we can conclude that the upper band VLF emissions analyzed here, are identified with confidence as being "half-gyrofrequency" VLF emissions, excited just around the equator, with their wave normals close to θ_{res}. It is a propagation effect which places the frequency gap at frequencies smaller than half the gyrofrequency at the observing points. Furthermore, it should be noted that the lower band chorus is believed to be generated in those source region by higher energy hot electrons.

As a generation mechanism of "half-gyrofrequency" VLF emissions, Ohmi and Hayakawa (1986) have proposed a theory in terms of an electrostatic electron cyclotron instability in the plasma condition consisting of cold electrons and low energy (suprathermal) anisotropic hot electrons with a temperature of the order of a few tens of eV. Then, the propagation of those waves has been discussed in a restricted latitude range, $\Lambda_m < 30°$ in the present study, but the propagation characteristics in the whole magnetosphere should be investigated, which will be published elsewhere.

As future works concerning half-gyrofrequency VLF emissions, we can list the following subjects: (1) A generation mechanism is proposed by Ohmi and Hayakawa (1986), but the calculation of the accumulated growth (and/or damping) of those waves along the ray path is highly required. This calculation is also closely related with the consideration of the bandwidth of those waves observed off the equator. (2) The generation mechanism by Ohmi and Hayakawa (1986) requires a temperature anisotropy of lower energy hot electrons and so it is of essential importance to compare the wave data with the corresponding simultaneous particle data so as to check the validity of the proposed theory. (3) The pitch-angle diffusion of hot electrons due to the interaction with half-gyrofrequency VLF emissions is very interesting as regards to the study of the loss mechanism of particles in the distant magnetosphere.

Acknowledgments

This work has been continued as a collaborative work with Drs. F. LEFEUVRE and M. PARROT, LPCE, CNRS (Orleans, France) to whom the author is grateful. This brief report is intended just to show some of important findings from this study and the paper including the detailed discussion will be published elsewhere. The contribution by Mr. H. MUTO of Nagoya University (now at Nippon Electric Company) is greatly appreciated.

References

CORONITI, F. V., FREDRICKS, R. W., KENNEL, C. F. and SCARF, F. L. (1971): Fast time resolved spectral analysis of VLF banded emissions. J. Geophys. Res., **76**, 2366–2381.

HAYAKAWA, M., YAMANAKA, Y., PARROT, M. and LEFEUVRE, F. (1984): The wave normals of magnetospheric chorus emissions observed on board GEOS 2. J. Geophys. Res., **89**, 2811–2821.

OHMI, N. and HAYAKAWA, M. (1986): On the generation of quasi-electrostatic half-electron-gyrofrequency VLF emissions in the magnetospheric plasma. J. Plasma Phys., **35**, 351–373.

(Received April 20, 1987; Revised manuscript received July 30, 1987)