CORRELATION ANALYSIS OF ELECTRIC FIELD AND ELECTRON DENSITY FLUCTUATIONS OBSERVED BY A SOUNDING ROCKET S-310JA-7

Hirotaka MORI[1], Eiichi SAGAWA[2], Tadahiko OGAWA[2], Toshio OGAWA[3] and Hisao YAMAGISHI[4]

[1]*Hiraiso Branch, Radio Research Laboratories, 3601, Isozaki, Nakaminato 311–12*
[2]*Radio Research Laboratories, Nukui-Kitamachi 4-chome, Koganei-shi, Tokyo 184*
[3]*Geophysical Institute, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606*
[4]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: A Faraday cup and a pair of double probes on board a rocket S-310JA-7 observed simultaneously intense quasi-sinusoidal waves, frequency of which was near the local ion cyclotron frequency over the *E* layer of the auroral region ionosphere. By a cross-correlation analysis of the both measurements, it is found that the frequency of the waves observed by the double probes is constantly lower by the rocket spin frequency than the frequency of the same waves observed by the Faraday cup. This result suggests that the waves have right-hand circularly or elliptically polarized electric fields.

1. Introduction

A sounding rocket S-310JA-7 was launched geomagnetically northward at 2215:50 LT on March 27, 1978 from Syowa Station in Antarctica just before the start of a substorm expansion phase, aiming at a southward-moving auroral arc in the northern sky. It was successfully launched and gave us much valuable information on the dynamics of the auroral region ionosphere. One of the remarkable results is that intense quasi-sinusoidal waves were observed by a Faraday cup and a pair of double probes simultaneously while the rocket passed through precipitation regions of auroral electrons. As the frequency of the waves was near the local ion cyclotron frequency, they were initially supposed to be electrostatic ion cyclotron waves which were theoretically discussed by KINDEL and KENNEL (1971). The instrumentations and the observed results including the above topic are discussed in detail in a special issue of the Memoirs (MIYAZAKI *et al.*, 1981; OGAWA, Tadahiko *et al.*, 1981; OGAWA, Toshio *et al.*, 1981; YAMAGISHI *et al.*, 1981). In order to investigate the waves more precisely, we have carried out a cross-correlation analysis of both measurements. The purpose of this paper is to present new results of the analysis.

2. Data Analysis

Analog data of plasma density fluctuations measured by a Faraday cup and electric field fluctuations measured by a pair of double probes were digitized with a sampling

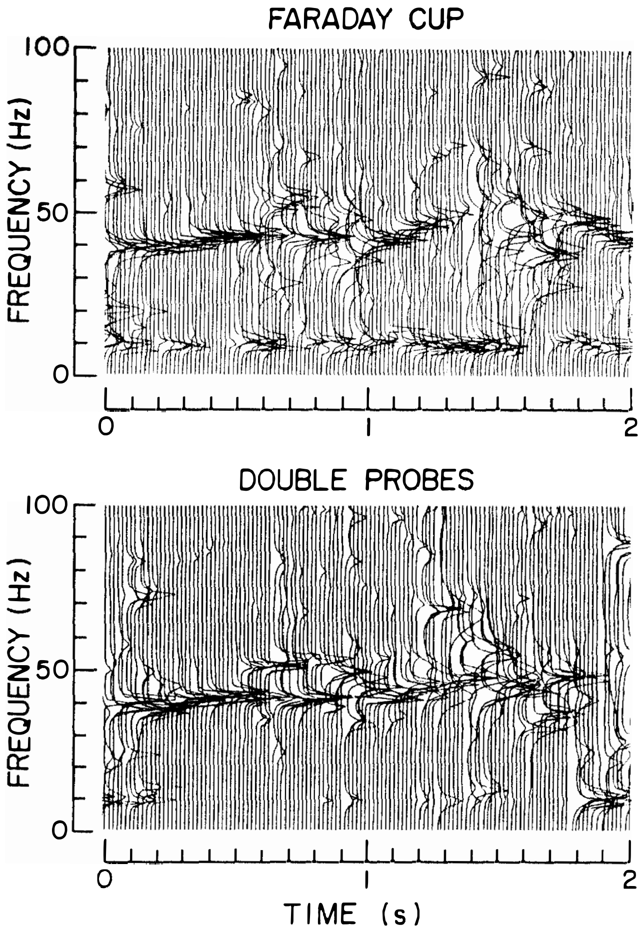

Fig. 1. Dynamic spectra of plasma density fluctuations measured by a Faraday cup (upper panel) and electric field fluctuations measured by a pair of double probes (lower panel) at the height of 210 km.

period of 1 ms, and recorded to a digital tape for computer analysis.

Quasi-sinusoidal waves, in which we are interested, were observed clearly in a height range of 200–220 km of the rocket trajectory. Figure 1 shows dynamic spectra of the Faraday cup and double probes data observed for 2 s at a height of 210 km of the descending path. Each dynamic spectrum is obtained every 15 ms by the maximum entropy method (MEM) spectrum analysis, the frequency range of which is 0–100 Hz. In the figure, narrow peaks around 10 Hz appearing only in the dynamic spectrum of the Faraday cup data are thought to be caused by some interactions of the rocket and the ambient plasma. There is another group of peaks associated with the quasi-sinusoidal waves in the frequency range of 40–55 Hz. It is remarkable that the peaks appear in both of the dynamic spectra, and that the patterns of them resemble closely, in spite of various differences between the two measurements. This fact suggests that the waves were naturally generated in the plasma.

In order to compare the two kinds of data more precisely, we computed the cross-correlation of them by the following relation

$$C(\tau) = \overline{\sum_{t} X(t) \cdot Y(t+\tau)}\,, \tag{1}$$

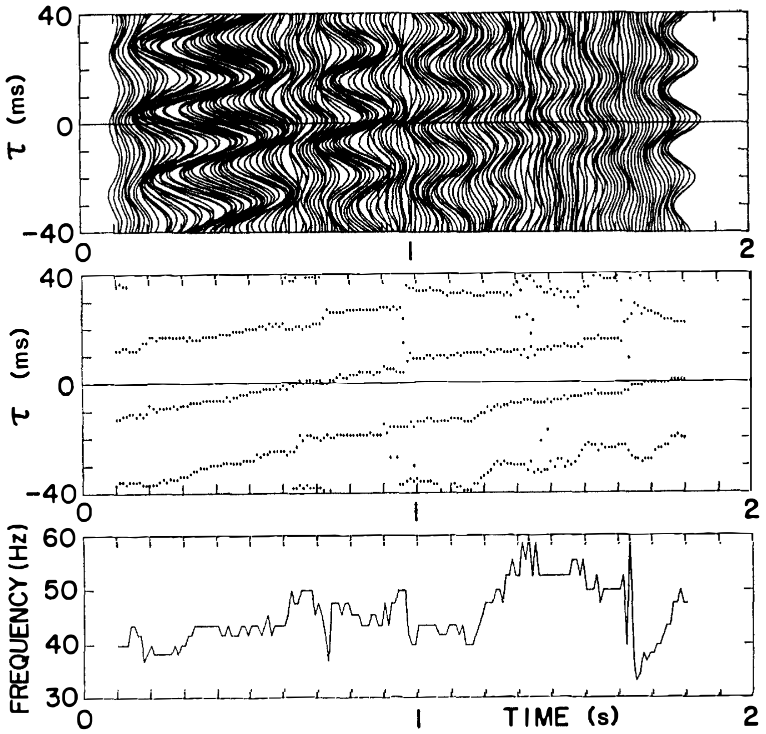

Fig. 2. Result of cross-correlation analysis of the quasi-sinusoidal waves observed at the height of 210 km.

where $X(t)$ and $Y(t)$ are digitized data of the Faraday cup and the double probes at time t, and $C(\tau)$ is the cross-correlation function. Figure 2 is one of the typical results computed with the same data set as those used for the above MEM analysis. The upper panel of the figure is made by arranging the cross-correlation functions *versus* τ (the ordinate) computed every 10 ms in time sequence. The middle panel is the plots of the peak positions of the above cross-correlation functions. The lower panel shows the time variation of the frequency which is calculated from a separation of peaks of each cross-correlation function. It is clearly seen from the figure that the peaks of the functions move linearly upward with time, and that the time interval of the points where the peaks cross the time axis is nearly equal to the rocket spin period (1.10 s). These results tell us that the frequency of the waves observed by the double probes is constantly lower by the rocket spin frequency than the frequency of the same waves observed by the Faraday cup. This is a common feature of the quasi-sinusoidal waves observed by the rocket S-310JA-7.

3. Discussion

In order to interpret the analyzed results, we must consider first how a pair of rotating double probes can detect waves generated in a plasma. We use the rocket-fixed coordintae system (x, y, z), in which the rocket axis is taken as the z-axis, and assume for simplification that the rocket spin axis coincides with the rocket axis. As shown by Fig. 3, a Faraday cup is put on the top of the rocket, and a pair of double

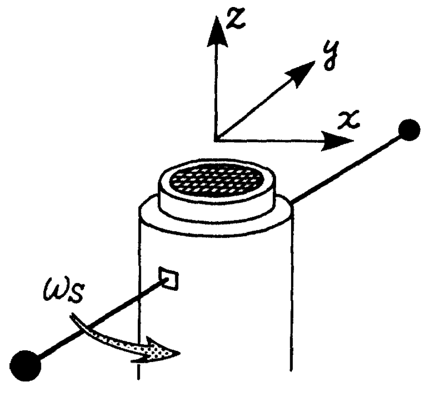

Fig. 3. Rocket-fixed coordinate system and arrangement of a Faraday cup and a pair of double probes on a rocket body.

probes are deployed perpendicular to the rocket axis.

If we assume that a plane wave is generated in the ambient plasma, and that an electric field component $\boldsymbol{E}_{xy}$ of the wave in the x–y plane is described by

$$\boldsymbol{E}_{xy}=E_x\boldsymbol{e}_x+E_y\boldsymbol{e}_y\ ,\quad E_x=E_{x_0}\sin(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})\ ,\quad E_y=E_{y_0}\cos(\omega t-\boldsymbol{k}\cdot\boldsymbol{r})\ , \tag{2}$$

the potential difference induced between a pair of double probes will be estimated by the following relation

$$\begin{aligned}\Delta\phi&=-\int_{-r_{\mathrm{L}}}^{r_{\mathrm{L}}}\{E_x\cos(\omega_{\mathrm{s}}t)+E_y\sin(\omega_{\mathrm{s}}t)\}\,\mathrm{d}r\\&=-\frac{2\sin\{k_\perp r_{\mathrm{L}}\cos(\omega_{\mathrm{s}}t)\}}{k_\perp\cos(\omega_{\mathrm{s}}t)}\{E_{x_0}\cos(\omega_{\mathrm{s}}t)\sin(\omega t)+E_{y_0}\sin(\omega_{\mathrm{s}}t)\cos(\omega t)\}\ ,\end{aligned} \tag{3}$$

where $\boldsymbol{e}_x$, $\boldsymbol{e}_y$, ω, ω_{s}, $\boldsymbol{k}$, $k_\perp$, and r_{L} mean the x-axis unit vector, the y-axis unit vector, the angular frequency of the wave, the spin angular frequency, the wave number vector of the wave, a component of the wave number vector in the x–y plane, and the length from the origin to a probe, respectively. In such a case that the wave is also accompanied by plasma density fluctuations, the Faraday cup will receive the AC current with the angular frequency ω.

Now we can calculate the cross-correlation function for the above idealized model by substituting $\sin\omega t$ and $\Delta\phi$ to X and Y of eq. (1). Figure 4 shows some examples of the calculations. Values of E_{x_0} and E_{y_0} used for each calculation are (a) $E_{x_0}=1$, $E_{y_0}=0$ for a plane polarized wave (an electrostatic wave), (b) $E_{x_0}=0.7$, $E_{y_0}=-0.3$ for a spin-wise elliptically polarized wave, (c) $E_{x_0}=0.5$, $E_{y_0}=-0.5$ for a spinwise circularly polarized wave, and (d) $E_{x_0}=0.5$, $E_{y_0}=0.5$ for an anti-spinwise circularly polarized wave. The $k_\perp r_{\mathrm{L}}$ is put equal to 0.5 which means that the wave length is much larger than the tip-to-tip length of the double probes. Comparing the four cases, case (b), or (c) seems to have a pattern similar to the upper panel of Fig. 3. If it is true, the waves observed by the rocket should have spinwise elliptically, or circularly polarized electric fields. Considering the sense of the rocket spin, and the direction of the geomagnetic field, we come to the conclusion that the waves should have right-hand elliptically, or circularly polarized electric fields. Both the above result and the fact that the waves also have intense plasma density fluctuations seem to suggest that

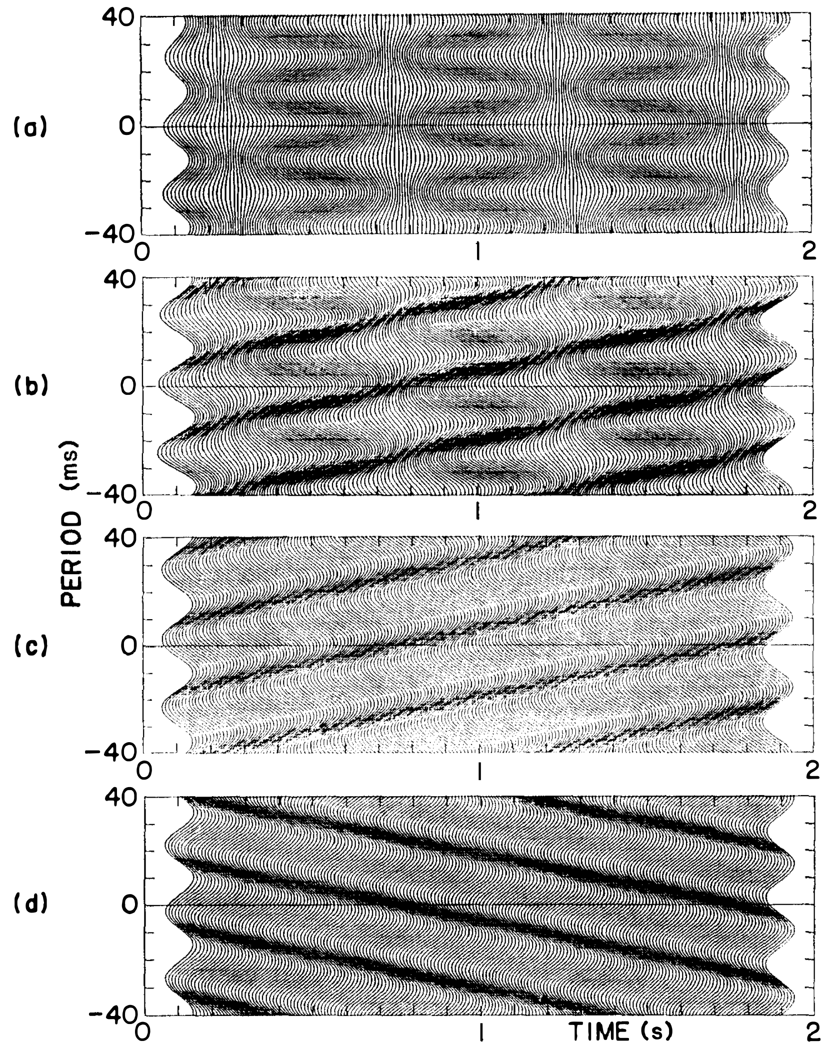

Fig. 4. Expected time variation of cross-correlation functions for (a) a plane, (b) a spinwise elliptically, (c) a spinwise circular, and (d) an anti-spinwise circular polarized waves where the frequency of the waves is 40 Hz, and the spin rate is 1 Hz.

the waves belong to an extraordinary mode of the electromagnetic waves.

It is proper in the beginning to examine the wave modes in a cold magnetized plasma. Figure 5 is the phase velocity–frequency diagram of electromagnetic wave modes calculated for the plasma of two ion species O^+ and NO^+, supposing ionospheric plasma around a height of 200 km. In the figure, $f_{C1}, f_{C2}, f_{LHR1}, f_{LHR2}$, and f_{CR} are the O^+ ion cyclotron frequency, the NO^+ ion cyclotron frequency, the first lower hybrid resonance frequency, the second lower hybrid resonance frequency, and the cross-over frequency, respectively. The mark ↺ or ↻ written in each subregion of the diagram shows the sense of polarization. Taking the sense of polarization and the frequency into account, the hatched region seems to be the most plausible region in which the observed waves belong. The uppermost frequency of the region is the cross-over frequency f_{CR} which depends on the density ratio of two ion species O^+ and NO^+. As we did not observe the ion composition, we cannot estimate local

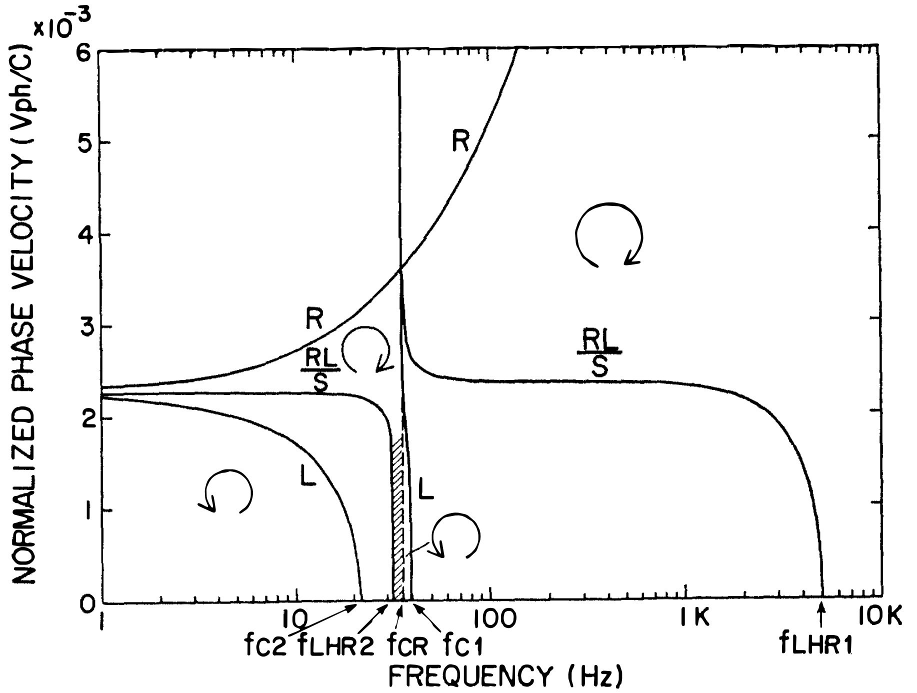

Fig. 5. Phase velocity-frequency diagram of electromagnetic wave modes calculated for the plasma of two ion species O^+ and NO^+, where the phase velocity is normalized by the light velocity C.

values of the f_{CR} but can only say that they never exceed the O^+ ion cyclotron frequency f_{C1} which is 40 Hz at a height of 200 km. Actually, the frequency of the observed waves at the same height range was between 40 to 55 Hz as shown by Fig. 1, which is somewhat higher than even the highest possible frequency of the f_{CR}. This discrepancy could be solved, if we take into account that the waves were observed on the rocket coordinate system which was moving relative to the ambient plasma.

If we measure a wave in a plasma on the moving system with the velocity v_p relative to the plasma, the observed angular frequency ω' is written by

$$\omega' = \left(1 - \frac{\boldsymbol{v}_p \cdot \boldsymbol{v}_{ph}}{|\boldsymbol{v}_{ph}|^2}\right)\omega\ , \tag{4}$$

where ω and $\boldsymbol{v}_{ph}$ are the angular frequency and the phase velocity of the wave. For the case of rocket measurement, $\boldsymbol{v}_p$ is given by the vector summation of the rocket velocity and the velocity of the $\boldsymbol{E}\times\boldsymbol{B}$ drift motion which is induced in the plasma by the geomagnetic field and the DC electric field in the ionosphere. Using the value of DC electric field which was measured by the double probes, $\boldsymbol{v}_p$ can be estimated to be about 700 m/s at a height of 200 km. Therefore, if the phase velocity of the observed waves $\boldsymbol{v}_{ph}$ is comparable with the above value, we can expect a large doppler shift for the observed frequency enough to explain a deviation from a theoretical value by eq. (4). According to the diagram of Fig. 5, the waves in the hatched region are permitted to have such a low phase velocity.

It is concluded from the above discussion that the most plausible mode of the quasi-sinusoidal waves which were observed over the auroral E region is a low phase velocity branch of the right-handed polarization mode of electromagnetic waves which is shown by a hatch in the diagram of Fig. 5.

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