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Key Points:

- The longitudinal extent of magnetospheric ELF/VLF waves was examined using six ground loop antennas at subauroral latitudes
- The typical extent of ELF/VLF wave are estimated as ~ 76 degrees in longitude
- The longitudinal extent increased with geomagnetic activity

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Longitudinal Extent of Magnetospheric ELF/VLF Waves using Multipoint PWING Ground Stations at Subauroral Latitudes

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Abstract Magnetospheric extremely low frequency/very low frequency (ELF/VLF) waves are plasma waves emitted from high-energy electrons in the magnetosphere. These waves have received much attention, as they contribute to the acceleration and loss of relativistic electrons in the radiation belts through wave-particle interactions. The longitudinal extent of ELF/VLF waves has not been well-understood, although the extent is important in quantitative evaluation of relativistic electron variations. In this study, we analyzed data from continuous ground-based simultaneous observations of ELF/VLF waves over a 2-month period in November and December of 2017, using six loop antennas located at roughly equal intervals around the north geomagnetic pole at $\sim 60^\circ$ magnetic latitudes. We estimated the longitudinal extent of magnetospheric ELF/VLF waves based on their occurrence rate. Our results showed that the ELF/VLF wave occurrence rate differed by twofold to threefold, depending on the longitudes of the observation sites. We explain this difference in terms of longitudinal differences in the ionosphere's magnetic field intensity, possibly due to the electron loss that occurs during the bounce motion at longitudes of small magnetic field intensity. Based on our statistical analysis, we estimated the typical longitudinal extent of ELF/VLF waves as $\sim 76^\circ$. Time series analysis results showed that the large longitudinal extent of the ELF/VLF waves occurs frequently during the main phase of geomagnetic storms and is also associated with substorms represented by the auroral electrojet index.

1. Introduction

Magnetospheric extremely low frequency (ELF) and very low frequency (VLF) waves are electromagnetic waves with frequency ranges of 0.3–3 and 3–30 kHz, respectively, that are generated by high-energy electrons of several keV to tens of keV in the magnetosphere (Kennel & Petschek, 1966). Helliwell (1965) categorized these waves into chorus, hiss, and quasiperiodic (QP) emission types based on their time-frequency properties.

Chorus emissions are electromagnetic waves with discrete intensity enhancement. They are mostly rising-tone emissions, showing a frequency increase over time. Falling-tone emissions, which show a frequency decrease with time, were also reported (e.g., Shiokawa et al., 2014; Ungstrup & Carpenter, 1974). Chorus emissions are generated near the equatorial plane in the magnetosphere by high-energy electrons with temperature anisotropy (e.g., Kennel & Petschek, 1966; LeDocq et al., 1998; Santolík et al., 2003). Chorus emissions are known to accelerate electrons to relativistic energy levels in the outer radiation belt and scatter them at the electron pitch angle through wave-particle interactions (e.g., Horne et al., 2007; Kasahara et al., 2018; Li et al., 2014; Meredith et al., 2003; Miyoshi et al., 2015; Ozaki et al., 2019).

Hiss emissions are categorized as continuous electromagnetic waves with broadband and non-structured features (Hayakawa et al., 1986). The generation mechanism has been considered to be a mixture of propagating and reflecting chorus waves in the magnetosphere (e.g., Bortnik et al., 2008; Chen et al., 2012).

Table 1
Location of Stations Used in This Paper

station	geolat	geolon	maglat	maglon	L-value
Kapuskasing (KAP)	49.4°N	277.8°E	58.7°N	354.0°E	3.7
Athabasca (ATH)	54.6°N	246.4°E	61.3°N	309.0°E	4.3
Gakona (GAK)	62.4°N	214.8°E	63.0°N	271.8°E	4.9
Maimaga (MAM)	63.1°N	129.6°E	58.0°N	202.6°E	3.6
Istok (IST)	70.0°N	88.0°E	66.1°N	162.7°E	6.0
Kannuslehto (KAN)	67.7°N	26.3°E	64.5°N	106.0°E	5.5

QP emissions are categorized as discrete electromagnetic waves with QP intensity enhancement on a time scale of ~ 10 – 400 s (e.g., Manninen et al., 2014, 2018; Nemec et al., 2016; Titova et al., 2015). QP emissions are further categorized into two types: Type 1 and Type 2 (Sazhin & Hayakawa, 1994). Type 1 QP emissions are correlated with Pc3–5 geomagnetic pulsations. Type 2 QP emissions are not correlated with geomagnetic pulsations.

These three types of magnetospheric ELF/VLF waves have received much attention, as they can change the electron distribution in the magnetosphere through wave-particle interactions, thus affecting space weather. In recent decades, studies of these magnetospheric ELF/VLF waves have focused mostly on their generation mechanism (e.g., Katoh & Omura, 2007; Tsurutani & Smith, 1974), their effects on phenomena in the magnetosphere, such as pulsating aurora and radiation belts (e.g., Demekhov & Trakhtengerts, 1994; Horne & Thorne, 1998; Kasahara et al., 2018), and the spatiotemporal structure of the wave source region (e.g., Meredith et al., 2003; Santolik et al., 2003).

Studies of the spatiotemporal structure of the wave source region have shown experimentally and theoretically that the chorus wave source is located near the equatorial plane in the magnetosphere (e.g., Katoh & Omura, 2007; Omura et al., 2009; Santolik et al., 2003). The occurrence rate of ELF/VLF waves as a function of magnetic local time (MLT) and L-value was examined using ground-based and spacecraft observations. Santolik et al. (2005) studied the L-value dependence of the whistler-mode chorus wave using the Double Star TC-1 spacecraft; they showed that the chorus wave intensity increased with the L-value, up to ~ 6 , until

it reached saturation. Li et al. (2009) obtained a global picture of the ELF/VLF wave distribution as functions of MLT and L-value through a statistical analysis of Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellite data and showed its geomagnetic activity dependence.

Despite extensive research efforts regarding the spatiotemporal structure of ELF/VLF waves, the instantaneous longitudinal extent of these waves is not well-known. Yonezu et al. (2017) statistically investigated the longitudinal extent of ELF/VLF waves by observing these waves simultaneously at three ground-based stations: Athabasca (maglat: 61.3° N, maglon: 309.0° E) in Canada, Kannuslehto (maglat: 64.5° N, maglon: 106.0° E) in Finland, and Syowa Station (maglat: 70.5° S, maglon: 39.6° E) in Antarctica. They determined the conditional probability of wave occurrence, defined as the occurrence rate of ELF/VLF waves when the other station observe the ELF/VLF waves as ~ 10 – 40% . They showed that the conditional probability decreased with increasing longitudinal separation between stations. However, they were unable to provide a specific value for the longitudinal extent of ELF/VLF waves, because only three stations were used, and these stations were located at both subauroral and auroral latitudes.

In this study, we report the results of our statistical analysis of the longitudinal extent of ELF/VLF waves using six ground-based stations located at subauroral latitudes around the Earth in the Northern Hemisphere. The average global distribution of magnetospheric ELF/VLF waves can

Figure 1. MLAT (magnetic latitude)-MLT (magnetic local time) map of the PWING stations. All stations are located at subauroral latitudes ($\sim 60^\circ$ magnetic latitude). ATH, Athabasca; GAK, Gakona; IST, Istok; KAN, Kannuslehto; KAP, Kapuskasing; MAM, Maimaga.

Figure 2. One-hour dynamic spectra observed at (a) KAP, (b) ATH, (c) GAK, (d) MAM, (e) IST, and (f) KAN. Hiss-type extremely low frequency/very low frequency (ELF/VLF) waves are observed for the entire spectra at KAP from 1 to 4 kHz. Chorus-type ELF/VLF waves exist in the spectra at ATH and GAK from 2 to 4 kHz. The spectra at MAM and IST do not show any magnetospheric ELF/VLF waves. (KAP: Kapuskasing, ATH: Athabasca, GAK: Gakona, MAM: Maimaga, IST: Istok, and KAN: Kannuslehto) The magnetic local times (MLTs) of this period at KAP, ATH, GAK, MAM, IST, and KAN are ~ 12 – 13 MLT, ~ 9 – 10 MLT, ~ 6 – 7 MLT, ~ 2 – 3 MLT, ~ 23 – 24 MLT, and ~ 19 – 20 MLT, respectively.

be obtained by statistical analysis of data from a single satellite or a single ground-based station. However, instantaneous longitudinal extent is observable only by using multipoint globally distributed ground-based observations. We here present the instantaneous longitudinal extent of the ELF/VLF waves based on the wave occurrence rate and its dependence on geomagnetic activity. We also report the longitudinal dependence of the ELF/VLF wave occurrence rate based on multipoint ground-based observations at similar latitudes.

2. Observation

2.1. Stations and Instruments

We conducted continuous simultaneous observations of ELF/VLF waves using loop antennas installed at six stations to estimate the longitudinal extent and distribution of ELF/VLF waves. The stations are located

Figure 3. Local hour occurrence rate of the magnetospheric ELF/VLF waves at (a) Kapuskasing (KAP), (b) Athabasca (ATH), (c) Gakona (GAK), (d) Maimaga (MAM), (e) Istok (IST), and (f) Kannuslehto (KAN) from 1 November 2017 to 31 December 2017. The total occurrence rates are shown at the top right of these panels.

Figure 4. Number of 10-min bins (counts) of simultaneous ELF/VLF waves as a function of longitudinal extent between stations. The green lines indicate the conceivable longitudinal extent, which indicates the range from minimum (longitudinal difference between the stations where the waves are observed) to maximum (longitudinal difference between the stations next to the wave-observing stations) possible longitudinal extent.

at Kapuskasing (KAP), Athabasca (ATH), Gakona (GAK), Maimaga (MAM), Istok (IST), and Kannuslehto (KAN), as listed in Table 1. Figure 1 shows a map of these stations in magnetic latitude and MLT coordinates. These stations are located within 58° – 66° north magnetic latitude and at roughly equal intervals around the magnetic north pole, with the exception of the Atlantic Ocean area. Excluding KAN, loop antennas were installed by the PWING project (study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations; <http://www.isee.nagoya-u.ac.jp/dimr/PWING/>) (Shiokawa et al., 2017). The antennas, as described by Ozaki et al. (2008), are all 10-loop delta-type loop antennas, with a height of 5.3 m. The antennas record magnetic fluctuations in east-west and north-south directions at a sampling rate of 40 kHz. The loop antennas at KAN were installed by the Sodankylä Geophysical Observatory. These antennas are 10-loop square-type loop antennas size of 10×10 m in size that record magnetic fluctuations in the east-west and north-south directions at a sampling rate of 78.125 kHz (Manninen, 2005). All of the KAN data were analyzed using sferics and power line harmonic radiation filters, described briefly in Manninen et al. (2016). Our 2-month (61 days) study took place from 1 November 2017 to 31 December 2017. All stations conducted continuous observations during this period.

2.2. Data Definition

In this section, we define ELF/VLF wave occurrence and the wave occurrence rate. We conducted fast Fourier transforms of the magnetic

Figure 5. Probability distribution of the longitudinal extent calculated from Figure 4.

fluctuations every 8,192 data points (0.2048 s) and 16,384 data points (0.2097 s) at KAN and at the other stations, respectively, and created dynamic spectra every hour. Figure 2 shows examples of the dynamic spectra observed at 1,700–1,800 UT on 5 December 2017. The intense spike-like emissions observed at 5–10 kHz at all stations were not magnetospheric ELF/VLF waves but rather sferics from lightning. Chorus emissions with discrete structures were evident at 2–5 kHz in the spectra at ATH and GAK. The KAP spectrum showed Hiss emissions, which have a more continuous structure than did the chorus waves observed at ATH and GAK. On the other hand, no magnetospheric ELF/VLF waves were observed in spectra from MAM, IST, or KAN.

In the statistical analysis, we defined the occurrence of ELF/VLF waves in 10-min increments using the following method. We first selected 10-min periods with spectra that were not significantly contaminated by sferics from lightning, and defined these 10-min periods as available bins.

In addition, we defined simultaneously available bins as intervals when all the six stations have available bins. We then defined ELF/VLF wave occurrence bins every 10 min using the criteria listed below, from all simultaneously available bins.

1. The spectra show the characteristics of chorus, hiss, and QP emissions in the frequency range of 1–8 kHz. Chorus and hiss are separated, independent of whether discrete structure is observed within the 1-h time frame of the spectra. QP emission can be recognized as such within the 1-h spectra. These separations were based on visual inspection; notably, at times, the division was somewhat ambiguous.
2. The wave power is greater than $1.0 \times 10^{-11} [\text{nT}^2/\text{Hz}]$ at 5 kHz ($5.0 \times 10^{-10} [\text{nT}^2/\text{Hz}]$ at 1 kHz) and can be distinguished from background noise level.
3. The magnetospheric ELF/VLF wave power is about one order higher than the background noise, so it can be easily distinguished from background noise.

Note that we used the spectra plotted in units of V^2/Hz based on the output voltages from loop antennas to identify ELF/VLF waves, except for KAN that uses $[\text{nT}^2/\text{Hz}]$. This is because the natural decreasing trend of the wave power with increasing frequency is compensated for by the higher sensitivity of the loop antenna at higher frequencies. In addition, the plotted spectra tend to become flat irrespective of the frequencies.

Following these criteria, we distinguished wave occurrence every 10 min (1 bin). We calculated the wave occurrence rate by dividing the number of wave bins by the number of simultaneously available bins. These criteria are the same as those used by Martinez-Calderon et al. (2015) and Yonezu et al. (2017).

Figure 6. Probability distribution of the longitudinal extent of ELF/VLF waves dividing by SYM-H index (quiet: $\geq 0 \text{ nT}$, moderate: $< 0 \text{ nT}$ and $\geq -20 \text{ nT}$, active: $< -20 \text{ nT}$).

Figure 7. Time series of the instantaneous longitudinal extent and the auroral electrojet (AE) index. The blue and orange lines indicate the AE index and the longitudinal extent (measured extent) of the ELF/VLF waves, respectively. The dashed line indicates the longitudinal extent of available stations (maximum possible range), which changes over time due to lightning noise and instrument issues.

3. Statistical Analysis

3.1. Occurrence Rate at Each Station

Figure 3 shows the ELF/VLF wave occurrence rate at each station during the simultaneously available period. The curves in these panels indicate the number of simultaneously available bins as a function of MLT. Because only simultaneously available bins were selected, the number of bins was the same for all stations. The number of 10-min bins exceeded 120 (over 20 h) at all MLT, sufficient for the statistical analysis of the occurrence rate. The occurrence rates of ELF/VLF waves as a function of MLT are shown by blue bars. This occurrence rate includes all types of ELF/VLF waves (chorus, hiss, and QP emissions). The total (or average) occurrence rate, defined as the ratio (percent) of the number of wave bins to the total simultaneously available bins over all MLTs, is shown in the top right of each panel. The occurrence rate as a function of MLT reached a maximum in the dawn-to-noon sectors at all stations. The total occurrence rate differed significantly among stations. The maximum value was obtained at KAN (32.4%), and the minimum value was recorded at KAP (9.7%).

3.2. Longitudinal Extent

Figure 4 shows the number of 10-min bins (counts) for each longitudinal extent of the ELF/VLF waves. The blue stars indicate longitudinal difference among multiple stations that observed the ELF/VLF waves simultaneously. The green lines indicate error bars of the estimated longitudinal extent, which is defined from longitudinal differences to the next available stations in both western and eastern sides that did not observe the ELF/VLF waves. For example, if the ELF/VLF waves were observed at ATH and GAK and not observed

Figure 8. Time series of the instantaneous longitudinal extent and the SYM-H index in the same format as in Figure 7. The vertical axis for the SYM-H index is reversed.

Figure 9. SYM-H and AE dependence of the instantaneous longitudinal extent of magnetospheric ELF/VLF waves. The vertical SYM-H axis is not reversed unlike Figure 8.

at KAP and MAM, the minimum value (blue stars) and maximum value (green line) of the ELF/VLF wave extent would be estimated as the longitudinal difference between ATH-GAK and KAP-MAM, respectively, as may be inferred from Figure 1. Minimum values (longitudinal differences among the stations) are shown as stars in Figure 4. Note that we did not distinguish the types of simultaneous waves (QP/chorus/hiss) when we estimated the longitudinal extent.

Figure 5 shows the probability distribution of the longitudinal extent of ELF/VLF waves obtained by integrating the counts in Figure 4 for all of the horizontal bars, and then calculating the fraction of the number of counts per each longitudinal difference with respect to the total number of counts. The peak of probability distribution of longitudinal extent is $\sim 76^\circ$ with a half maximum of $\sim 147^\circ$. Therefore, we concluded that the extent of the ELF/VLF waves during the analyzed period was typically $\sim 76^\circ$ in longitude. We also investigated the probability distribution of ELF/VLF waves by dividing by SYM-H index (quiet: ≥ 0 nT, moderate: < 0 nT and ≥ -20 nT, active: < -20 nT) at Figure 6. We can see the longitudinal extent tends to be larger with increasing geomagnetic activity.

3.3. Relationship Between Geomagnetic Activity and Longitudinal Extent

Figures 7 and 8 show the time variation in the auroral electrojet (AE) index (blue curve in Figure 7), the symmetric H-component (SYM-H) index (blue curve in Figure 8), and the instantaneous longitudinal extent of ELF/VLF waves (orange curve) from 1 November 2017 to 31 December 2017. Note that the vertical axis of SYM-H is reversed. In this section, the instantaneous longitudinal extent is defined as the longitudinal difference among multiple stations that observed ELF/VLF waves simultaneously. These values correspond to the minimum value of the longitudinal extent, as shown in Figure 4. If the instantaneous longitudinal extent had two or more values in a 10-min bin, then we used the maximum value. No data periods of longitudinal extent corresponds to the time during which none of the stations observed ELF/VLF waves. The black dashed line indicates the maximum longitudinal extent that can be observed. This black line may not be 360° (maximum when all stations are available), as some station's data were not available at this time,

Figure 10. Dependence of longitudinal extent of ELF/VLF waves on auroral electrojet (AE) and magnetic local time (MLT) of the westward edge of the magnetospheric ELF/VLF waves. Each circle corresponds to a 10-min bin. The color indicates the size of the instantaneous longitudinal extent.

Figure 11. Dependence of longitudinal extent of ELF/VLF waves on the SYM-H index and magnetic local time (MLT) of the westward edge of the magnetospheric ELF/VLF waves. Each circle corresponds to a 10-min bin. The color indicates the size of the instantaneous longitudinal extent.

because of noise contamination or instrumental trouble. From these figures, we can see that the ELF/VLF waves with a large longitudinal extent were associated with AE index enhancement and the main phase of minor geomagnetic storm as defined by the SYM-H index.

Figure 9 shows the dependence of the longitudinal extent on the SYM-H and AE indices. In this analysis, we concentrated on the simultaneously available bins for all six stations. The AE indices were then averaged over the previous 1-h period to consider the effect of substorm electron injection. According to this figure, the size of the longitudinal extent of the ELF/VLF waves tended to increase with decreasing SYM-H. However, we were unable to resolve an obvious dependence of the longitudinal extent with the 1-h averaged AE index.

Figures 10 and 11 show the dependence of the MLT of ELF/VLF waves on AE and SYM-H indices, respectively. We defined the MLT as the MLT of the west-most station in the simultaneous observation chain. Because the electrons drift eastward, we used the MLT of the west-most station. The instantaneous longitudinal extent is indicated by color. The data show that the instantaneous longitudinal extent increased from the morning to the midnight sector. A smaller number of events occurred during the dusk sector (~ 18 MLT) when AE and SYM-H values were high. These results suggest that electron injection by storms and substorms does not occur at ~ 18 MLT and that the injected electrons from the nightside drift downward to the dayside to generate the observed ELF/VLF waves in the magnetosphere.

4. Discussion

4.1. Occurrence Rate at Each Station

The wave occurrence rate as a function of MLT showed a high value in the dawn-to-noon sectors, as shown in Figure 3. This feature has been reported in previous studies (e.g., Martinez-Calderon et al., 2015; Tsurutani & Smith, 1977; Yonezu et al., 2017) and is considered due to the eastward drift of electrons injected from the nightside and compression of the dayside magnetosphere by the solar wind.

For the total occurrence rate of the ELF/VLF waves shown in the top right of each panel in Figure 3, we found that the rates varied significantly from $\sim 10\%$ to $\sim 30\%$ depending on station. As indicated by the red curve in Figure 3, the UT variation of the number of simultaneously available bins was less than 30%. Therefore, the ~ 2 – 3 times differences in the total occurrence rates were not caused by local time differences in the number of simultaneously available bins.

Figure 12. Occurrence rate of magnetospheric ELF/VLF waves as a function of magnetic latitude.

Figure 13. Occurrence rate of magnetospheric ELF/VLF waves as a function of magnetic longitude. The green and blue curves indicate the magnetic field intensity at 60° N and 60° S, respectively, at an altitude of 700 km.

The occurrence rate of ELF/VLF waves is known to increase with the L-value (e.g., Li et al., 2009; Meredith et al., 2003; Santolik et al., 2005). Figure 12 shows the dependence of the total occurrence rate of ELF/VLF waves with respect to the magnetic latitudes of the six stations used in this study. There may be some magnetic latitude dependence among KAP ($L = 3.7$), ATH ($L = 4.3$), GAK ($L = 4.9$), and KAN ($L = 5.5$), with the occurrence rate increasing with L-values. However, the occurrence rate at MAM ($L = 3.6$), which is at the lowest latitude among the six stations, was 25%, twofold higher than that at KAP ($L = 3.7$). Therefore, the latitude dependence cannot fully explain the observed differences in the total occurrence rates at the six stations.

In this study, we also investigated the relationship between the total occurrence rate and the model magnetic field intensity at the longitude of the six stations. In Figure 13, the blue and green curves indicate the magnetic field intensity in the upper ionosphere (height: 700 km) calculated by the IGRF-12 model (Thébault et al., 2015) at latitudes of 60° S and 60° N, respectively. The total occurrence rates are indicated by the bars. We can see a clear association between the total occurrence rates and the longitudinal distribution of magnetic field intensity if we take the weaker magnetic field intensity between the northern and southern conjugate hemispheres in Figure 13. This result suggests that the ELF/VLF waves are less likely to be generated at longitudes with weaker magnetic field intensity. This is because the electrons at energies of several to tens keV (the source electrons of the magnetospheric ELF/VLF waves; e.g., Jaynes et al., 2015) are lost into the ionosphere at longitudes with weaker magnetic field intensity during their longitudinal drift and north-south bounce motion along magnetic field lines.

There are several previous observation that support our results of longitudinal variation of wave occurrence. Asikainen and Mursula (2008) showed that relativistic energy particles precipitate to the ionosphere and disappear from the magnetosphere at the South Atlantic Anomaly (SAA). In a statistical study of QP emissions using the DEMETER satellite, Hayosh et al. (2014) observed a low occurrence rate of QP emission near the SAA. In the present observation, KAP is located in the longitude of SAA and shows the lowest wave occurrence though we did not distinguish wave types in our analysis.

4.2. Longitudinal Extent of the ELF/VLF Waves

We estimated the longitudinal extent of the ELF/VLF waves as $\sim 76^\circ$ in longitude. In this analysis, we did not consider the propagation effect of the ELF/VLF waves below the ionosphere. It is known that the ELF/VLF waves with the frequency of 1–8 kHz can propagate $\sim 1,000$ km (18° in longitude at 60° latitudes) between the ionosphere and ground with attenuation of >5 – 10 dB (e.g., Smith et al., 2010; Wait & Spies, 1965). Ozaki et al. (2008) showed that ELF/VLF waves propagate from the incident point of the ionosphere to the ground, with 250-km horizontal spreading ($\pm 4^\circ$ of longitude deference at latitude 60°). Thus, the longitudinal extent ($\sim 76^\circ$) of the ELF/VLF waves estimated in this study applies to that in the equatorial plane of the magnetosphere, the expansion of the ELF/VLF waves below the ionosphere appears to be a minor effect.

4.3. Relation Between Geomagnetic Activity and Longitudinal Extent

According to Figures 7 and 8, the longitudinal extent of the ELF/VLF wave occurrence increased with the AE index and during the main phase of geomagnetic storms. Li et al. (2009) showed that the chorus amplitude in the midnight sector increased with the AE index. Further, Tsurutani and Smith (1977) showed that ELF waves occur after substorms and that the delay time between wave occurrence and substorm onset is consistent with the time scale of electron gradient drift from midnight. Figure 9, however, shows that the

longitudinal extent of the ELF/VLF waves increases with decreasing SYM-H index and increasing AE index. This dependence become unclear for $AE < 200nT$ and $SYM-H > -10nT$. It is known that the ELF/VLF waves are less able to propagate to the ground during periods of geomagnetic disturbance periods (e.g., Golkowski et al., 2011; Simms et al., 2019). This fact may cause under estimation of longitudinal extent in geomagnetically active time.

5. Conclusions

We conducted ground-based simultaneous observation of ELF/VLF waves using six PWING stations located at roughly equal intervals around the earth at $\sim 60^\circ$ north latitudes. We analyzed the occurrence rate of magnetospheric ELF/VLF waves statistically to estimate the longitudinal extent of the waves. The results of this study are summarized below.

1. The total occurrence rate of the waves differed significantly depending on the station. The maximum and minimum values were recorded at KAN (32.4%) and KAP (9.7%), respectively. The total occurrence rate was related with the longitudinal distribution of the magnetic field intensity in the ionosphere at the weaker side of the northern and southern hemispheres. This indicates that ELF/VLF waves are less generated at the longitudes of both hemispheres with weaker ionospheric magnetic field intensity due to the loss of high-energy electrons. These electrons, which are the energy source of the magnetospheric ELF/VLF waves, become lost to the ionosphere in areas with weaker magnetic field intensity. This indicates that the ionospheric magnetic field of the conjugate point affects the number of high-energy electrons in the magnetosphere and the ELF/VLF wave occurrence in both hemispheres.
2. We statistically estimated the longitudinal extent of the ELF/VLF waves. The peak of probability distribution of longitudinal extent is $\sim 76^\circ$ with a half maximum of $\sim 147^\circ$.
3. The temporal variation in the longitudinal extent of the ELF/VLF waves indicated that the extent increased with AE index enhancement and during geomagnetic storms.
4. The size of the longitudinal extent of the ELF/VLF waves became larger with decreasing SYM-H index and increasing AE index.
5. The longitudinal extent increased from the morning to the midnight sector. A smaller number of events occurred in the dusk sector. These results suggest that the injected electrons from the nightside drift downward to the dayside to generate the observed ELF/VLF waves.

These results show, for the first time, the longitudinal extent of magnetospheric ELF/VLF waves, which is important in estimating the quantity of relativistic electrons generated by magnetospheric ELF/VLF waves. However, further study is required for temporal and spatial variation in the extent of these waves using ground and satellite conjugate observations and comparisons with global simulations. Such a study is expected to improve the simulation code for a quantitative estimation of relativistic electron generation.

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