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Substorm effects on magnetospheric VLF hiss observed by ISIS satellites

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Abstract: Narrow-band VLF electric field data at 300 Hz, 1.5 kHz, 5 kHz, 8 kHz, 16 kHz, and 20 kHz received from ISIS satellites at Syowa station, Antarctica are compared with AE and AL indices between February, 1982 and January, 1983 for investigating substorm effects on magnetospheric VLF hiss. The telemetry coverage for ISIS satellites from Syowa Station is from about 80° to about 50° in geomagnetic invariant latitude. In geomagnetic quiet and weak substorm recovery phase periods, a narrow-band mid-latitude hiss and a broad-band polar hiss appear, respectively, at invariant latitudes from 50° to 63° and from 66° to 78° from the afternoon to the midnight in MLT. In substorm expansion phase, the polar hiss region moves to lower latitudes and approaches the mid-latitude hiss region, and also, a LHR hiss whose intensity peak latitude increases with decreasing frequency (from 20 kHz to 1.5 kHz) appears in the mid-latitude hiss region near the plasmapause. Statistical study of VLF hiss shows that the mid-latitude hiss occurs most often in the quiet period and is independent of the substorm activity. While, the occurrence rate of polar hiss is 61% in the substorm period (200 nT $<AE\leqq$ 924 nT and -100 nT $>AL\geqq -583$ nT) and 29% in the quiet period (30 nT $<AE\leqq$ 200 nT and -2 nT $>AL\geqq -100$ nT). Hence, the generation of polar hiss is clearly influenced by the substorm.

1. Introduction

Latitudinal variations of VLF emissions observed by low-altitude polar orbiters represent integrated spectra of the whistler-mode magnetospheric VLF emissions which primarily propagate along geomagnetic field lines toward the ionosphere. So, the latitudinal variations of VLF emissions observed in the topside ionosphere reflect magnetospheric conditions influenced by the substorm activity. In other words, the latitudinal variations of whistler-mode VLF emissions in the topside ionosphere can be used to monitor the magnetospheric conditions. Since the VLF hiss is most frequently observed by ISIS satellites, narrow-band VLF intensity data at 300 Hz, 1.5 kHz, 5 kHz, 8 kHz, 16 kHz, and 20 kHz are produced for a study of magnetospheric VLF hiss from wide-band ISIS VLF electric field data (50 Hz–30 kHz) by narrow-band amplifiers with a minimum reading circuit similar to a ground VLF receiver. Output signals from the minimum reading circuit in the narrow-band amplifiers are compressed by a logarithmic amplifier for chart recording. Charging and discharging time constants of the minimum reading circuit are 10 s and 10 millis, respectively, and dynamic range for the relative intensity variation of the narrow-band VLF data is about 30 dB in arbitrary scale, while that of the *f-t* spectrum data is about 10 dB (Ondoh, 1990).

In this paper, VLF electric field data received at Syowa station, Antarctica from polar orbiting satellites of ISIS-1 (500–3500 km) and ISIS-2 (~1400 km) are compared with AE and AL indices (WDC-C2 for geomagnetism) from February, 1982 to January, 1983, in order to study a substorm effect on the latitudinal variations of magnetospheric VLF hiss. The narrow-band VLF intensity data are quoted from the Radio and Space Data, No. 15, 1984 published from Radio Research Laboratories, Japan. In the narrow-band VLF intensity data, we can discriminate the polar hiss, saucer emission, and diffused whistler, but not the chorus.

The polar hiss has been interpreted by the whistler-mode Cerenkov radiation generated from inverted-V precipitating electrons in the polar magnetosphere (Ondoh, 1990, 1991; Sonwalker and Horikumar, 2000). The whistler-mode refractive index at altitudes below 10000 km in the polar magnetosphere and ionosphere is $n = f_P/(f f_H \cos\theta)^{1/2}$ which is obtained from $n^2 = 1 + f_P^2/f(f_H\cos\theta - f)$ because of $f_H \gg f$ in the above region, where f_H is the electron gyrofrequency, f_P the electron plasma frequency, f the whistler-mode wave frequency, and θ the wave normal angle to the geomagnetic field. The frequency of the whistler-mode Cerenkov radiation, $f = Ef_P^2\cos\theta/250 f_H$ is obtained from the Cerenkov resonance condition of $c/n = v\cos\theta$ and the electron energy of $E = 250\ (v/n)^2$ keV where v is the electron velocity parallel to the geomagnetic field line (Ondoh, 1990). The frequency of the whistler-mode Cerenkov radiation depends on the parallel electron energy, electron density, geomagnetic field, and wave normal angle. For a fixed electron energy, high frequency components of the whistler-mode Cerenkov radiation are generated at relatively lower altitudes in the polar magnetosphere where the electron density is high and $f_P > f_H$, and its low frequency components are generated at higher altitudes above several thousands km in the polar magnetosphere where the electron density is low and $f_P \sim f_H$. In the outer magnetosphere ($>4\ R_E$) where $f_H \sim f$ and low energy electrons ($v/c \ll 1$) are dominant, the frequency of the whistler-mode Cerenkov radiation approximately becomes $f \simeq f_H\cos\theta$ under the whistler-mode propagation condition of $f_H\cos\theta > f$. This approximate frequency is obtained from the whistler-mode Cerenkov frequency in the magnetosphere (Ondoh, 2000),

$$f = (f_H\cos\theta/2)\cdot[1 + \{1 - (2f_P v/c f_H)^2 \cdot 1/(1 - v^2\cos^2\theta/c^2)\}].$$

Low frequency components below 2 kHz of the polar hiss seem to be the whistler-mode Cerenkov waves which propagate to the polar ionosphere along geomagnetic field lines from low-energy electron sources in the outer magnetosphere.

So, the whistler-mode Cerenkov radiation model for the polar hiss is consistent with the view that the latitudinal variations of VLF hiss observed by the polar orbiters represent the integrated effect of the whistler-mode VLF waves which propagate from wide-altitude sources in the magnetosphere.

2. Comparisons of latitudinal variations of magnetospheric VLF hiss and time variations of AE and AL indices

In this section, we discuss in detail 11 cases of latitudinal variations of magnetospheric VLF emissions (mainly VLF hiss) observed by ISIS-2 in quiet and substorm periods. A latitudinal coverage in the ISIS-2 telemetry from the Syowa Station, Antarctica is, on the average, from 50° to 80° in geomagnetic invariant latitude, and an average satellite pass time over the above latitudes is about 25 min. Since three-hourly K_p index is too coarse to represent geomagnetic conditions during an ISIS-2 flight time of about 25 min, we compare time variations of the AE and AL indices with latitudinal variations of narrow-band VLF intensity data at 300 Hz, 1,5 kHz, 5 kHz, 8 kHz, 16 kHz, and 20 kHz bands observed by the ISIS-2.

Figure 1a shows dawn-midnight latitudinal variations of the narrow-band VLF data observed from 0219 UT (0525 MLT, 54° INV LAT, 1432 km ALT) to 0234 UT (2253 MLT, 78° INV LAT, 1426 km ALT), Nov. 23, 1982 ($K_p=0$) in a geomagnetically very quiet time of $AE=34$ nT and $AL=-14$ nT, where MLT denotes the geomagnetic local time, INV LAT the geomagnetic invariant latitude, and ALT the satellite altitude. We define AE and AL indices of the satellite pass as $(A_t+A_{t+1})/2$ when the satellite pass is between t hour UT and $(t+1)$ hour UT, and when an hourly value of AE or AL indice is A_t at t hour UT and A_{t+1} at $(t+1)$ hour UT. Hence, the AE and AL indices of the ISIS-2 pass on Nov. 23, 1982 are $AE=34$ nT and $AL=-14$ nT which are mean values of AE and AL indices at 02 hour UT and 03 hour UT, since the ISIS-2 pass is between 02 and 03 hour UT.

Figure 1b is time variations of the AU, AL, AE, and AO indices on Nov. 23, 1982 where an upward arrow indicates the ISIS-2 pass time of Fig. 1a. Hereafter, we discuss only time variations of the AE and AL indices since their substorm variations are characteristic. Since the AE and AL variations for the ISIS-2 pass of Nov. 23, 1982 were very quiet as shown in Fig. 1b, no polar hiss was observed in the dawn. Diffuse whistlers at 5 and 8 kHz bands were observed at invariant latitudes below 63° in the early morning, and ELF hiss was observed to about 72° in the dawn from below 54° in the early morning. The plasmaspheric hiss which is generated by an electron cyclotron instability near the equatorial plasmapause propagates downward repeating LHR reflections in the plasmasphere, and it is observed as the ELF hiss in the ionosphere (Ondoh *et al.*, 1983; Thorne *et al.*, 1973). The ELF hiss extension to 72° suggests that the plasmasphere extended outward in the very quiet period. This is an exceptionally quiet case of magnetospheric VLF activity. Right-hand noises at all bands in Fig. 1a mean that FM telemetry signals from the ISIS-2 could not be received at Syowa Station since the satellite was beyond the telemetry coverage.

Figure 2a shows postnoon-morning latitudinal variations of the narrow-band VLF data observed from 1057 UT (1317 MLT, 50.3° INV LAT) to 1112 UT (0818 MLT, 78.2° INV LAT), Aug. 8, 1982 ($K_p=2_-$) in a very quiet time of $AE=98$ nT and $AL=-33$ nT (Fig. 2b). A narrow-band mid-latitude hiss at 5 and 8 kHz bands occurred from invariant latitude 50° to 63° in the postnoon, and a polar hiss occurred at invariant latitudes above 75° in the morning. An ELF hiss extension to invariant latitude 75° at 1.5 kHz and 300 Hz bands suggests the plasmasphere expansion in a quiet time, although the ELF hiss would propagate appreciably beyond the plasmapause. In Fig. 2a, a VLF hiss valley at 5 and 8 kHz bands is seen over the auroral zone between the mid-latitude hiss and polar hiss regions around the noon.

Figure 3a shows late evening-PM latitudinal variations of the narrow-band VLF data observed from 1820 UT (2148 MLT, 52.5° INV LAT) to 1838 UT (1316 MLT, 74.5° INV LAT), April 24, 1982 ($K_p=5_+$) in a quiet time of $AE=51$ nT and $AL=-13$

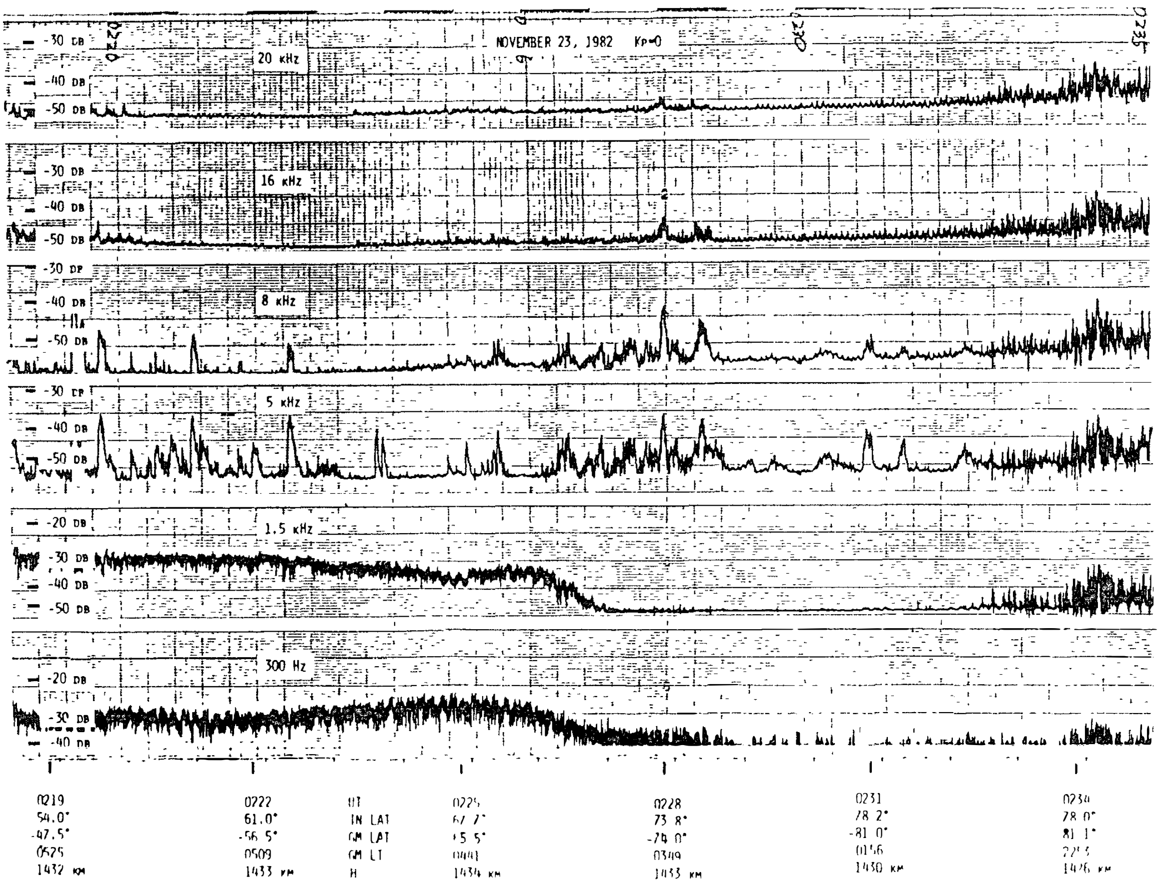

Fig. 1a. Dawn-midnight latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a geomagnetically very quiet time on Nov. 23, 1982 ($K_p=0$). In the bottom of Fig. 1a, the first line is the time in UT, the second line the geomagnetic invariant latitude (IN LAT), the third line the satellite geomagnetic latitude (GM LAT), the forth line the geomagnetic local time (GM LAT), and the fifth line the satellite altitude in km.

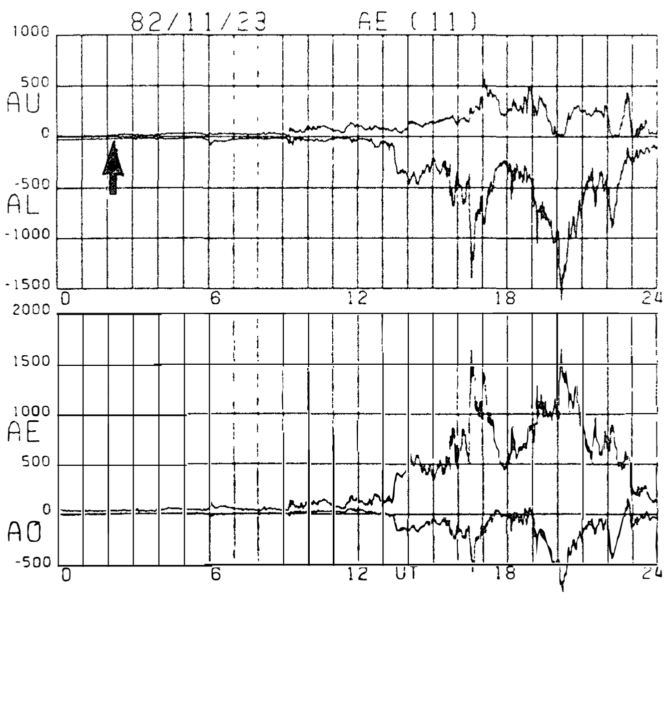

Fig. 1b. Time variations of AL (upper diagram) and AE (lower diagram) indices on Nov 23, 1982, where the longitude is the intensity in nT and the abscissa is the time in UT.

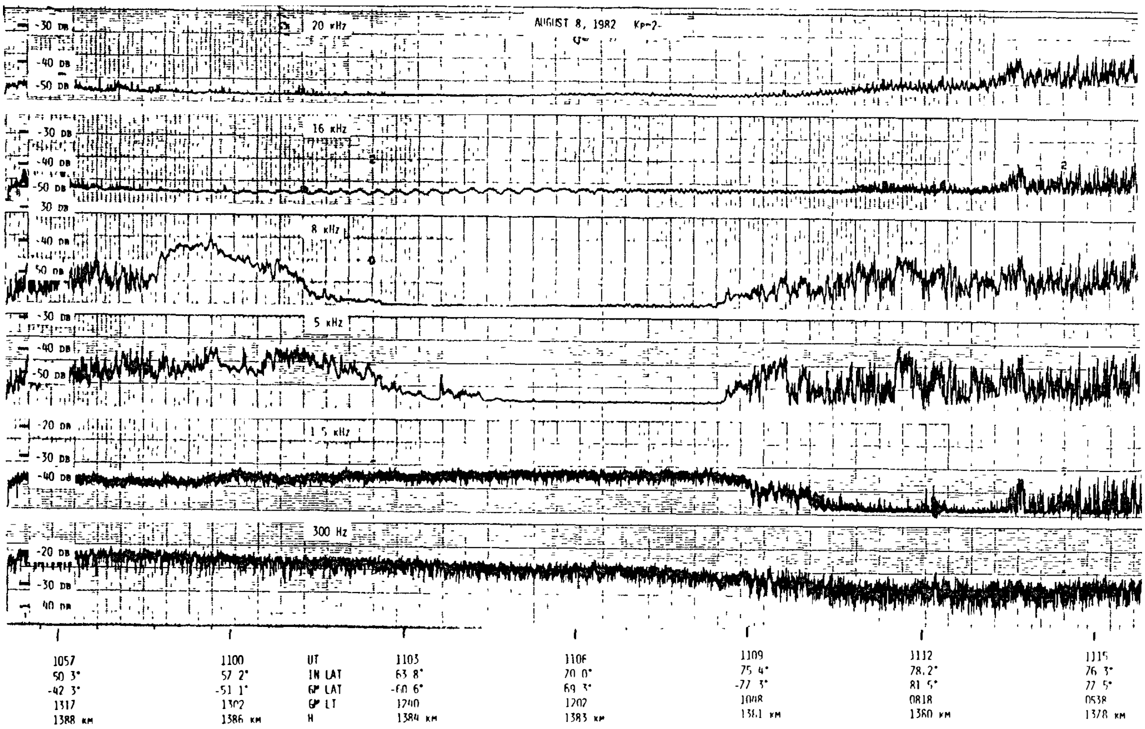

Fig. 2a. Postnoon-morning latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a quiet time on Aug. 8, 1982 (K_p =2−).

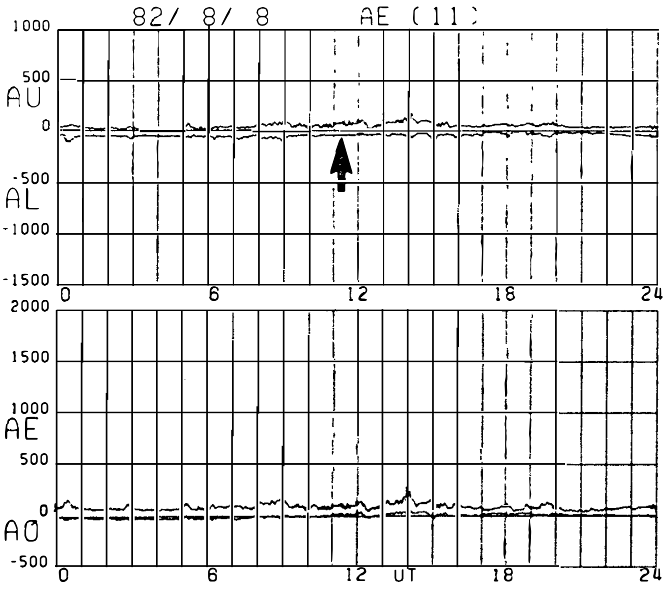

Fig. 2b. Time variations of AL and AE indices on Aug. 8, 1982.

nT after a small substorm. A narrow-band 5 kHz hiss, so called the plasmapause hiss (Ondoh, 1993) occurred at invariant latitudes of 58°–63° in the late evening, but no strong ELF hiss occurred at 1.5 kHz band at latitudes below 65° in the late evening. A broad-band polar hiss at 1.5, 5, 8, 16, and 20 kHz bands occurred at invariant latitudes above 67° in the evening-PM. A VLF hiss valley is also seen at 5 and 8 kHz bands between 63° and 67° in the evening as seen between 64° and 75° around the quiet noon

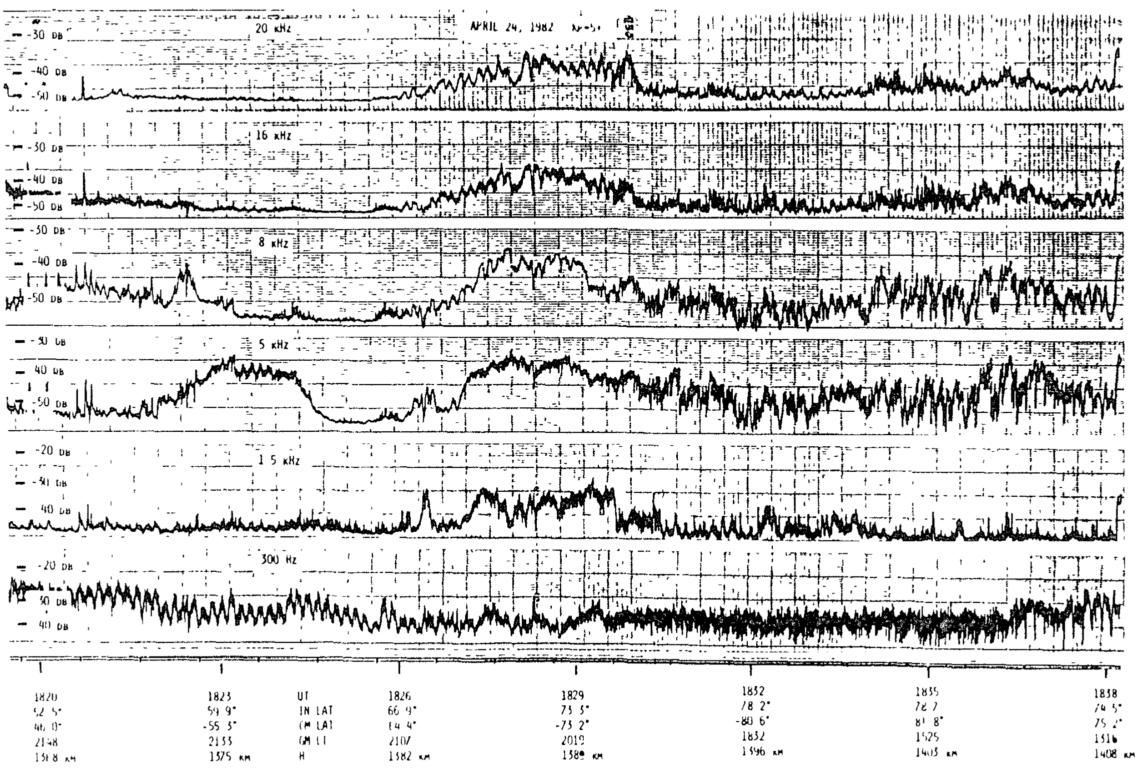

Fig. 3a. Late evening-afternoon latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a quiet time after a small substorm on April 24, 1982 ($K_p = 5$).

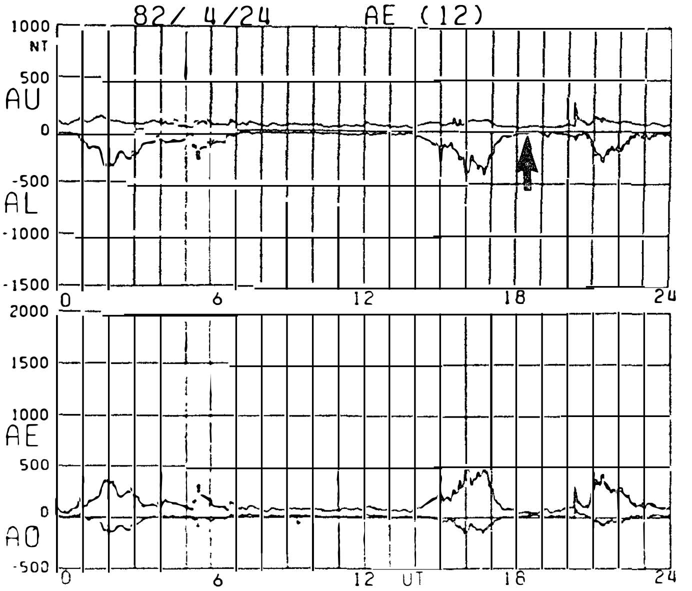

Fig. 3b. Time variations of AL and AE indices on April 24, 1982

in Fig. 2a. This ISIS-2 pass was received after a small substorm, but no substorm effect is detected in the magnetospheric VLF activity.

Figure 4a shows late evening-PM latitudinal variations of the narrow-band VLF data observed from 1739 UT (2042 MLT, 52.9° INV LAT) to 1754 UT (1433 MLT, 78.2° INV LAT), May 8, 1982 ($K_p = 1$) in a quiet period of $AE = 211$ nT and $AL = -119$

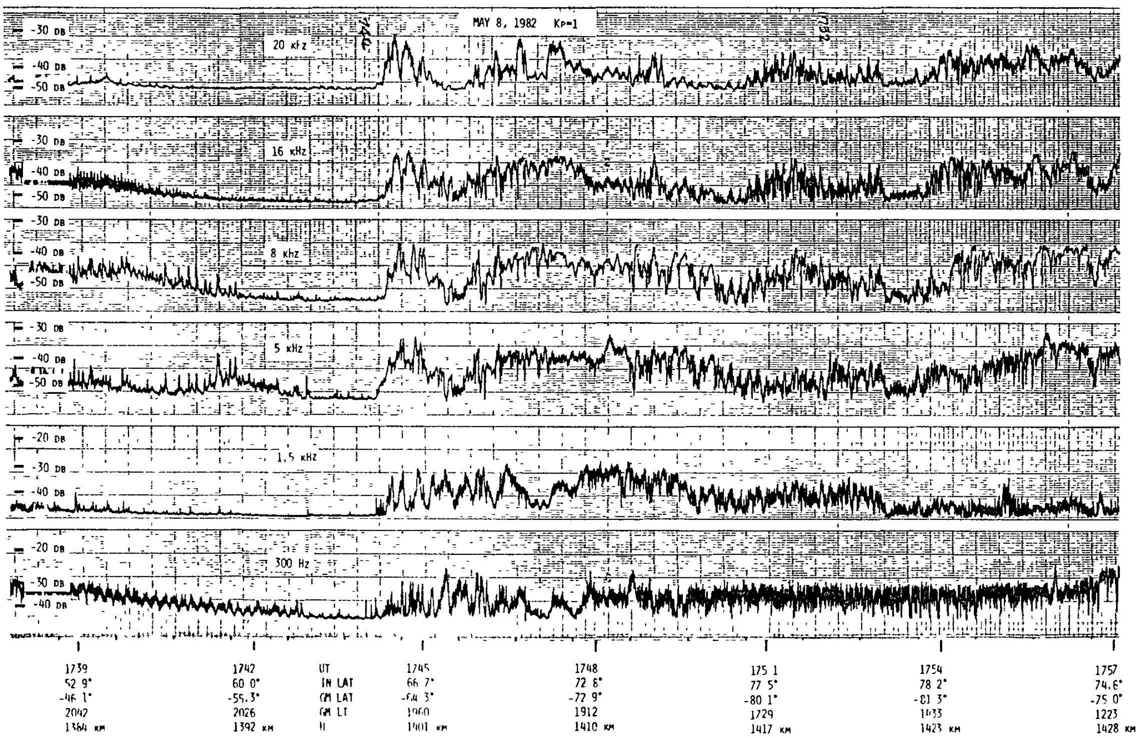

Fig. 4a Late evening-afternoon latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a quiet time on May 8, 1982 (K_p=1).

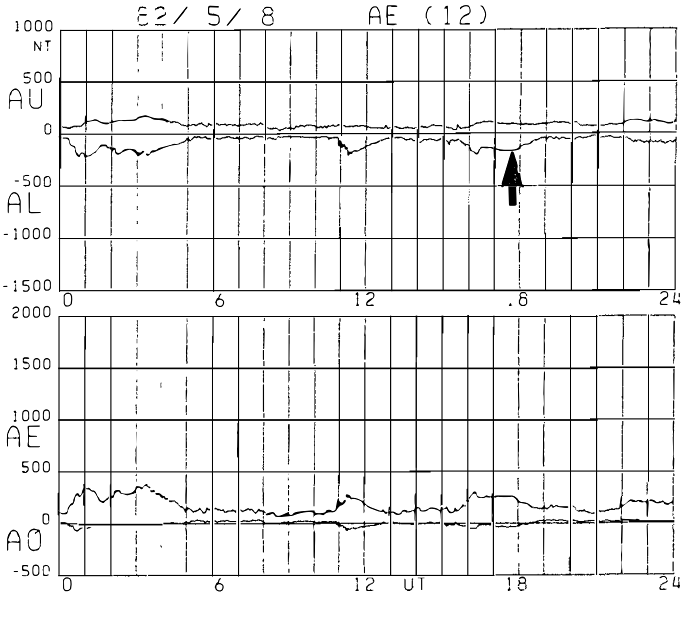

Fig. 4b. Time variations of AL and AE indices on May 8, 1982.

nT. The satellite MLT variation of this pass is similar to that of Fig. 3a. No substorm occurred from May 4 to May 8, 1982 before this pass. Weak mid-latitude hiss at 5, 8, and 16 kHz bands occurred together with whistlers as shown by coincident noise-spikes superposing on slow hiss variations at 8 and 5 kHz bands at invariant latitudes below 60° in the late evening, but no ELF hiss occurred. Such whistlers were also seen at 8 and 5 kHz bands at invariant latitudes below 63° in Fig. 1a. The whistlers were confirmed

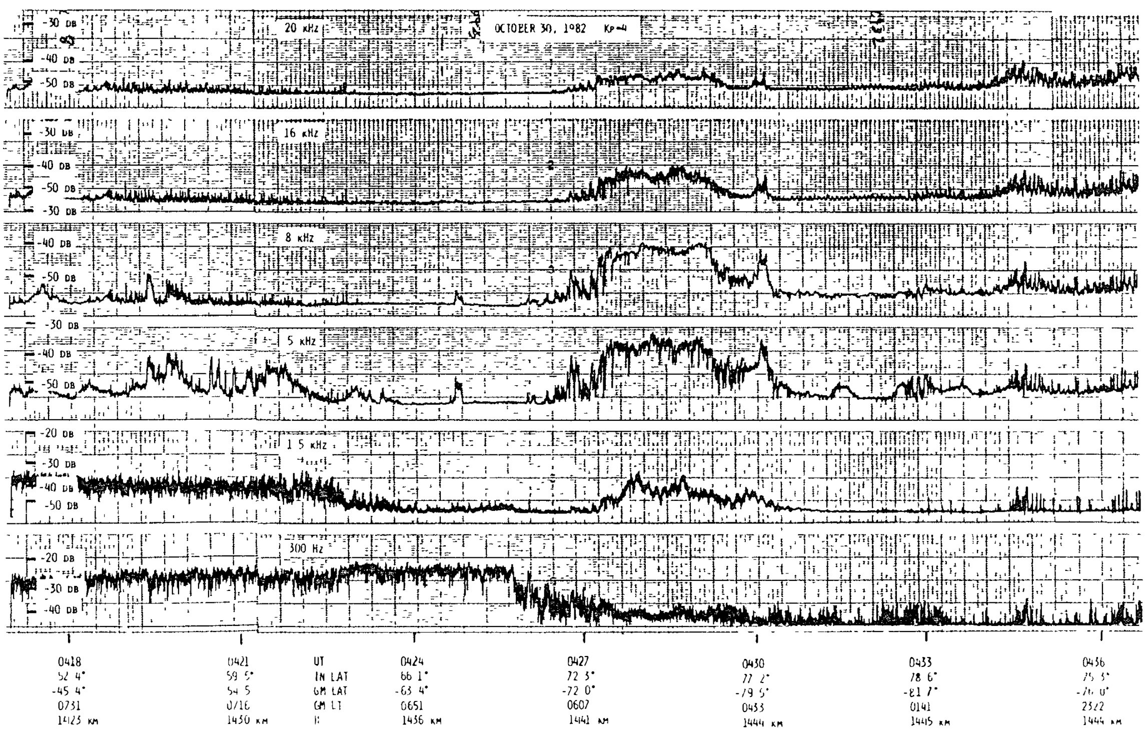

Fig. 5a. Morning-midnight latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a quiet time between substorms on Oct. 30, 1982 (K_p=4).

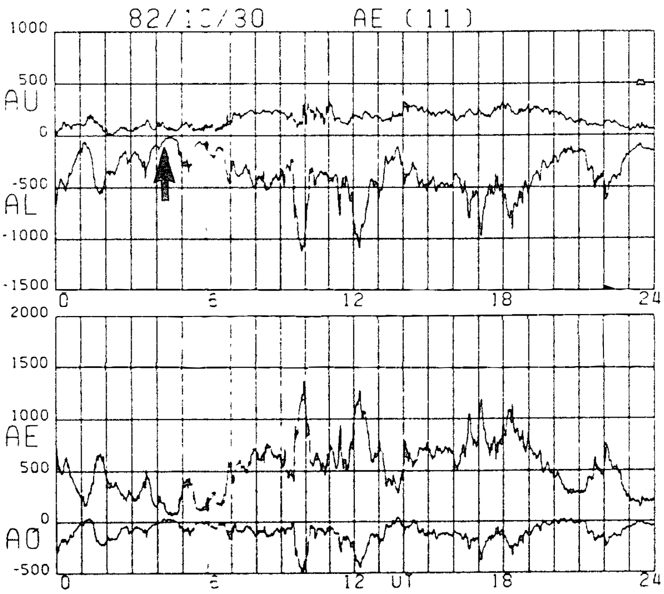

Fig. 5b. Time variations of AL and AE indices on Oct. 30, 1982.

by whistler sounds from a loud-speaker at times of the whistler spikes during VLF data processing of ISIS wide-band tapes. Broad-band polar hiss with large intensities above 5 kHz band occurred at all bands at latitudes above 65° in the evening. Two intensity peaks which join around a LHR frequency of 300 Hz are seen at 20, 16, 8, 5, and 1.5 kHz bands on both sides of 66° in the evening. This is a V-shaped hiss or large-scale saucer emission. The polar hiss ended around 78° and weak fine intensity variations appeared at 1.5, 5, 8, 16, and 20 kHz bands between latitudes of 78° and 78.2° around 1432 MLT. This may be a polar cusp crossing (Ondoh, 2000). A VLF hiss valley is also seen between 62° and 66° in the evening as shown in Fig. 3a of the evening pass.

Figure 5a shows morning-midnight latitudinal variations of the narrow-band VLF data observed from 0418 UT (0713 MLT, 52.4° INV LAT) to 0433 UT (0141 MLT, 78.6° INV LAT), Oct. 30, 1982 ($K_p=4$) in a quiet period of $AE=202$ nT and $AL=-118$ nT between substorms. A narrow-band 5 kHz hiss of two peaks occurred at invariant latitudes from 55° to 64°, and a strong ELF hiss at 300 Hz band occurred at invariant latitudes below 70° in the morning. Broad-band polar hiss occurred at invariant latitudes from 72° to 78° in the dawn. In most latitudinal variations of ISIS VLF emissions, the ELF hiss region changes places with the polar hiss region in latitude as shown in Fig. 5a of the morning, Fig. 2a of the AM, and Fig. 6a near the noon. A VLF hiss valley is seen at 5 kHz band between invariant latitudes of 65° and 72° in the morning.

Figure 6a shows daytime latitudinal variations of the narrow-band VLF data observed from 1056 UT (1305 MLT, 49.5° INV LAT) to 1111 UT (0834 MLT, 77.9° INV LAT), Aug. 11, 1982 ($K_p=4$) in a substorm last phase of $AE=321$ nT and $AL=-166$ nT. A variational mid-latitude hiss at 5 and 8 kHz bands occurred at invariant latitudes from 50° to 60° in the postnoon, and an ELF hiss at 1.5 kHz and 300 Hz bands appeared from 50° to 73° in the daytime. A broad-band polar hiss at 5, 8, 16, and 20 kHz bands was observed from 69° to 78° in the morning, and a cusp-like region of fine intensity variations at 5 and 8 kHz bands is seen from 72° to 75° for 1050–1130 MLT. A wide VLF hiss valley at 5 and 8 kHz bands was also observed between invariant latitudes of 60° and 69° around the noon in the substorm last phase. This wide valley is similar to the valley of 63°–75° around the noon in the quiet period of Fig. 2a as well as the ELF hiss region. These latitudinal structures of magnetospheric VLF hiss around the geomagnetic noon in the storm last phase are little influenced by the small substorm.

Figure 7a shows midnight-evening latitudinal variations of the narrow-band VLF data observed from 2137 UT (0019 MLT, 51.1° MLT) to 2152 UT(1835 MLT, 78.8° INV LAT), Jan. 23, 1983 ($K_p=4$) in a small substorm expansion phase of $AE=363$ nT and $AL=-226$ nT (Fig. 7b). A LHR hiss whose intensity peak latitude increases with decreasing frequency occurred at invariant latitudes from 51° to 63° near the midnight, and sharp intensity drops of the LHR hiss at 5 and 8 kHz bands are seen at 63°. A broad-band polar hiss at 5, 8, 16 and 20 kHz bands occurred at invariant latitudes from 65° to 73° in the premidnight. A narrow VLF hiss valley is seen for 63°–65° between the LHR hiss and polar hiss regions. In this pass, the polar hiss which normally occurs till invariant latitude 78° did not occur at latitudes above 73° in the late evening. The polar hiss region in the premidnight moved toward lower latitude region or inner L-shell region in the substorm expansion phase. These anomalous variations seem to be effects of the small substorm expansion phase on the magnetospheric VLF activity.

Figure 8a shows daytime latitudinal variations of the narrow-band VLF data observed from 1059 UT (1341 MLT, 52.0° INV LAT) to 1114 UT (0742 MLT, 78.5° INV LAT), Aug. 2, 1982 ($K_p=5$) in a medium substorm expansion phase of $AE=640$ nT and $AL=-338$ nT. Mid-latitude hiss at 5, 8, and 16 kHz bands occurred at

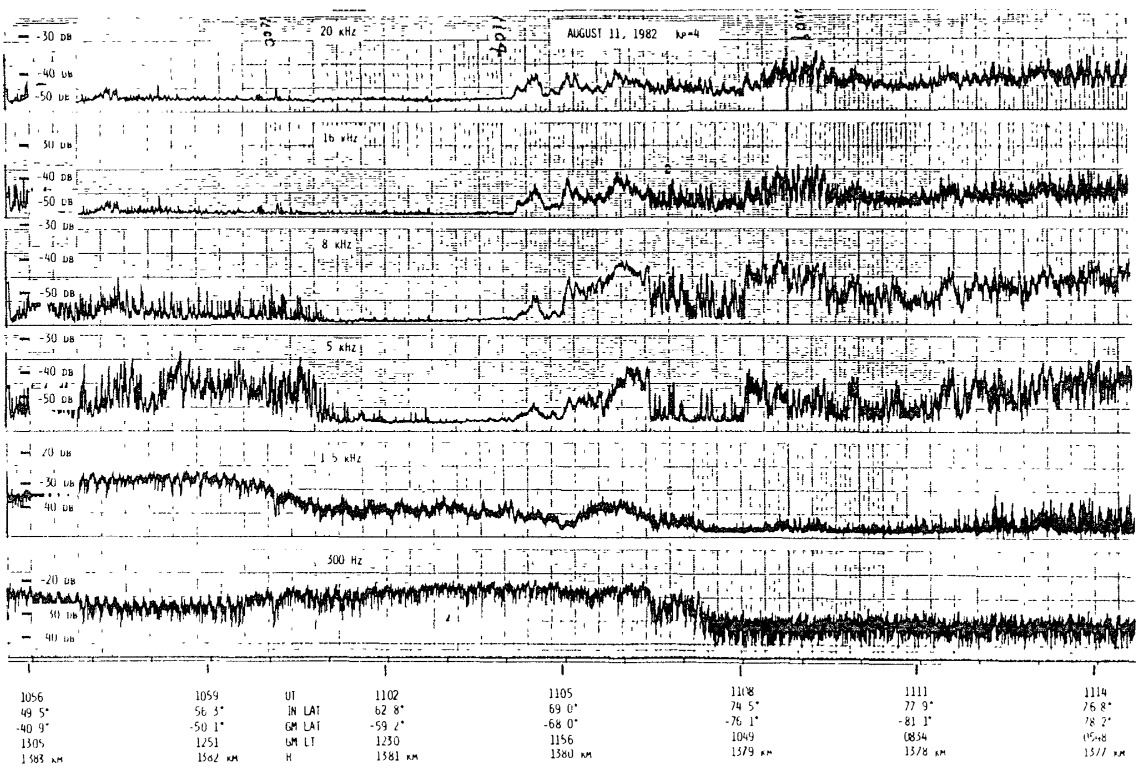

Fig. 6a. Daytime latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a storm last phase on Aug. 11, 1982 (K_p=4).

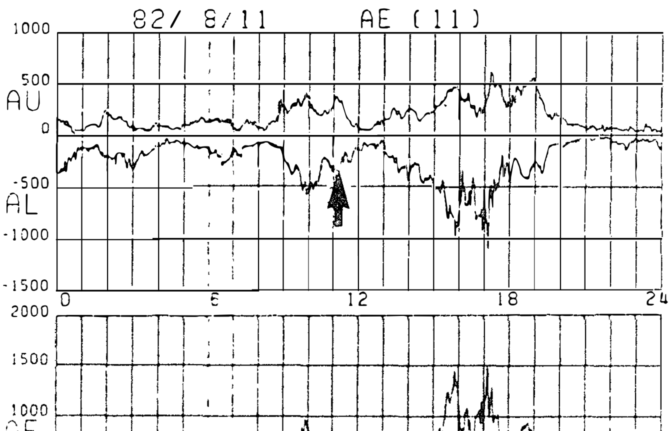

Fig. 6b Time variations of AL and AE indices on Aug. 11, 1982.

invariant latitudes below 58° in the postnoon. A broad-band polar hiss at 5, 8, 16, and 20 kHz bands occurred at invariant latitudes from 63° to 74° for the postnoon to the noon. The polar hiss intensity abruptly decreased at 69° which was also a high latitude limit of ELF hiss at 1.5 kHz and 300 Hz bands. Cusp-like fine intensity variations at 1.5, 5, 8, 16, and 20 kHz bands are seen between 69° and 72° around the geomagnetic noon in the substorm expansion phase (K_p=5). Between 63° and 69°, the polar hiss

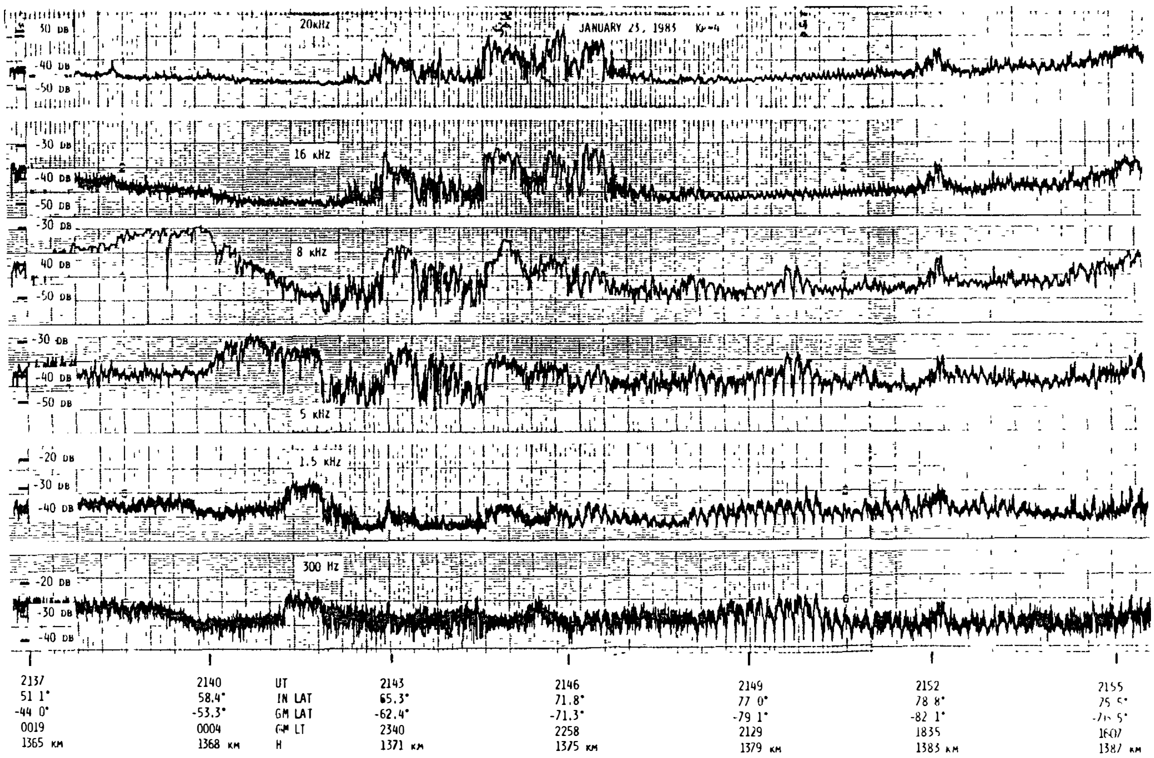

Fig. 7a. Midnight-evening latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a small substorm expansion phase on Jan. 23, 1983 (K_p=4).

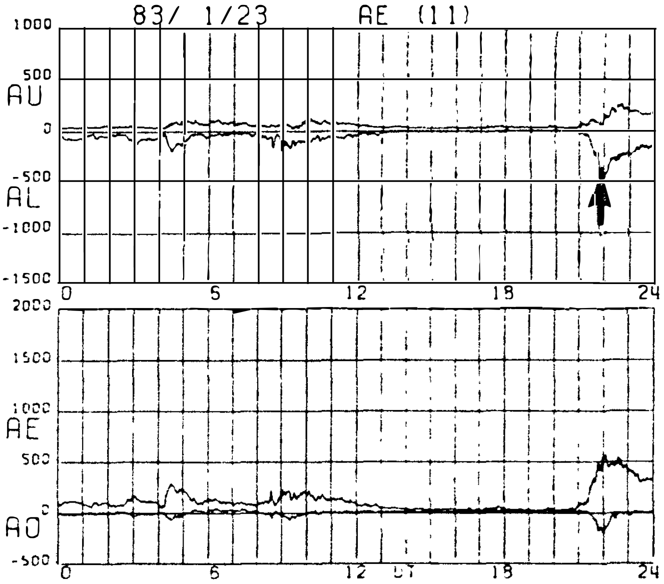

Fig. 7b. Time variations of AL and AE indices on Jan. 23, 1983.

region overlaps the ELF hiss region which normally corresponds to the plasmasphere. The latitudinal overlap of the polar hiss and ELF hiss around the noon auroral zone and the abrupt intensity drop of the polar hiss and ELF hiss on the lower latitude edge of the cusp-like fine intensity variation region are also seen at 72° around the noon in the substorm last phase (Fig. 6a). No polar hiss occurred at invariant latitudes above 74° in the morning, while the average occurrence-rate map of the polar hiss has an active

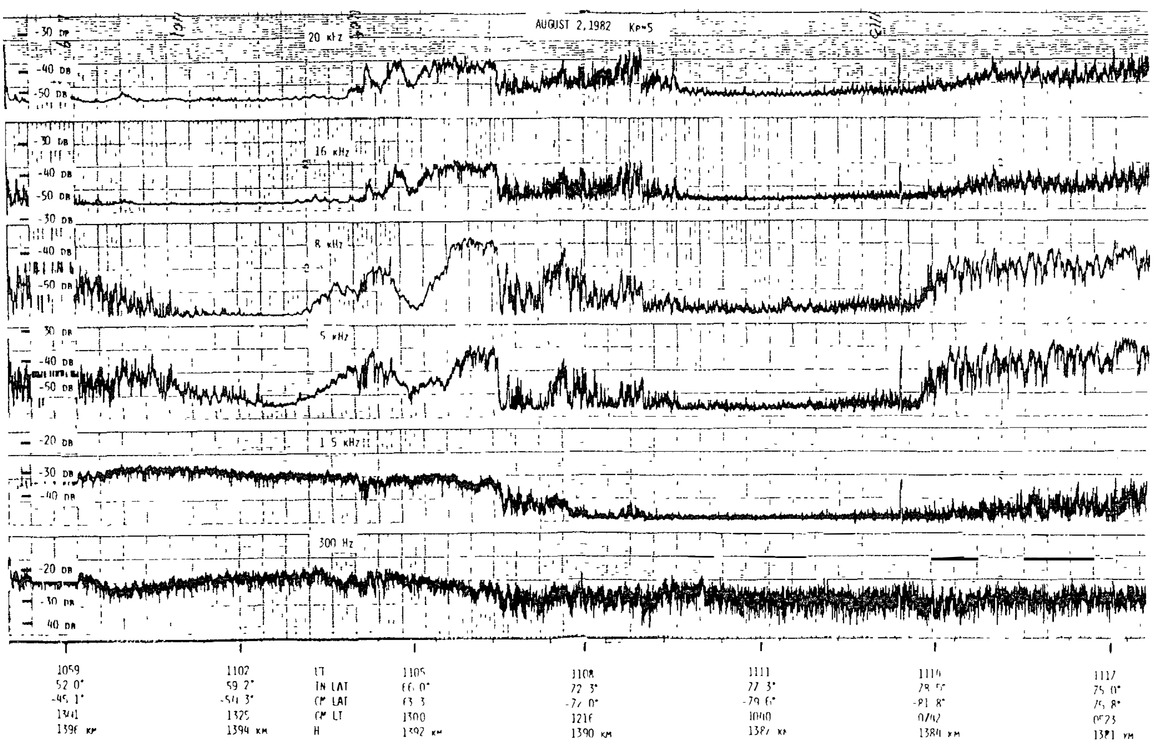

Fig. 8a. Daytime latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a medium substorm expansion phase on Aug. 2, 1982 (K_p=5).

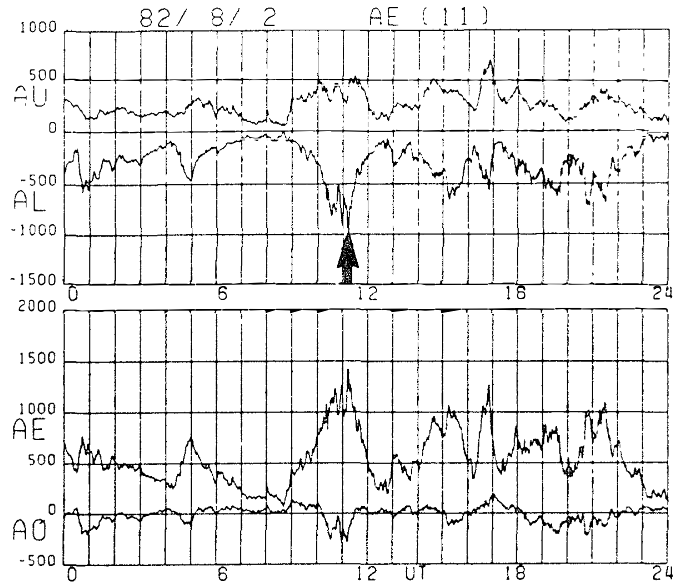

Fig. 8b. Time variations of AL and AE indices on Aug. 2, 1982.

region at latitudes above 75° in the geomagnetic morning (Ondoh, 1990, 1991). A narrow VLF hiss valley at 5 and 8 kHz bands is seen between 58° and 63° in the postnoon. Thus, the lower latitude shift of the polar hiss region, the abrupt intensity drop of the polar hiss at lower latitude edge of the cusp like region, and the reduction of VLF hiss valley region are regarded as substorm effects on the magnetospheric VLF activity.

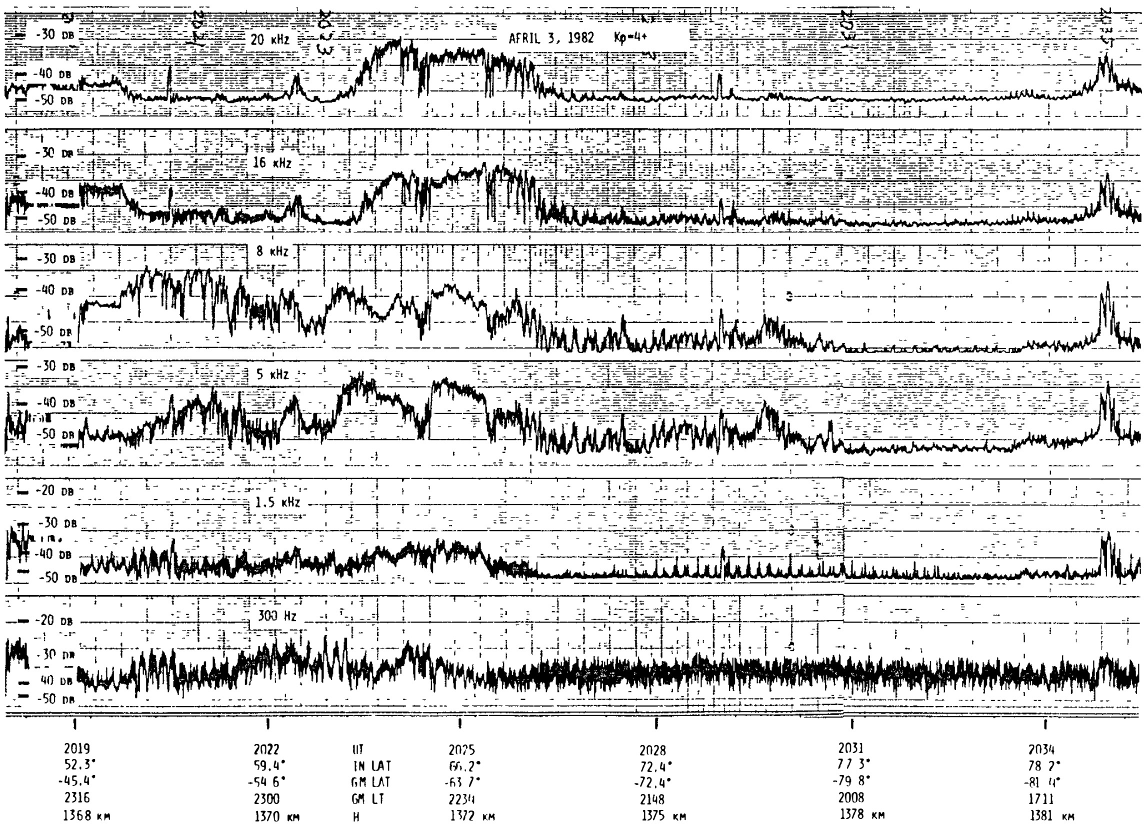

Fig. 9a. Premidnight-evening latitudinal variations of narrow-band VLF data observed by ISIS-2 in a medium substorm last phase on April 3, 1982 ($K_p=4_+$).

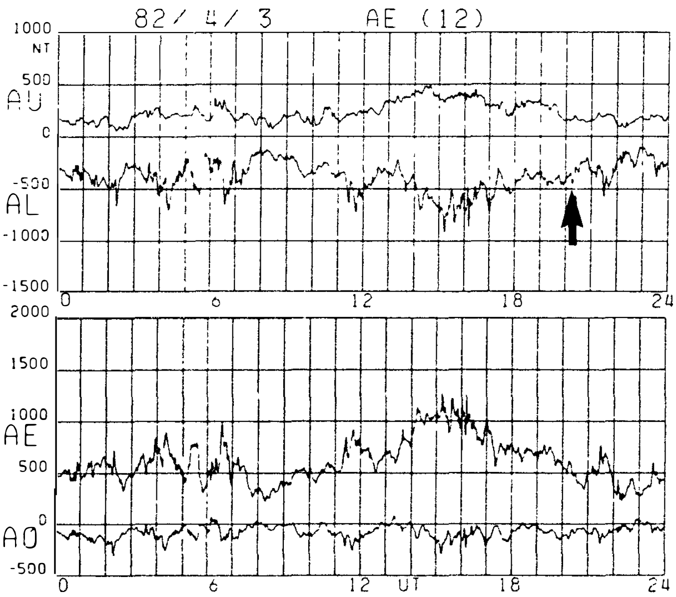

Fig. 9b. Time variations of AL and AE indices on April 3, 1982.

Figure 9a shows premidnight-evening latitudinal variations of the narrow-band VLF data observed from 2019 UT (2316 MLT, 52.3° INV LAT) to 2034 UT (1711 MLT, 78.2° INV LAT), April 3, 1982 ($K_p=4_+$) in a long substorm last phase of $AE=$ 520 nT and $AL=-344$ nT. A LHR hiss appeared first at 20 and 16 kHz bands at invariant latitudes below 54° (on the upper left-side of Fig. 9a) and its intensity peak shifted to higher latitudes with decreasing frequency as seen at 8 and 5 kHz bands at latitudes from 55° to 59°. The LHR hiss at 5 kHz band occurred at latitudes below 59° in the premidnight and a broad-band polar hiss at 5, 8, 16, and 20 kHz bands occurred from 60° to 70°. Then, a narrow-band polar hiss at 5 and 8 kHz bands appeared from 70° to 77° in the late evening. Especially, the polar hiss intensities at 20 and 16 kHz bands were stronger than the intensities at 8 and 5 kHz bands between 62° and 70°. The broad-band polar hiss disappeared rapidly at 70°. An weak ELF hiss appeared to about 69° in the premidnight and overlapped the polar hiss region as shown in the postnoon substorm expansion phase of Fig. 8a. The LHR hiss region is adjacent to the broad-band polar hiss region in the premidnight substorm last phase, and no VLF hiss valley occurred. The closeness of the polar hiss and mid-latitude hiss regions was also observed in the midmight substorm expansion phase (Fig. 7a) and in the postnoon substorm expansion phase(Fig. 8a). In addition to this, the strong LHR hiss at latitudes below 59° and strong high frequency polar hiss at 20 and 16 kHz bands are substorm effects.

Figure 10a shows evening latitudinal variations of the narrow-band VLF data observed from 1818 UT (2107 MLT, 52.3° INV LAT) to 1833 UT (1522 MLT, 78.1° INV LAT), May 3, 1982 ($K_p=5_-$) in a large substorm expansion phase of $AE=704$ nT and $AL=-470$ nT. In this pass, no mid-latitude hiss at 5 and 8 kHz bands was observed at latitudes below 56° and also no ELF hiss at 1.5 kHz and 300 Hz bands appeared at latitudes below 61°, but a narrow-band 5 kHz polar hiss appeared at latitudes above 56° in the late evening. A broad-band polar hiss at 1.5, 5, 8, 16, and 20 kHz bands was observed from about 61° to 72° in the evening, but no polar hiss occurred at latitudes above 72° where the polar hiss normally occurs often. Polar hiss intensities at 16 and 20 kHz bands were stronger than those in the quiet period. Since large 3 substorms of above $AE=1000$ nT continued before this pass as shown in Fig. 10b, the magnetosphere was significantly disturbed. Consequently, the polar hiss region largely moved to lower latitudes or inner L shells in the substorm expansion phase of late-evening as well as those in the daytime substorm expansion phase (Fig. 8a) and in the premidnight substorm recovery phase (Fig. 9a). The VLF phenomena shown in Fig. 10a were strongly influenced by this large magnetospheric substorm.

Figure 11a shows dawn-midnight latitudinal variations of the narrow-band VLF data observed from 0140 UT (0458 MLT, 54.6° INV LAT) to 0152 UT (0108 MLT, 79.0° INV LAT), Nov. 28, 1982 ($K_p=6$) in a large substorm expansion phase of $AE=$ 632 nT and $AL=-530$ nT (Fig. 11b). No polar hiss was observed along the whole pass. Strong LHR hiss at 20 kHz band was first observed at invariant latitude 53°, and its peak intensity latitude increased with decreasing frequency. The LHR hiss at 1.5 kHz band ended at 65°, and the ELF hiss was not at all observed in this pass. Since large substorms of above $AE=1000$ nT occurred every day from Nov. 21 to Nov. 29, 1982, the magnetosphere must be strongly disturbed by hot plasma streams from the magnetotail in the substorm expansion phase. These situations seem to reduce the magnetosphere and there must be no energetic electron to generate the polar hiss in the outer magnetosphere. Therefore, the strong LHR hiss which appeared at latitudes below 65° must be one of the substorm effects. All LHR hisses in Figs. 11a, 9a, and 7a

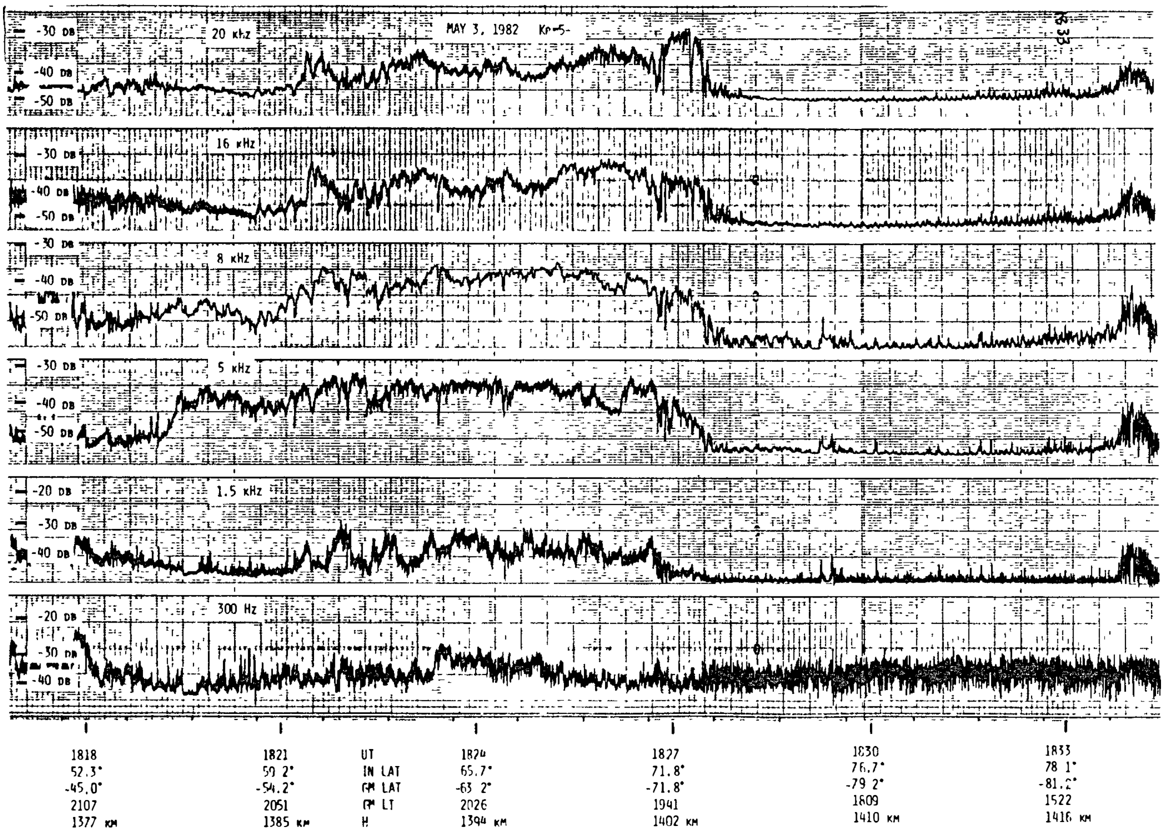

Fig. 10a. Evening latitudinal variations of narrow-band VLF data on May 3, 1982.

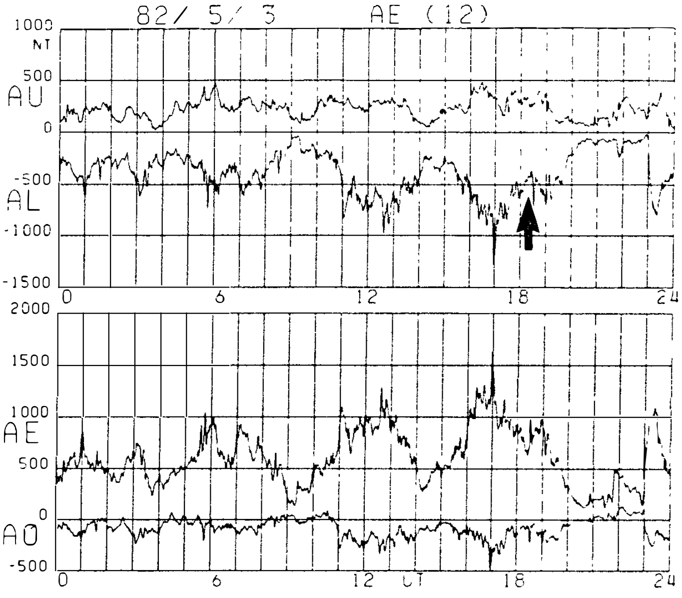

Fig. 10b. Time variations of AL and AE indices on May 3, 1982.

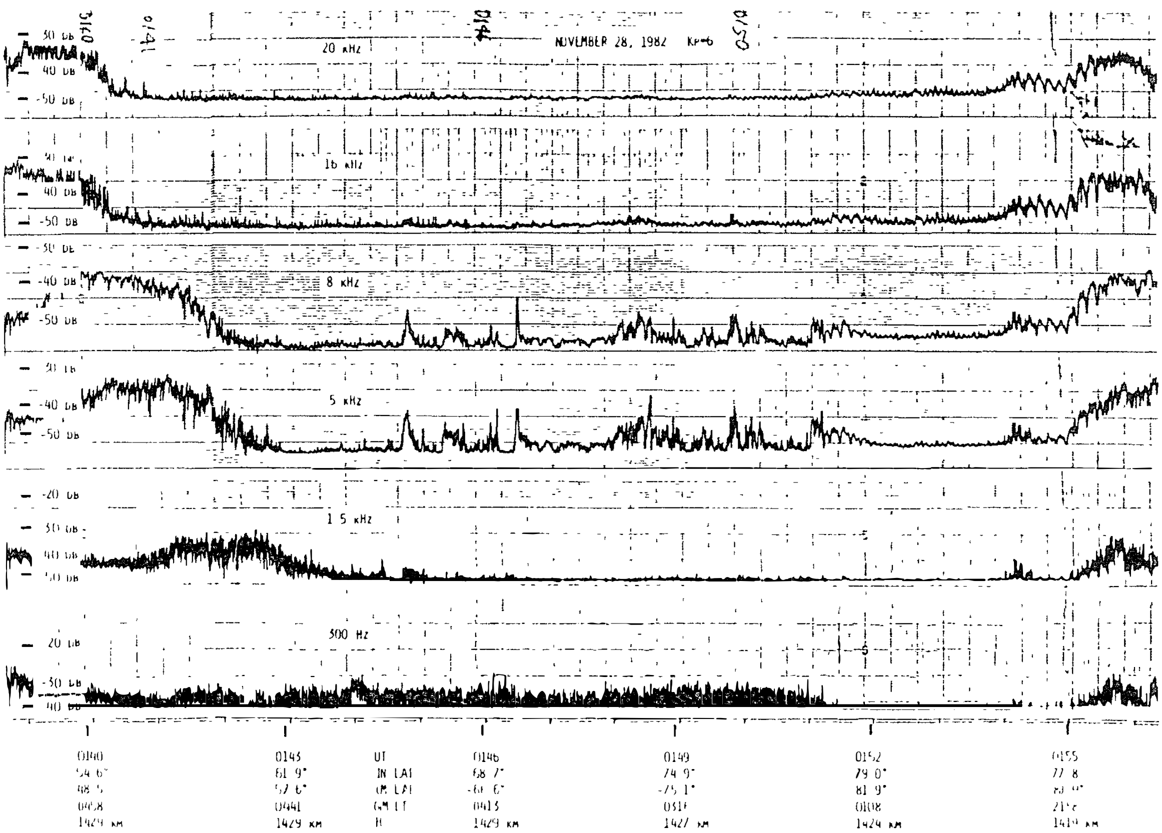

Fig. 11a. *Dawn-midnight latitudinal variations of narrow-band VLF intensity data observed by ISIS-2 in a large substorm expansion phase on Nov. 28, 1982 (K_p=6)*

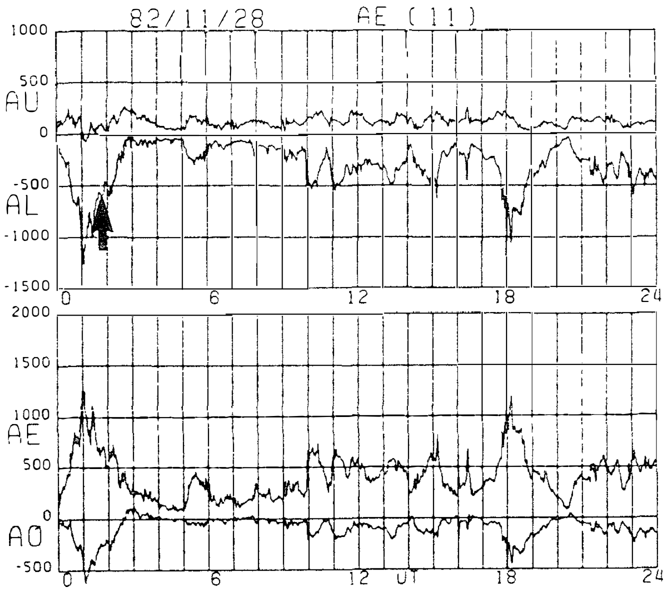

Fig. 11b. *Time variations of AL and AE indices on Nov. 28, 1982.*

were observed below the plasmapause invariant latitude ($\lesssim 63°$) which depends on the K_p, for the nighttime in the substorm expansion phase and recovery phase. The generation of LHR hisses observed during the substorm is related to ion constituent variations in the topside ionosphere associated with a heat conduction along geomagnetic field lines near the plasmapause from the nightside disturbed magnetosphere (Wrenn and Raitt, 1975).

3. Statistical result of substorm effect on polar hiss

We define the geomagnetic quiet period by a period of $AL \geqq -300$ nT, and the substorm period by a period with a maximum AL decrease of $AL < -300$ nT. According to the pattern classification of AL time variation, we further define a substorm growth phase by a slow AL decrease part within one hour before the rapid AL decrease at the substorm onset, the substorm expansion phase by a period from the substorm onset to a recovery level of one half the maximum decrease of $AL < -300$ nT, and the substorm last phase by a recovery period from the level of one half the maximum decrease to the quiet level. Thus, we can determine the substorm phase in which an individual satellite pass is included as shown by an upward arrow in Figs. 1b–11b.

We select 65 passes which contain the mid-latitude hiss and 74 passes which contain the polar hiss from ISIS VLF passes received at Syowa Station between February 1982 and January 1983. Table 1 indicates the occurrence number (rate) distribution of mid-latitude hiss and polar hiss in the substorm phase and quiet period. Table 1 does not give any clear dependence of the VLF hiss occurrence on the substorm, since we have not so many ISIS VLF passes for substorms. But, it is clear that both of the polar hiss and mid-latitude hiss occur most frequently in the quiet time and next in the substorm last phase. This statistical relation of the polar hiss *vs.* substorm phase is very similar to that of inverted-V electron precipitation *vs.* substorm phase in Table 2 (Hoffman and Lin, 1981; Lin and Hoffman, 1982).

Gurnett and Frank (1972) observed simultaneous occurrences of auroral (polar) hiss and inverted-V electron precipitations by Injun-5, and they have shown that the auroral hiss is generated by intense fluxes of precipitating inverted-V electrons with wide

Table 1. Statistical occurrence distributions of the mid-latitude hiss and polar hiss in the substorm phase.

	Quiet time	Growth phase	Expansion phase	Last phase
Mid-latitude hiss	43 (66%)	3 (5%)	6 (9%)	13 (20%)
Polar hiss	49 (66%)	5 (7%)	7 (9%)	13 (18%)

Table 2. Inverted-V events vs. substorm phase. Number of passes between 20 and 24 hours MLT containing inverted-V events.

Magnetically quiet	Before Bay < 0.5 hr	Bay	Recovery
30	8	12	27

energies from about 100 eV to about 40 keV. The energy of inverted-V electrons precipitated from the plasmasheet boundary layer is in a range of 500 eV to 12 keV for 16–00 MLT and in a range of 200 eV–7 keV for 01–11 MLT, although the inverted-V event is dominant for 19–01 hours MLT (Hoffman and Lin, 1981).

Ondoh (1990) has shown that the polar map of the occurrence rate of polar hiss obtained from 347 ISIS VLF passes for $K_p = 0$–7 is very similar to the polar occurrence map of 280 inverted-V electron precipitation events observed by the Atmospheric Explorer-D (Hoffman and Lin, 1981), and also that the broad-band polar hiss is generated by the whistler-mode Cerenkov radiation from inverted-V precipitating electrons with energies from a few hundreds eV to several keV in the magnetosphere. The occurrence rate map of polar hiss and the occurrence map of inverted-V events are symmetric with respect to the 10–22 hours MLT meridian, while the auroral zone is symmetric with respect to the 12–00 hours MLT meridian. Furthermore, the latitudinal and longitudinal widths of individual polar hiss and inverted-V event are about ten times those of auroral arcs (Ondoh, 1991; Lin and Hoffman, 1982). Therefore, even if we take into account the spatial spreading effect of the whistler-mode polar hiss waves which propagate from the magnetospheric sources, the similarity between Tables 1 and 2 seems reasonable.

Table 3 is occurrence distributions of the mid-latitude hiss and polar hiss with the grade of AE and AL indices. Table 3 indicates that the occurrence frequency of the mid-latitude hiss is maximum in the geomagnetic quiet period and it decreases with increasing AE or AL-index grade. This implies that the generation of mid-latitude hiss is independent of the substorm activity as shown by the AE and AL indices. In fact, the mid-latitude hiss is most likely to be generated by the electron cyclotron instability in the equatorial magnetosphere since many properties of the plasmaspheric VLF hiss seem to be related to the same electron cyclotron instability (Hayakawa and Sazhin, 1992; Ondoh, 1995). But, the region of mid-latitude hiss or plasmaspheric VLF hiss moves toward lower latitudes or inner L-shells associated with the plasmasphere reduction during the geomagnetic storm and storm-substorm.

However, the occurrence frequency of the polar hiss is maximum in a medium grade of the AE and AL indices. Taking a sum of the occurrence frequency of polar

Table 3. Relations of the occurrence frequency for 65 mid-latitude hisses and 74 polar hisses with the AE and AL indices (in nT).

	$30 < AE \leqq 200$	$200 < AE \leqq 500$	$500 < AE \leqq 750$
Mid-latitude hiss (65)	35 (54%)	22 (34%)	8 (12%)
	$30 < AE \leqq 200$	$200 < AE \leqq 500$	$500 < AE \leqq 924$
Polar hiss (74)	29 (39%)	35 (47%)	10 (14%)

	$-2 \geqq AL \geqq -100$	$-100 > AL \geqq -300$	$-300 > AL \geqq -530$
Mid-latitude hiss (65)	31 (48%)	23 (35%)	11 (17%)
	$-2 \geqq AL \geqq -100$	$-100 > AL \geqq -300$	$-300 > AL \geqq -583$
Polar hiss (74)	29 (39%)	32 (43%)	13 (18%)

hiss for $AE > 200$ nT and $AL < -100$ nT, we have occurrence rate of 61% in $AE > 200$ nT and $AL < -100$ nT for the polar hiss. This occurrence rate of 61% in the substorm period is about twice that of 29% in the geomagnetic quiet period. Therefore, we can say that the polar hiss is generated more frequently in the substorm period than the quiet period.

4. Discussions and conclusion

Typical 11 latitudinal-variations of the narrow-band VLF electric field data received from the ISIS-2 at Syowa Station, Antarctica are discussed together with time variations of AE and AL indices from February 1982 to January 1983. The telemetry range for the ISIS satellites from Syowa Station is from about 50° to 80° in geomagnetic invariant latitude.

In geomagnetic quiet and weak substorm recovery-phase periods, the narrow-band mid-latitude hiss at 5 and 8 kHz bands occurs, on the average, from 50° to 62° in geomagnetic invariant latitude, the broad-band polar hiss at 5, 8, 16, and 20 kHz bands occurs at latitudes from 68° to 80° in both the geomagnetic daytime and nighttime, and VLF hiss valley exists from 62° to 68° in the ionospheric plasma trough. The polar VLF hiss region recedes toward higher latitude above 75° and sometimes completely disappears as well as the mid-latitude VLF hiss on the geomagnetic dawn and morning side in a very quiet time. The intense ELF hiss at 300 Hz and 1.5 kHz bands appears up to invariant latitude just below the polar VLF hiss region in the daytime, but not in the nighttime.

The mid-latitude VLF hiss is generated near the equatorial plasmapause by the electron cyclotron instability of a few keV electrons convected from the magnetotail (Ondoh, 1995), and the polar VLF hiss is the whistler-mode Cerenkov radiation generated from inverted-V precipitating electrons in the high-latitude magnetosphere. The ELF hiss generated by the electron cyclotron instability in the equatorial plasmasphere propagates downwards in the plasmasphere repeating LHR reflections in the both plasmaspheric hemispheres. So, the high-latitude extension of the ELF hiss implies the plasmasphere expansion in a quiet time. The VLF hiss valley depends mainly on the generation and propagation conditions of the whistler-mode VLF hiss which are equatorial locations of the radiation-zone slot, plasmapause, and energetic electron trajectories convected from the tail, and also the plasma density and geomagnetic field in the magnetosphere.

In the substorm expansion phase, the mid-latitude hiss (below 58°) and polar hiss (74°–60°) regions move toward lower latitudes, and the both regions become closer on the nightside than on the dayside. Therefore, the VLF hiss valley becomes very narrow. Especially, it vanishes on the nightside in a large substorm expansion phase, and the both hiss regions finally join. In a substorm expansion phase of $AE > 600$ nT, a broad-band polar hiss from 1.5 kHz band to 20 kHz band occurred from 56° to 72°, but no hiss at latitude above 73° and below 56° respectively. In another strong substorm expansion phase of $AE > 600$ nT, only a strong broad-band LHR hiss from 1.5 kHz band to 20 kHz band occurred at latitudes below 63°, but no polar hiss at latitudes above 63° in the geomagnetic dawn.

In the substorm expansion phase, energetic electrons precipitating from the plasmasheet inner edge along auroral field lines into the ionosphere produce the broad-band whistler-mode polar hiss which propagates toward the high-latitude ionosphere, and another energetic electrons drifting inward in the equatorial magnetotail produce the mid-latitude hiss propagating toward the ionosphere near the equatorial plasmapause. However, since the near-Earth plasmasheet inner edge comes closer to the reducing plasmapause as the substorm becomes stronger, the mid-latitude hiss and polar hiss regions move to lower latitudes and the nightside VLF hiss valley becomes narrower in the substorm expansion phase.

In the substorm expansion phase, the LHR hiss of which intensity peak latitude increases with decreasing frequency from 20 kHz to 1.5 kHz appears at latitudes from 50° to 63° of the mid-latitude hiss region. The appearance of LHR hiss results from changes of the ionospheric ion constituent caused by the field-aligned heat conduction near the plasmapause from the nightside magnetosphere. Statistical distributions of the occurrence rate for 65 mid-latitude hisses and 74 polar hisses are obtained at grades of AE and AL indices. The occurrence rate of the mid-latitude hiss decreases with increasing AE index grade. This implies that the occurrence of the mid-latitude hiss is independent of the substorm activity. While, the occurrence rate of the polar hiss in the substorm period ($200\,\mathrm{nT} < AE \leqq 924\,\mathrm{nT}$ and $-100\,\mathrm{nT} > AL \geqq -583\,\mathrm{nT}$) is about twice that in the quiet period ($30\,\mathrm{nT} < AE \leqq 200\,\mathrm{nT}$ and $-2\,\mathrm{nT} > AL \geqq -100\,\mathrm{nT}$). Therefore, the occurrence of the polar hiss clearly depends on the substorm activity. Further study is required to elucidate the substorm effect on the magnetospheric VLF hiss.

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