SIMULTANEOUS OBSERVATION OF VLF PHASE AND ABSORPTION ANOMALIES AT SYOWA STATION, ANTARCTICA IN ASSOCIATION WITH MAGNETOSPHERIC SUBSTORMS

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***Abstract*:** Ionospheric disturbances associated with magnetospheric substorms were detected with VLF (f=10.2 and 13.6 kHz) radio wave propagation and a riometer simultaneously at Syowa Station, Antarctica. It is shown that the phase of the OMEGA REUNION signals (10.2 and 13.6 kHz, La Reunion) advances significantly in association with geomagnetic bays and ionospheric absorptions. In correspondence to these disturbances, VLF phase anomalies are also observed on the OMEGA ALDRA signal (13.6 kHz, Aldra, Norway) as received at Inubo, Japan. The conjugacy of occurrence of the VLF phase anomalies in the northern and southern hemispheres indicates that ionospheric disturbances responsible for VLF phase anomalies are caused by precipitation of energetic electrons from the magnetosphere. Local time characteristics of VLF phase and absorption anomalies are obtained from data recorded during a period from September 1, 1980 to January 31, 1981. Precipitation of energetic electrons responsible for VLF phase anomalies takes place predominantly in the evening sector peaked around 22 MLT, whereas electron precipitation responsible for absorption anomalies takes place in the morning sector peaked around 0230 and 0730 MLT. The discrepancy in these local time characteristics is due to a difference in height of the ionosphere responsible for the VLF phase anomaly (h<80 km) and the ionospheric absorption (h=80–100 km). It is suggested that absorption anomalies are caused by energetic electrons with energies>30 keV and VLF phase anomalies by more energetic electrons with energies>300 keV. This conclusion is confirmed qualitatively by observational facts that a significant phase anomaly is observed on the REUNION (10.2 kHz) signal which is reflected from the lowermost part of the ionosphere, whereas no corresponding disturbances either on the REUNION (13.6 kHz) signal and in ionospheric absorption.

1. Introduction

VLF radio wave propagation over auroral paths is often disturbed at a time of magnetospheric substorms (REDER *et al.*, 1964; EGELAND and NAUSTVIK, 1967; EGELAND *et al.*, 1969; SVENNESSON, 1973; WESTERLUND and REDER, 1973; KIKUCHI, 1981;

KIKUCHI and EVANS, 1983). VLF phase anomalies with a time scale of 0.5–3 h are a consequence of *D*-region ionizations caused by energetic electrons precipitated from the magnetosphere. The energy of the precipitating electrons was estimated by several authors as $>$40 keV (POTEMRA and ROSENBERG, 1973) and $>$60 keV (SVENNESSON, 1973; WESTERLUND and REDER, 1973) on an assumption that VLF waves are reflected at the lower ionosphere at altitudes of 80–90 km during the night. Therefore, it was considered that the VLF phase anomalies were generally consistent with ionospheric absorption anomalies detected with the riometer. However, some authors pointed out that no absorption anomaly was associated with VLF phase anomalies during the day (WESTERLUND and REDER, 1973; KIKUCHI, 1981). This suggests a contribution of more energetic electrons with energies greater than 200 keV for daytime VLF phase anomalies.

KIKUCHI (1981) studied local time characteristics of occurrence of VLF phase anomalies based on VLF phase data obtained at Inubo, Japan (35°42′N, 140°52′E). It was shown that VLF phase anomalies appeared at all local times with peaks in the morning (8 MLT), pre-midnight (2230 MLT) and afternoon to evening (1630 MLT) sectors, although absorption anomaly is predominant in the morning and pre-midnight sectors (HARTZ *et al.*, 1963; JELLY and BRICE, 1967; HARGREAVES and COWLEY, 1967; JELLY, 1970). KIKUCHI (1981) concluded that electrons causing VLF phase anomalies are not identical with electrons causing absorption anomaly, at least in the afternoon to evening sector. He estimated the energy of electrons causing the nighttime VLF phase anomaly as $>$150 keV, which is much higher than estimated before. Furthermore, KIKUCHI and EVANS (1983) studied quantitative relations between the VLF phase anomalies and precipitating energetic electrons with energies $>$30, $>$100 and $>$300 keV detected onboard the TIROS-N and NOAA-6 satellites. From the local time characteristics of the quantitative relations, they concluded that VLF phase anomalies are caused by electrons with energies greater than 300 keV even during the night, while absorption anomalies are caused by less energetic electrons with energies, *e.g.*, $>$30 keV.

Although the above-referred observations infer that occurrence features of VLF phase anomalies are different from those of absorption anomalies, this should be confirmed by simultaneous observation of VLF phase anomalies and absorption anomalies at the same location. For this purpose, we made simultaneous measurements of VLF phase and ionospheric absorption at Syowa Station, Antarctica (69°00′S, 39°35′E). Observational results will show that VLF phase anomalies appear frequently in the afternoon to evening sector, while absorption anomalies are predominated in the morning sector. These results are consistent with the conclusion of KIKUCHI and EVANS (1983): absorption anomalies are caused by energetic electrons with $E>30$ keV and VLF phase anomalies by more energetic electrons with $E>300$ keV.

2. Observations

VLF navigational signals, OMEGA REUNION (10.2 and 13.6 kHz, La Reunion, 20°58′S, 55°17′E), ARGENTINA (13.6 kHz, Argentina, 43°03′S, 65°11′W) and LIBERIA (13.6 kHz, Liberia, 06°18′N, 10°40′W) have been received at Syowa Station, Antarctica since September 1, 1980. Phase measurements are made by means of a rubidium frequency standard. Among these signals, the REUNION (10.2 and 13.6 kHz) signals are used in the following analyses because of good quality of the data.

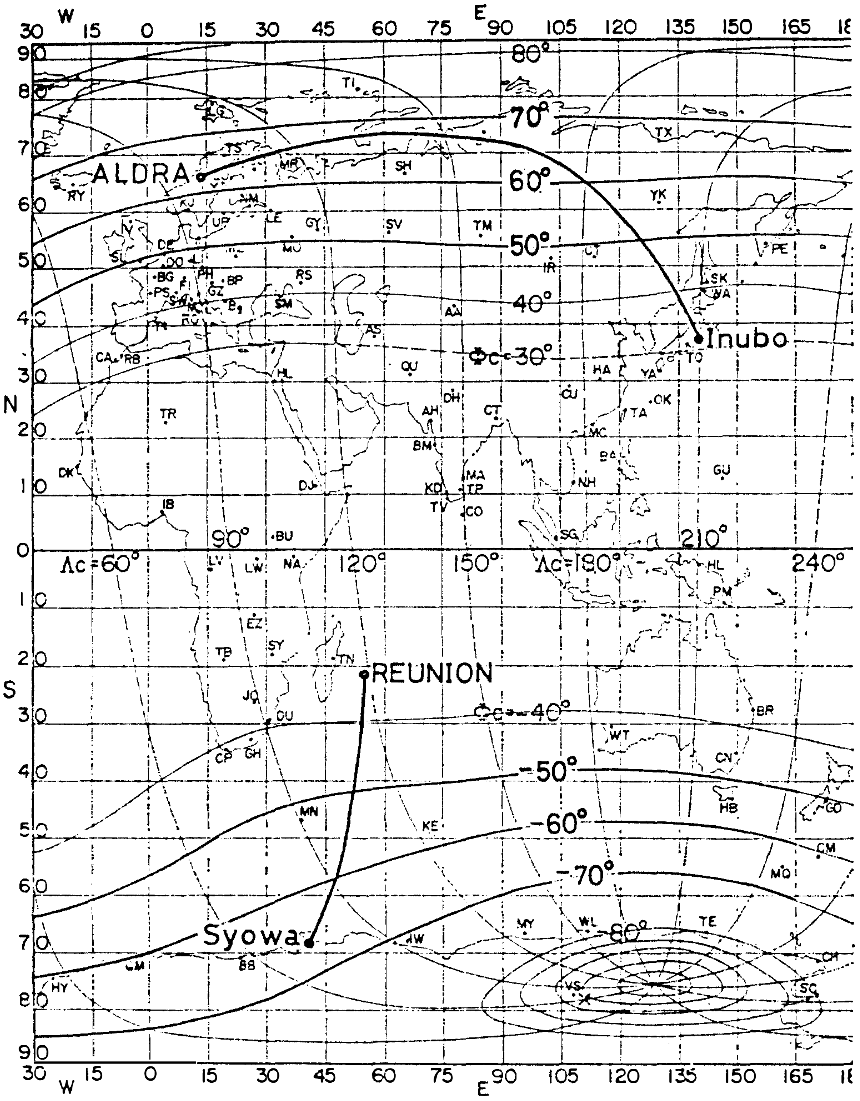

Fig. 1. Propagation paths of VLF signals: OMEGA REUNION–Syowa, Antarctica and OMEGA ALDRA–Inubo, Japan. Λ_C and Φ_C denote the corrected geomagnetic longitude and latitude, respectively. The VLF paths traverse the auroral zone (Φ_C=60°–70°) in both hemispheres, which are nearly at a conjugate location of each other.

The propagation path from Reunion to Syowa Station is plotted in Fig. 1. The path length is 5447 km. Measurements of ionospheric absorption have been routinely made at Syowa Station with a riometer for a purpose of monitoring ionospheric disturbances due to energetic particle precipitation.

It should be noted that VLF phase anomalies are a consequence of integral effects of charged particle precipitation along the whole VLF propagation path. The wide coverage of the VLF path in the auroral zone is a major reason for high sensitivity of detecting the energetic electron precipitation, although it makes indefinite determination of a location of precipitation. On the other hand, the riometer detects precipitation just above the observation point. In the present situation (Fig. 1), the region of electron precipitation over the REUNION–Syowa path is within one hour in longitude apart from Syowa Station, if we assume precipitation takes place in the auroral zone between 60° and 70° corrected geomagnetic latitude (CGL). Therefore, the precipitation on the REUNION–Syowa path would generally be correlated with precipitation above Syowa Station, because precipitation associated with substorms takes place over a wide longitudinal range of several hours (KIKUCHI and EVANS, 1983).

Magnetograms recorded at Syowa Station are used to identify the VLF phase disturbances and ionospheric absorptions with ionospheric substorms, although as shown below not all ionospheric disturbances are correlated with geomagnetic disturbances at Syowa Station. In the following analyses, VLF phase data obtained at Inubo, Japan (35°42′N, 140°52′E) are used to investigate conjugacy of occurrence of VLF phase anomalies in the northern and southern hemispheres. The path from OMEGA ALDRA (13.6 kHz, Norway, 66°25′N, 13°09′E) to Inubo is shown in Fig. 1. The path traverses the auroral zone in the northern hemisphere several hours east of the conjugate region of the path from REUNION to Syowa Station. In spite of this longitudinal difference, VLF phase anomalies were observed simultaneously in both hemispheres in many cases as shown below. It should be emphasized that the conjugacy of the VLF phase disturbances makes it certain that the phase anomalies are caused by energetic electron precipitation from the magnetosphere.

Figure 2 shows diurnal variations of magnetic H-component, phase of OMEGA REUNION (13.6 kHz) and ionospheric absorption (riometer) as observed at Syowa Station. The diurnal phase variation of OMEGA ALDRA (13.6 kHz) as received at Inubo is also depicted in the lower column. Diurnal VLF phase variations are essentially in a trapezoidal form which corresponds to a diurnal variation of D-region ionization caused by solar radiation.

The phase of the REUNION signal started to advance at 1640 UT September 9, 1980. A positive geomagnetic bay was associated with this phase anomaly. Ionospheric absorption also increased slightly at the time of this event. Since the magnetic local time at Syowa Station is approximately equal to the universal time, the precipitation of energetic electrons responsible for the VLF phase and absorption anomalies took place in the late afternoon. Furthermore, a very remarkable phase advance was associated on the ALDRA signal as observed at Inubo. Undoubtedly, these disturbances correlated in both hemispheres are due to precipitation of energetic electrons from the magnetosphere in association with magnetospheric substorm. The correlated disturbances on the REUNION signal and the riometer indicate that precipitating electrons have a wide energy spectrum responsible for ionizations of D- and E-regions of the ionosphere. The simultaneous occurrence of the phase anomalies on the REUNION and ALDRA signals indicates a conjugacy of energetic electron precipitation in the northern and southern hemispheres. As mentioned before, precipitation region on the ALDRA–Inubo path is located several hours east of that on the REUNION–Syowa path. Consequently, the precipitation took place over a wide longitudinal range in the afternoon to evening sector auroral zone. Another significant phase advance took place on the ALDRA signal two hours before the 1640 UT event. At the time of this event, no geomagnetic and no ionospheric disturbances were observed at Syowa Station, although the phase of REUNION was in a rapid change due to sunset transition and the riometer was interfered with telecommunications.

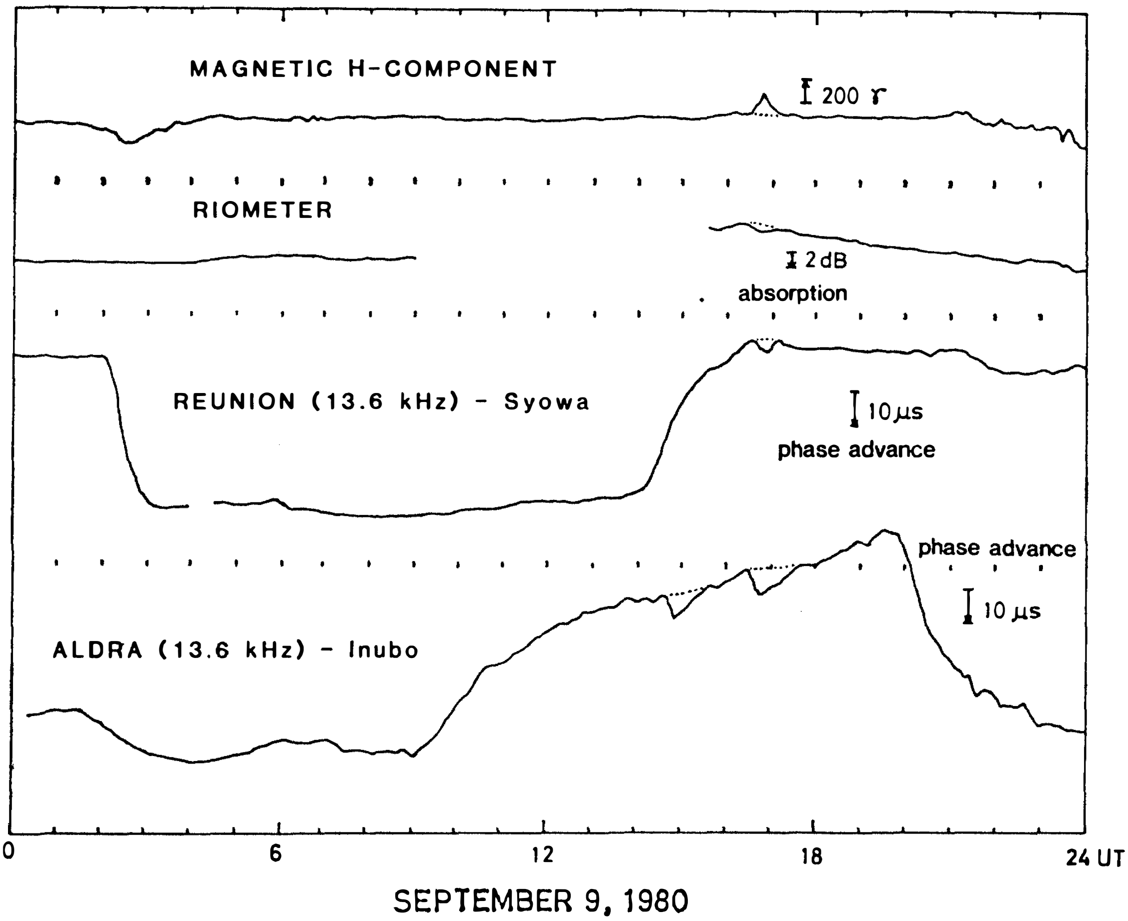

Fig. 2. Diurnal variations of magnetic H-component, ionospheric absorption (RIOMETER) and the phases of the REUNION (13.6 kHz) signal as received at Syowa and of the ALDRA (13.6 kHz) signal as received at Inubo. Precipitation of energetic electrons associated with the geomagnetic bay starting at 1640 UT causes increased ionospheric absorption and significant phase advances on both VLF signals.

Figure 3 shows another example of substorm events which occurred around the midnight meridian. At Syowa Station, a geomagnetic bay started at 0026 UT September 8, 1980 and reached a maximum around 0050 UT. The phase of the REUNION signal started to advance at 0012 UT and reached a maximum around 0030 UT. It should be noted that the time histories are very similar to each other, but the phase anomaly on the REUNION signal preceded the geomagnetic bay by 14 min. This suggests that the energetic electron precipitation on the REUNION–Syowa path preceded the development of electrojet currents over Syowa Station. On the other hand, the riometer data in Fig. 3 show that precipitation of energetic electrons took place right above the Syowa Station, almost simultaneously with the geomagnetic bay. We further note that the phase advance on the ALDRA signal as observed at Inubo started at 00 UT, which preceded both the phase anomaly on the REUNION signal and the ionospheric absorption. If we assume a complete conjugacy of electron precipitation in the northern and southern hemispheres, these observations indicate that the precipitation of energetic electrons responsible for ionizations of the lower ionosphere moved westward in the early morning to midnight sector. The westward movement of the electron precipitation is

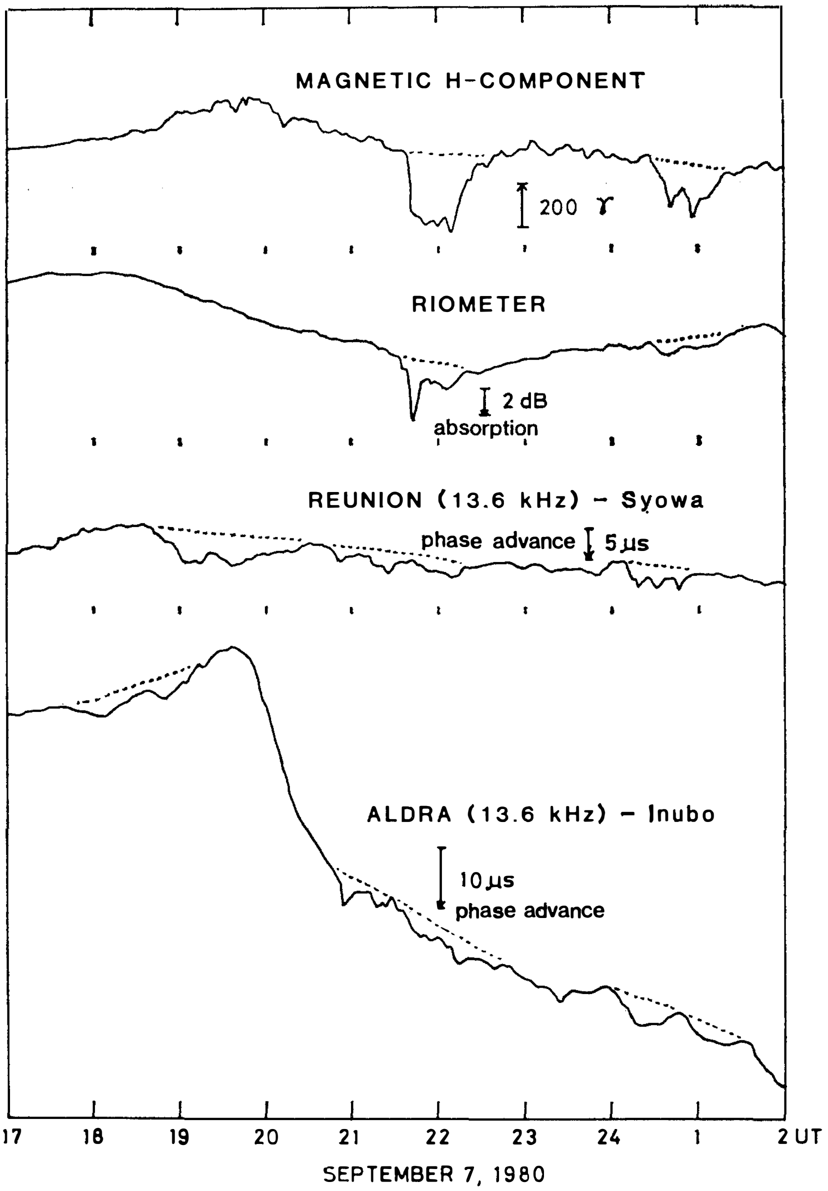

Fig. 3. Ionospheric absorption and VLF phase anomalies caused by substorm-associated energetic electron precipitation in the evening to post-midnight sector (MLT≃UT at Syowa). The absorption anomalies are completely correlated with geomagnetic bays, while VLF anomalies preceded these disturbances (see text).

a consequence of movement of the source electrons in the plasmasheet (HULTQVIST, 1975; KIKUCHI and EVANS, 1983), although several authors (DRIATSKY and SHUMILOV, 1972) suggested a possibility of a westward drift of injected electrons in the magnetosphere.

Figure 3 also shows a substorm event in the pre-midnight. The geomagnetic *H*-component abruptly decreased at 2140 UT September 7, 1980 after a gradual increase and succeeding decrease. Simultaneously with the negative bay, a large amplitude ionospheric absorption started at 2139 UT. This indicates that intense precipitation of energetic electrons took place over Syowa Station simultaneously with a development of auroral electrojet currents. The disturbance of phase of the REUNION signal also indicates precipitation of energetic electrons on the REUNION–Syowa path during this event. However, the VLF phase was disturbed for an hour before the geomagnetic bay event. This different feature of precipitation derived from the VLF phase anomaly may indicate that more energetic electrons cause the VLF phase disturbances compared with electrons responsible for ionospheric absorption (KIKUCHI, 1981; KIKUCHI and EVANS, 1983). It is interesting to note that the phase of the REUNION signal as received at Syowa Station was severely disturbed during the period of a gradual increase of geomagnetic *H*-component starting at 1843 UT. We further note that the phase of the ALDRA signal as received at Inubo advanced significantly with the onset around 1742 UT. This might indicate the "pre-event" of electron precipitation which has been reported by several authors (JELLY, 1970; BERKEY *et al.*, 1974; KIKUCHI, 1981), although geomagnetic substorms might have been observed in other auroral zone stations during a period of this "pre-event".

Figure 4 shows geomagnetic substorms and the corresponding absorption anom-

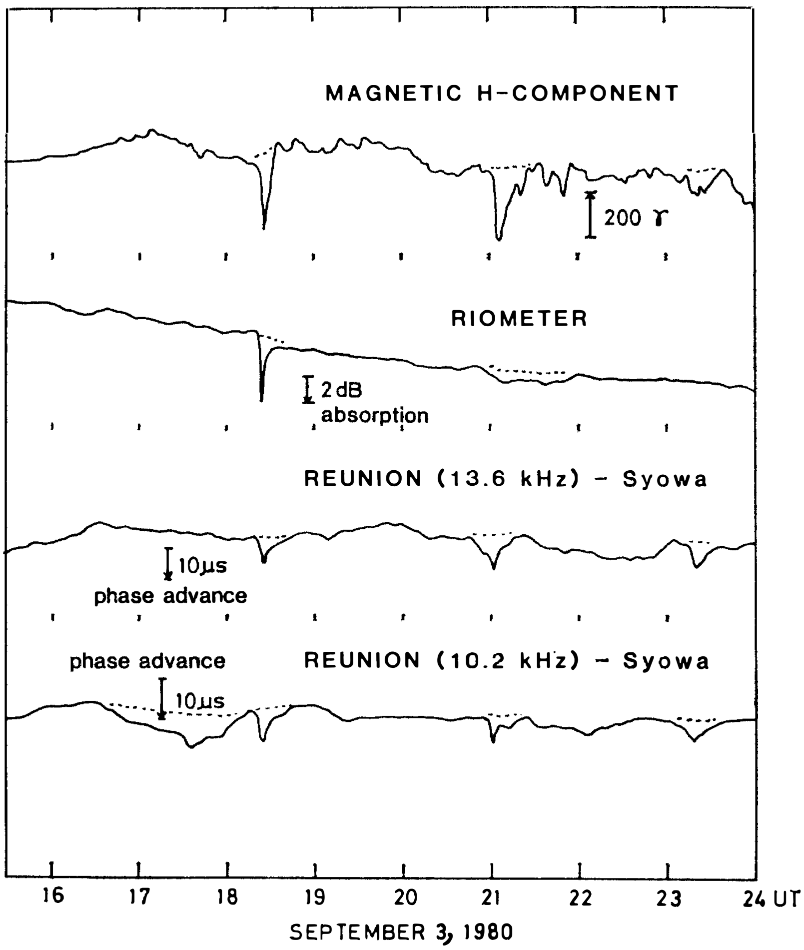

Fig. 4. Simultaneous appearance of substorm effects on the riometer and VLF phase observation in the evening sector. The phase of the REUNION (10.2 kHz) signal advances considerably during the period of a gradual increase in the geomagnetic H-component, while no disturbances are recognized on the REUNION (13.6 kHz) signal and in the ionospheric absorption.

alies and VLF phase anomalies on the REUNION (10.2 and 13.6 kHz) signals in the evening sector. Time behaviors of these disturbances are very similar to each other in the event starting at 1822 UT September 3, 1980. This indicates that intense precipitation of energetic electrons responsible for ionizations in the *D*- and *E*-regions of the ionosphere took place accompanying a development of auroral electrojet currents. A gradual increase and successive decrease of geomagnetic *H*-component preceded this geomagnetic substorm. A significant phase advance is associated with this gradual geomagnetic variation on the REUNION (10.2 kHz) signal, whereas no disturbances are observed on the REUNION (13.6 kHz) and in the ionospheric absorption. The selective appearance of effects of electron precipitation on the REUNION (10.2 kHz) indicates that the altitude of ionizations caused by energetic electron precipitation is lower than that responsible for phase anomalies on the REUNION (13.6 kHz) signal and absorption anomalies. This suggests that more energetic electron precipitation is associated with this substorm event than could be detected with the REUNION (13.6 kHz) signal and riometer observations. It is important to note that substorm-associated VLF phase anomalies depend on the wave frequency. The discrepancy between the two VLF signals provides an information about the energy spectrum of the precipitating electrons: even more energetic electrons are responsible for phase anomalies on the lower frequency VLF signals.

3. Local Time Characteristics of Absorption Anomalies and VLF Phase Anomalies

It has been shown in the previous section that VLF phase anomalies do not always accompany ionospheric absorption anomalies. This suggests that electrons responsible for VLF phase anomalies are not necessarily identical with electrons responsible for absorption anomalies. In this section we examine local time characteristics of both types of ionospheric disturbances and conclude that electrons responsible for VLF phase anomalies are more energetic than electrons responsible for absorption anomalies.

In order to obtain local time characteristics of electron precipitation, we use riometer and VLF phase (REUNION 13.6 kHz) data recorded at Syowa Station during 5 months from September 1, 1980 to January 31, 1981. The VLF phase data of the ALDRA (13.6 kHz) signal as received at Inubo, Japan during the same period are also used to examine a conjugacy of electron precipitation in the northern and southern hemispheres. The riometer observation suffered frequently an interference with ionosonde which was operated routinely every 15 minutes. To avoid ambiguities due to the interference on the riometer data, we extract large absorption anomaly events with magnitude ≥ 1 dB. As shown below, local time characteristics of absorption anomaly based on this criterion are in good agreement with general characteristics of absorption anomalies.

On the other hand, VLF phase anomalies are more clearly recognized on the data charts compared to absorption anomaly (*e. g.*, Figs. 2 and 4). The VLF phase anomaly is defined as a phase advance from an undisturbed phase level with magnitude ≥ 3 μs for the REUNION signal and ≥ 4 μs for the ALDRA signal.

Figure 5 shows a local time distribution of occurrence frequency of energetic electron precipitation which causes absorption anomalies with magnitude ≥ 1 dB. The

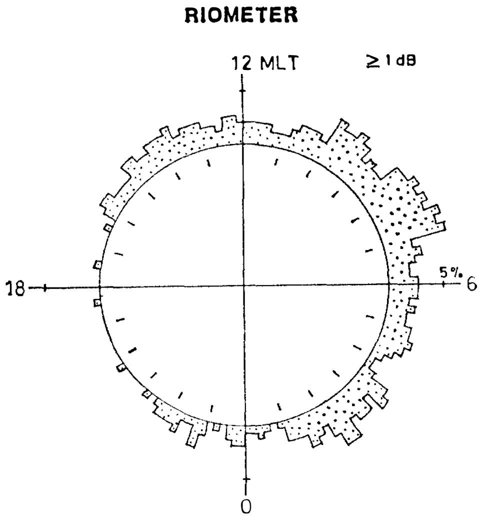

Fig. 5. Local time distribution of occurrence frequency of absorption anomaly at Syowa. Absorption anomalies with magnitude ≧ 1 dB are extracted from data obtained during a period from September 1, 1980 to January 31, 1981.

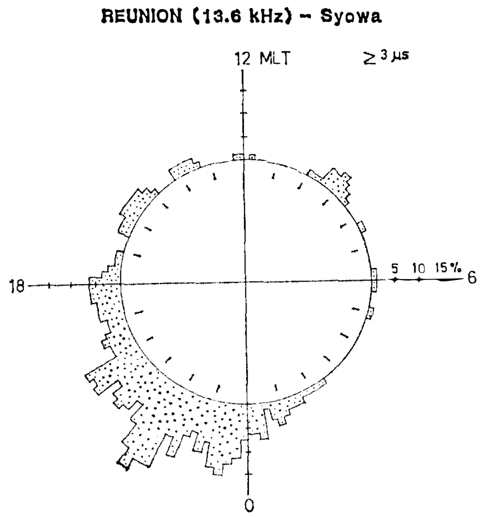

Fig. 6. Local time distribution of occurrence frequency of phase anomaly on the REUNION (13.6 kHz) signal as received at Syowa. Phase anomalies with magnitude ≧ 3 μs are extracted from data obtained during the same period as in Fig. 5.

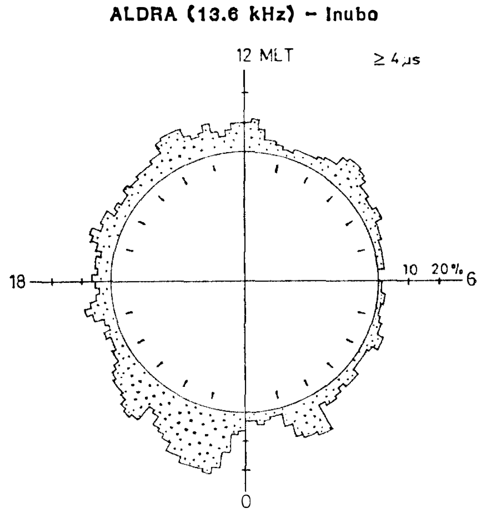

Fig. 7. Local time distribution of occurrence frequency of phase anomaly on the ALDRA (13.6 kHz) signal as received at Inubo. Phase anomalies with magnitude ≧ 4 μs are extracted from data obtained during the same period as in Figs. 5 and 6.

absorption anomaly is predominant in the post-midnight (0230 MLT) and morning sectors (0730 MLT). It is remarkable that precipitation is least frequent in the evening sector. This local time characteristic is in good agreement with those given by HARGREAVES and COWLEY (1967) and JELLY (1970).

Occurrence frequency of VLF phase anomalies is plotted in Figs. 6 and 7 based on data from the REUNION (13.6 kHz) and ALDRA (13.6 kHz) signals, respectively. It should be noted that these local time features are essentially identical, although these signals propagate in the opposite hemisphere. This conjugacy between the northern and southern hemispheres indicates that the VLF phase anomalies are caused by energetic electrons precipitated from the magnetosphere. Figures 6 and 7 show predominant occurrence of VLF phase anomalies in the evening to pre-midnight sector and less frequent occurrence in the morning sector. It is apparent that this feature is quite different from that of absorption anomalies. Consequently, precipitation of energetic electrons responsible for VLF phase anomalies is predominant in the evening to pre-midnight sector and that for ionospheric absorption is predominant in the morning sector.

4. Discussion

KIKUCHI and EVANS (1983) studied quantitative relations between VLF phase anomaly and the precipitating electron fluxes with energies greater than 30, 100 and 300 keV. They showed that electrons with $E>30$ keV are predominated in the morning sector with flux of one order of magnitude greater than the flux precipitating in the evening sector. This is in good agreement with the local time feature of absorption anomalies given in Fig. 5. They also showed that electrons with $E>300$ keV are precipitated at all local times with a peak in the evening sector. This is in agreement with the local time feature of occurrence of VLF phase anomalies (Fig. 7).

We now conclude that ionospheric absorption is caused by relatively low energy ($E>30$ keV) electrons, while VLF phase anomalies by more energetic electrons ($E>300$ keV) as suggested by KIKUCHI and EVANS (1983). It should be noted that the relatively low energy electrons ($E>30$ keV) are precipitated mainly in the morning sector, while more energetic electrons at all local times with a peak in the evening sector. This implies separate sources or acceleration mechanisms for the two electron populations. It seems definite that the lower energy electrons ($E>40$ keV) are precipitated from the quasi-trapped electron population in the outer radiation belt (JELLY and BRICE, 1967). On the other hand, the source or the acceleration mechanism for more energetic electrons ($E>300$ keV) has not been known. One possible mechanism for acceleration is that electrons diffuse into the inner magnetosphere adiabatically. However, it should be noticed that this acceleration is a slow process which is not consistent with simultaneous onsets and similar time behaviors of geomagnetic bays and VLF phase anomalies (KIKUCHI and EVANS, 1983). KIKUCHI and EVANS (1983) pointed out that the acceleration should work in association with a development of magnetosphere–ionosphere current circuit producing geomagnetic bays on the ground. It seems, therefore, that electrons are accelerated in the plasma sheet. HEIKKILA and PELLINEN (1977) proposed a mechanism for acceleration of electrons with energies up to 1 MeV which is caused by rotational electric fields produced by an irregular flow of plasma sheet currents.

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