SHORT-PERIOD MAGNETIC PULSATIONS INDUCED BY PERIODIC VLF EMISSIONS

Takashi MATSUDO[1] and Natsuo SATO[2]

[1] *University of Electro-Communications, 5–1, Chofugaoka 1-chome, Chofu-shi, Tokyo 182*
[2] *National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: A one-to-one correlated event between periodic VLF emissions and short-period magnetic pulsations has recently been reported by N. SATO (J. Geophys. Res., **89**, 2781, 1984). By using this event we examined relative phases between periodic VLF emissions and the H component of short-period magnetic pulsations. The relative phases between the increase of periodic VLF emission intensities and the increase of northward magnetic field were approximately 180° different. From this phase difference we calculated the time delay between particle precipitations into the ionosphere induced by periodic VLF emissions and the current flow in the ionosphere by the enhancement of conductivity by the model proposed by SATO. Though there was some ambiguity in calculating the value, we estimated the relaxation time to be approximately one second.

1. Introduction

SATO (1984) has recently reported short-period magnetic pulsations associated with periodic VLF emissions ($T \sim 5.6$ s). As for the origin of the short-period magnetic pulsations they suggested that the periodic precipitating electron fluxes induced by periodic VLF waves would modify the ionospheric conductivity. The periodic enhancements of the conductivity in the ionospheric D and E regions would modify the $S_q{}^p$ current flow in the ionosphere, resulting in the magnetic variations observed on the ground.

The purpose of this paper is to extend the study reported by SATO (1984) and to examine in detail the cross correlations, especially the phase relation between the periodic VLF emissions and the magnetic pulsations observed at Syowa Station (−66.1°, 70.8° in invariant geomagnetic coordinates, L=6.1) in Antarctica and at Husafell (66.0°, 70.2° in invariant geomagnetic coordinates, L=6.1) in Iceland. Husafell is located at the geomagnetic conjugate point of Syowa Station. The data of intensity variations of VLF emissions and ULF waves by the search coil magnetometer were recorded on digital magnetic tapes by microcomputer at both stations with the sampling frequency of 0.5 Hz. Analogue data were also recorded on magnetic tapes.

2. Observations

2.1. Geomagnetic conjugacy of periodic VLF emissions

Periodic emissions are believed to show good geomagnetic conjugacy because the

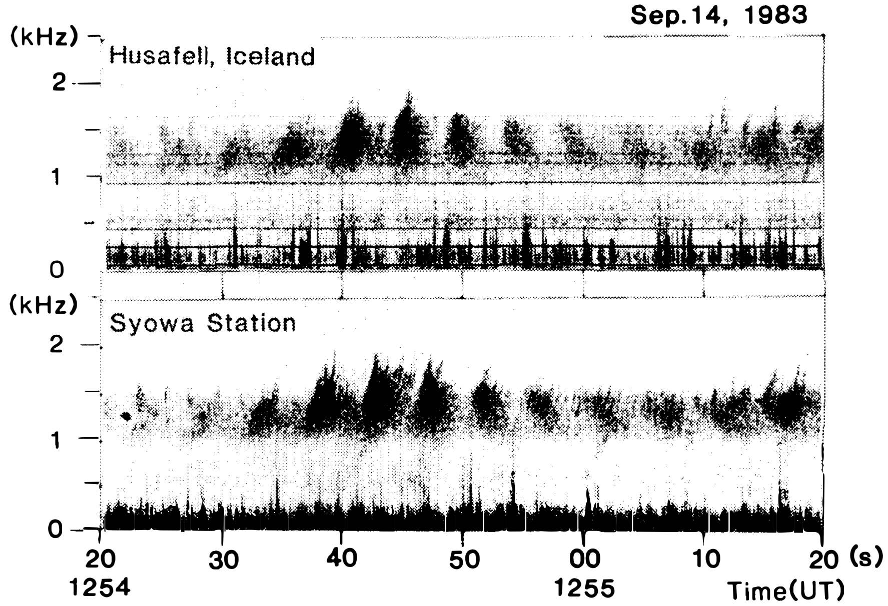

Fig. 1. Frequency-time spectra of periodic VLF emissions observed simultaneously at geomagnetic conjugate-pair stations, Syowa Station in Antarctica and Husafell in Iceland during the interval of 1254:20–1255:20 UT on September 14, 1983.

period of periodic VLF emissions usually is almost equal to the propagation time of two hops of whistler mode waves (HELLIWELL, 1965). At first we will confirm the geomagnetic conjugacy of periodic VLF emissions observed at Syowa Station and Husafell. Figure 1 shows the frequency-time spectra of periodic VLF emissions observed simultaneously at conjugate-pair stations on September 14, 1983. From the *f-t* spectra, this periodic emission will belong to dispersive type according to HELLIWELL's catalog (1965). It is easily understood that the time difference of enhancement of emission intensity is out of phase between conjugate-pair stations, and dispersion of emission frequency with time is almost the same at both stations. However, it is worth noting that the enhancement of discrete chorus elements associated with periodic emissions does not show one-to-one correspondence between the two stations. It is suggested that new emissions are enhanced by wave-particle interactions near the equatorial plane in the magnetosphere associated with the source of periodic emissions. Figures 2a and 2b show *f-t* spectra for the envelope of intensity fluctuations at 1.2 kHz VLF band observed at Husafell and Syowa Station during the period of 1200–1320 UT on September 14, 1983. In this analysis, the emission intensity data are sampled by A/D converter from analogue magnetic tapes at the frequency of 12.5 Hz.

It is clearly shown that the periodic frequency of the periodic VLF emissions is noticeable at the constant frequency of 0.2 Hz, and weak harmonic bands of 0.4, 0.8 Hz, ... are also enhanced at both stations. Figure 2c shows the relative phases of periodic emissions observed at Syowa and Husafell. In this figure the periodic frequency band is selected at $\sim$208 mHz. It is evident from this figure that the relative phases of periodic emissions observed at conjugate-pair stations are almost 180° different. So it is concluded that periodic emissions are observed out of phase at the

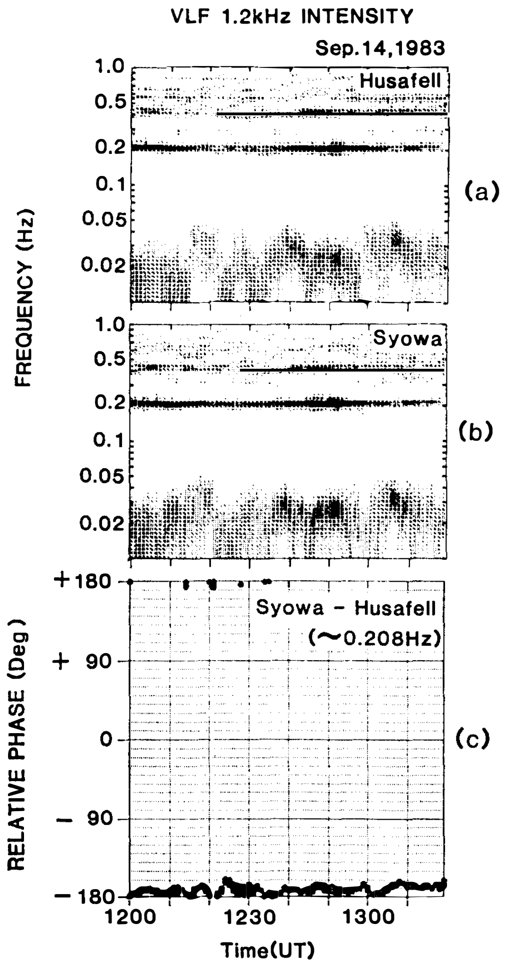

Fig. 2. Frequency-time spectra for the envelope of intensity variations at 1.2 kHz VLF band observed at Husafell and Syowa Station (Figs. 2a and 2b), and relative phases of the periodic variations centered at ~208 mHz between the emissions observed at Syowa Station and at Husafell (Fig. 2c) during the interval of 1200–1320 UT on September 14, 1983.

geomagnetic conjugate point. Details of the geomagnetic conjugacy of periodic emissions and related magnetic pulsations will be reported by another paper in the near future.

2.2. *Relative phases between periodic VLF emissions and short-period magnetic pulsations*

In this section we will examine the correlation between periodic VLF emissions and magnetic pulsations by the search coil magnetometer. Figure 3 shows the frequency-time spectrum for the envelope of a filtered band at 750 Hz, the H and the D components of magnetic pulsations observed at Syowa in the interval of 1400–1655 UT on August 8, 1981. As already reported by SATO (1984), the periodic VLF emissions in this event are enhanced at the frequency of ~180 mHz, and the H component of magnetic pulsations shows the same frequency bands. On the other hand, intensity of the D component of magnetic pulsations associated with these periodic VLF emissions is very weak compared with the H component. Figure 4a shows the relative power spectra for the periodic VLF emissions at 750 Hz band, the H and the D components of magnetic pulsations in the time interval of 1520–1524 UT on August 8, 1981. In this figure, a sharp spectral peak is seen on 750 Hz and ULF (H) spectra

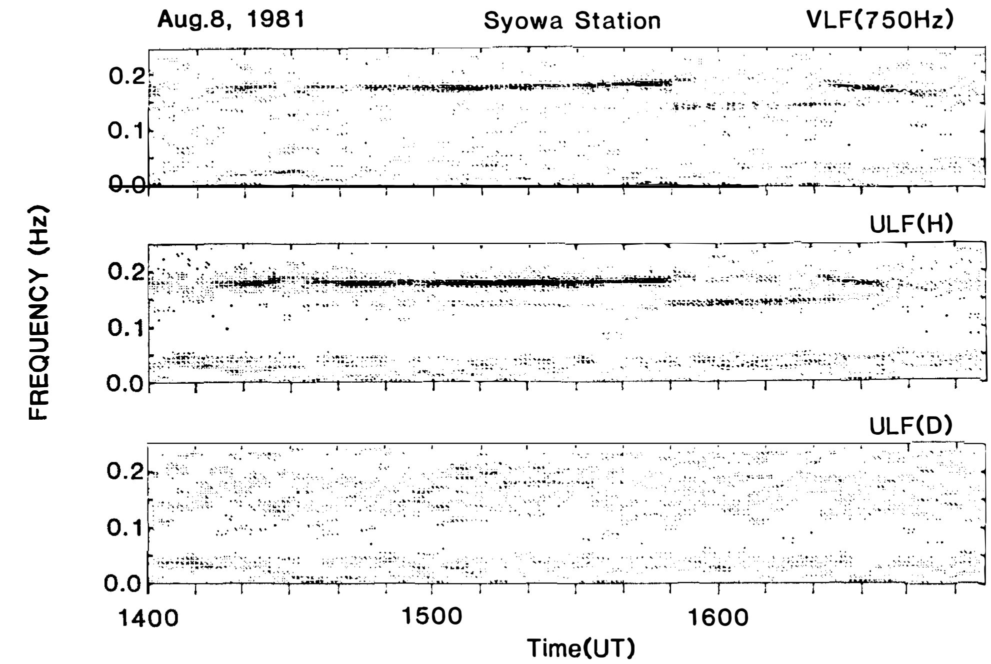

Fig. 3. Frequency-time spectra for the envelope of intensity variations of VLF at 750 Hz (upper panel), the H component of magnetic pulsations (middle panel) and the D component of magnetic pulsations (bottom panel) observed at Syowa Station during the interval of 1400–1700 UT on August 8, 1981.

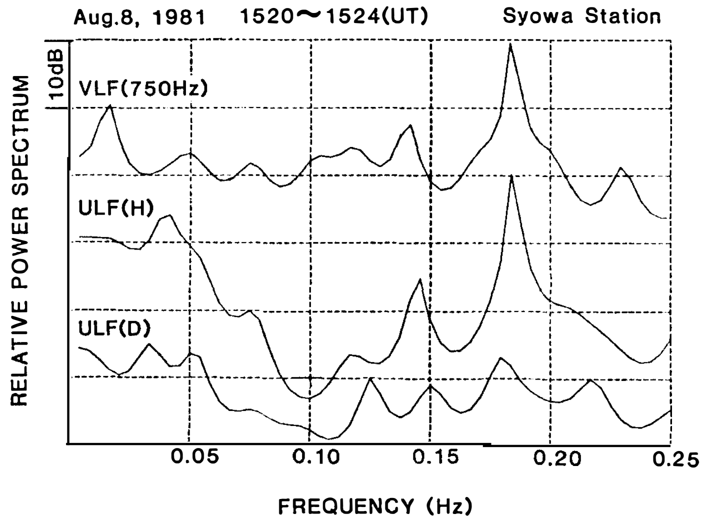

Fig. 4a. Relative power spectra for the intensity variations at 750 Hz band, the H and the D components of magnetic pulsations in the time interval of 1520–1524 UT on August 8, 1981. Periodic VLF emissions and related magnetic pulsations are noticeable at ~180 mHz.

at ~180 mHz. The power of the *D* component of magnetic pulsations at ~180 mHz is relatively 20 dB less than that of the *H* component of magnetic pulsations. Figure 4b shows the coherency and relative phases between VLF emissions at 750 Hz and the *H* component of magnetic pulsations. The coherency between 750 Hz and ULF (*H*) reaches almost 1.0 at ~180 mHz. The relative phases between periodic VLF emissions and magnetic pulsations at ~180 mHz show −90°. Figure 5a shows dy-

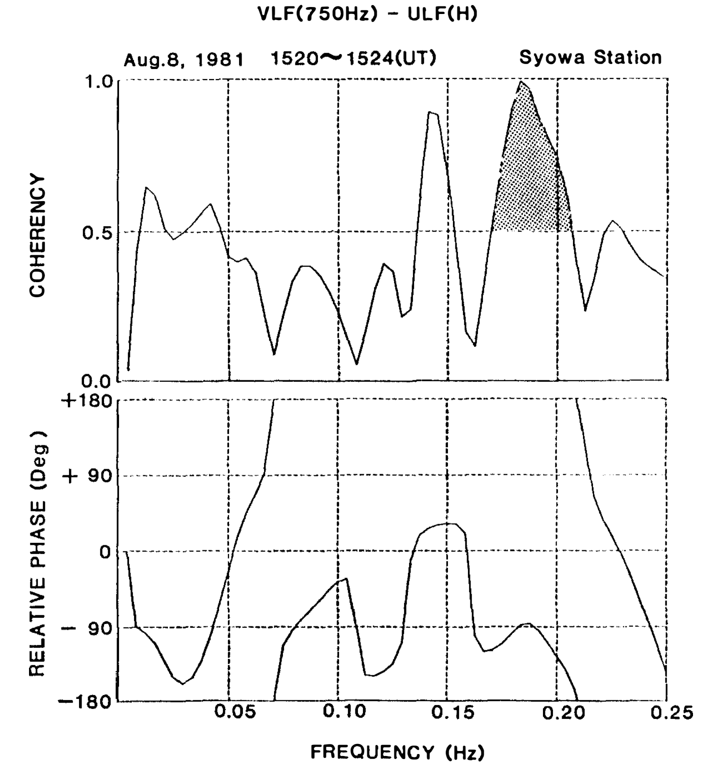

Fig. 4b. Coherency and relative phases between intensity variations of 750 Hz band VLF emission and the H component of magnetic pulsations during the same time interval as Fig. 4a.

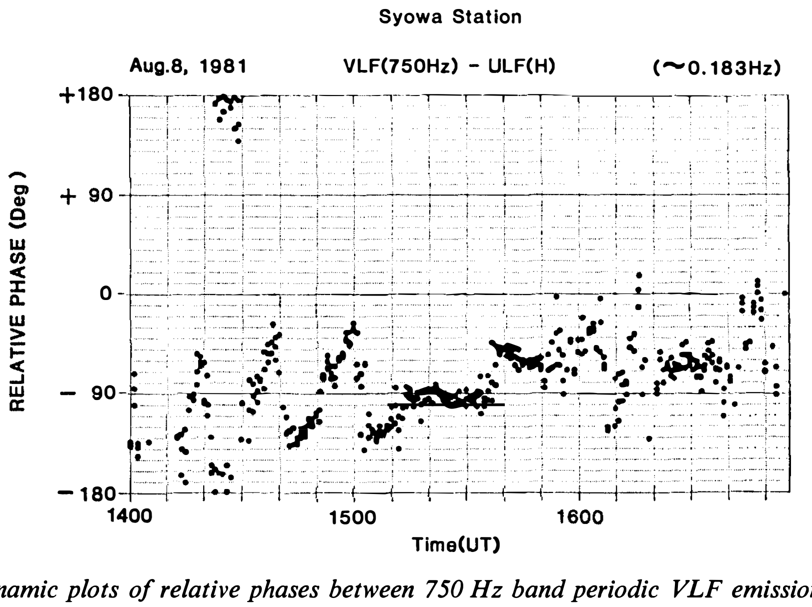

Fig. 5a. Dynamic plots of relative phases between 750 Hz band periodic VLF emissions and the H component of magnetic pulsations at selected frequency band of 183 mHz in the time interval of 1400–1655 UT on August 8, 1981. In this figure, coherency larger than 0.5 between periodic VLF emission and the H component of magnetic pulsation was plotted.

namic plots of relative phases between 750 Hz band periodic VLF emissions and the *H* component of magnetic pulsations at the selected frequency band of 183 mHz in the time interval of 1400–1655 UT on August 8, 1981. In this figure, coherency larger

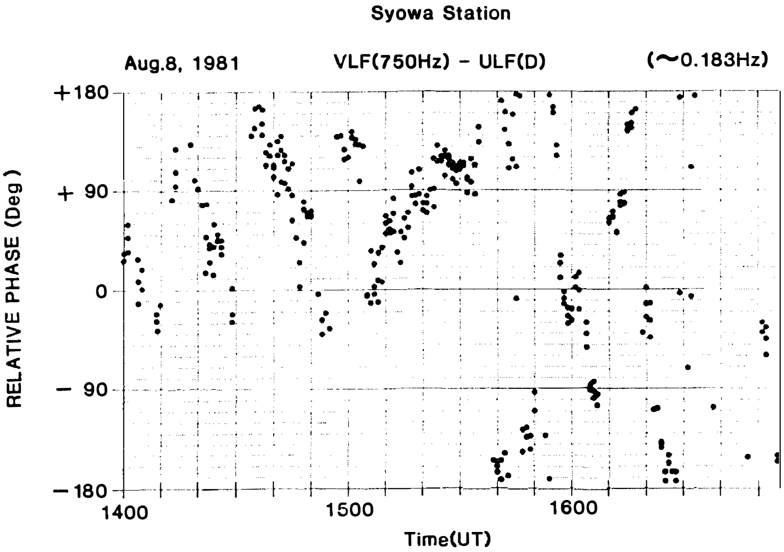

Fig. 5b. The same as Fig. 5a except the relative phases between 750 Hz band periodic VLF emissions and the D component of magnetic pulsation.

than 0.5 between periodic VLF emissions and the *H* component of magnetic is plotted. It is very interesting that relative phases are not much diverged and show around −90° ±90°. Especially, the phases are converged on −90° in the time interval of 1510–1540 UT, the most intensified time interval of periodic emissions as shown in Fig. 3. Figure 5b shows relative phases between 750 Hz band periodic emissions and the *D* component of magnetic pulsations at selected frequency of 183 mHz. The coherency larger than 0.5 between them was plotted in this figure. It is easily found that relative phases between 750 Hz periodic emissions and the *D* component of magnetic pulsations are much more scattered than those between 750 Hz periodic emissions and the *H* component of magnetic pulsations shown in Fig. 5a. It is noticeable that the relative phases between periodic VLF emissions and the *H* component of magnetic pulsations converge around −90°. Furthermore, the relative phases between the *H* and the *D* components of magnetic pulsations are roughly −180°.

3. Discussion

We examined mainly the relative phases between periodic VLF emissions and short-period magnetic pulsations of the event of August 8, 1981 from a few tens of examples. This event is the most typical phenomenon showing one-to-one correlation between periodic VLF emissions and the *H* component of short-period magnetic pulsations as reported by SATO (1984). SATO (1984) expected that the periodic enhancements of conductivity induced by particle precipitation in the ionosphere associated with periodic emissions would modify the $S_q{}^p$ current flow in the ionosphere, resulting in the *H* component of magnetic variations observed on the ground.

It is an important result that there are meaningful phase lags between periodic emissions and the *H* component of magnetic pulsations. The relative phases between the emissions and the magnetic pulsations are approximately −90° as shown in Fig.

5a. Magnetic pulsation data analyzed in this report were the data observed at Syowa Station using the search coil magnetometer. The search coil magnetometer data shifts +90° earlier than that of fluxgate magnetometer data by inductance effect. So our results shown in Fig. 5a mean that the relative phase between periodic VLF emissions and related magnetic field variations of the *H* component is approximately −180°.

We discuss in the following the meaning of the relative phase between periodic VLF emissions and magnetic variations. Periodic VLF emission waves are bouncing between Syowa Station and Husafell along the geomagnetic field line. The periodic emissions are intensified near the equatorial plane in the magnetosphere by the wave-particle interaction mechanism (HELLIWELL, 1965). In this case, high-energy electrons may be precipitated periodically in association with periodic VLF emissions. Evidences for the wave-induced electron precipitations associated with VLF emissions have been obtained by ROSENBERG *et al.* (1971, 1981) and HELLIWELL and MENDE (1980). For the origin of the short-period magnetic pulsations associated with the periodic emissions we have assumed the enhancements of the ionospheric conductivity due to wave-induced precipitations. A transient enhancement of conductivity in the ionospheric *D* and *E* regions would modify the current flow in the ionosphere, resulting in magnetic variations observed on the ground as discussed by BELL (1976), KOKUBUN *et al.* (1981) and SATO (1984).

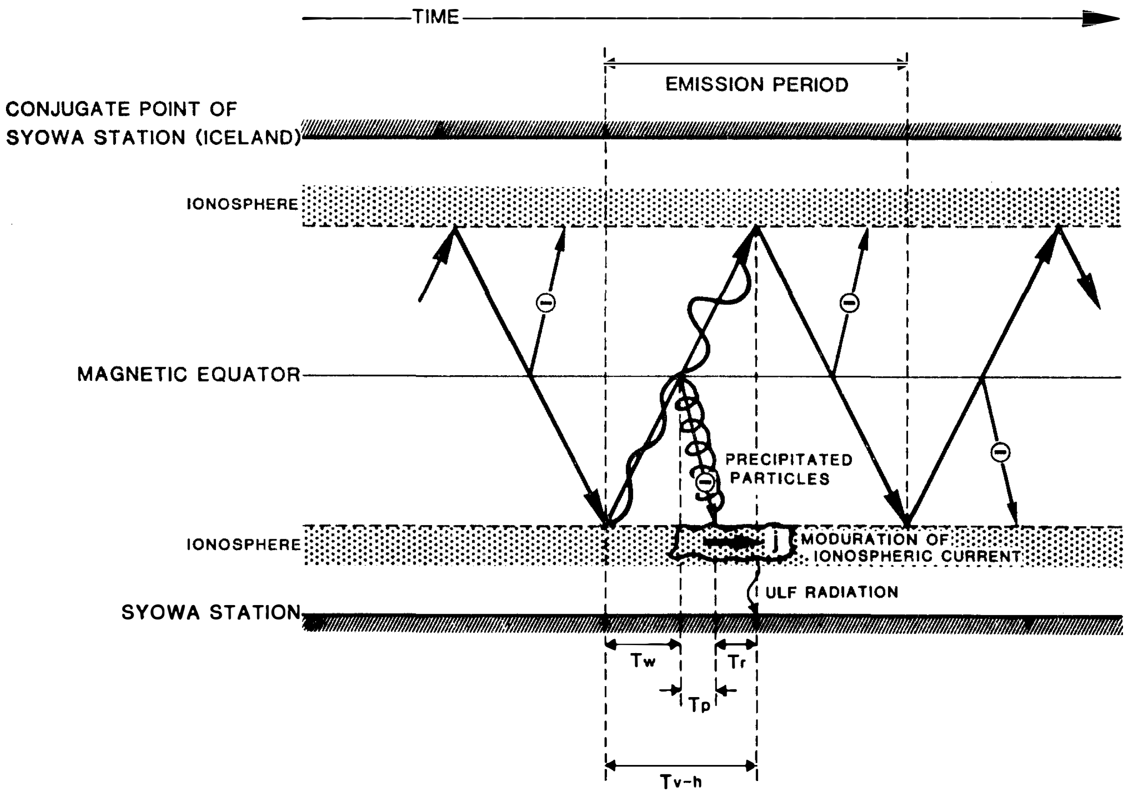

Fig. 6. A time diagram indicating the relation among periodic emission, particle precipitation and magnetic field variation. T_W, T_P and T_r show propagation time of VLF wave and high-energy electron from equatorial plane to the ionosphere, and relaxation time between particle precipitation in the ionosphere and following current flow induced by the enhancement of conductivity, respectively.

We try to calculate the time delay, the time difference between particle precipitation in the ionosphere and the current flow induced by the enhancement of conductivity in the ionosphere, from the model proposed by SATO (1984). Figure 6 shows a simple time diagram indicating the relation between these phenomena. T_w and T_p are propagation time of VLF waves and high-energy electrons from equatorial plane to the ionosphere along the field line, respectively. T_r is the time delay between particle precipitation in the ionosphere and the current flow induced by the enhancement of conductivity in the ionosphere. The time difference (T_{v-h}) between enhancement of VLF emission intensity and the magnetic field variation on the ground may be calculated from the following equation.

$$T_{v-h}=T_w+T_p+T_r. \quad (1)$$

For the August 8, 1981 event, the bounce period of periodic emission is 5.5 s, resulting in

$$T_w=5.5/4=\sim 1.4 \text{ (s)}. \quad (2)$$

The phase relation between periodic VLF emissions and magnetic variations is approximately out of phase with the period of 5.5 s, resulting in

$$T_{v-h}=5.5/2=\sim 2.8 \text{ (s)}. \quad (3)$$

If the periodic VLF emissions at 750 Hz are intensified by high-energy electrons with the energy of 20–200 keV near the equatorial plane in the magnetosphere, the bounce period (T_b) of high-energy electrons at $L=6.1$ becomes T_b $\sim$2.4 s at 20 keV and T_b $\sim$0.8 s at 200 keV calculated from Dippole model (LYONS and WILLIAMS, 1984). $T_p(T_b/4)$ may be estimated to be

$$0.2<T_p<0.6 \text{ (s)}. \quad (4)$$

From the eqs. (1)–(4), T_r may be estimated as

$$0.8<T_r<1.2 \text{ (s)}. \quad (5)$$

The results of coherency (relative phase) analysis always have ambiguity of $\pm 2\pi n$ for the periodic phenomena, where n is integer. The result of eq. (5) becomes

$$0.8\pm 5.5n<T_r<1.2\pm 5.5n \text{ (s)}. \quad (6)$$

SIREN *et al.* (1980) estimated the recombination time of electrons in the ionosphere using the data of X-ray burst and CNA data observed at $L=4$. They concluded that the recombination time is approximately 2 s. LANZEROTTI and ROSENBERG (1983) also reported the response time of magnetic variations associated with CNA variations. They estimated the response time of magnetic variations induced by impulsive electron precipitation to be from 2 to 4 s. When we compare the result of eq. (6) with the previous work (SIREN *et al.*, 1980; LANZEROTTI and ROSENBERG, 1983), it is suggestible that n may be 0 or $+1$ in the eq. (6). It is evident that the short periodic magnetic pulsation in the August 8, 1981 event indicated in Figs. 3 and 6 is appearing with constant amplitude for a long time more than one hour. If the time delay is longer than one period of magnetic pulsations, the relative phases depend strongly on their modulation frequency, because the rate of increase in relative phase differences with the increase of modulation frequency is proportional to the value of the time delay in this case as discussed by SATO *et al.* (1985). However, we have never found such effects in the events we ever analyzed. So we can propose that the time delay between particle precipitation into the ionosphere induced by periodic VLF emissions and the current flow in the ionosphere by the enhancement of conductivity is around one second in the August 8, 1981 event.

Acknowledgments

We wish to express our acknowledgment to T. YOSHINO, University of Electro-Communications for his kind help and support in initiating this study. We thank T. HIRASAWA, H. FUKUNISHI, T. OGUTI, S. KOKUBUN, H. YAMAGISHI, H. MIYAOKA and Y. TONEGAWA for their valuable discussions and suggestions. We also thank all members of Data Analysis Division, National Institute of Polar Research for their kind support in operating the HITAC M-180 computer system. It is our pleasure to acknowledge all the members of the wintering party of the 22nd Japanese Antarctic Research Expedition and T. H. SAEMUNDSSON and S. JOHANESSON for their kind support in making the observations at Syowa Station in Antarctica and at Husafell in Iceland.

References

BELL, T. F. (1976): ULF wave generation through particle precipitation induced by VLF transmitters. J. Geophys. Res., **81**, 3316–3326.

HELLIWELL, R. A. (1965): Whistler and Related Ionospheric Phenomena. Stanford, Stanford University Press, 349 p.

HELLIWELL, R. A. and MENDE, S. B. (1980): Correlations between λ4278 optical emissions and VLF wave events observed at $L\sim 4$ in the Antarctic. J. Geophys. Res., **85**, 3376–3386.

KOKUBUN, S., HAYASHI, K., OGUTI, T., TSURUDA, K., MACHIDA, S., KITAMURA, T., SAKA, O. and WATANABE, T. (1981): Correlations between very low frequency chorus bursts and impulsive magnetic variations at $L\sim 4.5$. Can. J. Phys., **59**, 1034–1041.

LANZEROTTI, L. J. and ROSENBERG, T. J. (1983): Impulsive particle precipitation and concurrent magnetic field changes observed in conjugate areas near $L=4$. J. Geophys. Res., **88**, 9115–9124.

LYONS, L. R. and WILLIAMS, D. J. (1984): Quantitative Aspects of Magnetospheric Physics. Dordrecht, D. Reidel, 231 p. (Geophysics and Astrophysics Monographs, Vol. 23).

ROSENBERG, T. J., HELLIWELL, R. A. and KATSUFRAKIS, J. P. (1971): Electron precipitation associated with discrete very-low-frequency emissions. J. Geophys. Res., **76**, 8445–8452.

ROSENBERG, T. J., SIREN, J. C., MATTHEW, D. L., MARTHINSEN, K., HOLTET, J. A., EGELAND, A., CARPENTER, D. L. and HELLIWELL, R. A. (1981): Conjugacy of electron microbursts and VLF chorus. J. Geophys. Res., **86**, 5819–5832.

SATO, N. (1984): Short-period magnetic pulsations associated with periodic VLF emissions ($T\sim$ 5.6 s). J. Geophys. Res., **89**, 2781–2787.

SATO, N., SHIBUYA, S., MAEZAWA, K., HIGUCHI, Y. and TONEGAWA, Y. (1985): CNA pulsations associated with quasi-periodic VLF emissions. J. Geophys. Res., **90**, 10968–10974.

SIREN, J. C., ROSENBERG, T. J., DETRICK, D. and LANZEROTTI, L. J. (1980): Conjugate observation of electron microburst groups by bremsstrahlung X ray and riometer techniques. J. Geophys. Res., **85**, 6760–6768.

(Received November 25, 1985; Revised manuscript received February 26, 1986)