Ultra Low Frequency Modulation of Energetic Electron Precipitation in the D-Region Ionosphere in a Magnetically Quiet Time Using OCTAVE Very Low Frequency and Low Frequency (VLF/LF) Observations

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Abstract – There are several studies of energetic electron precipitation (EEP) modulated by ultra low frequency (ULF) during substorms, although there are few in geomagnetically quiet times. At present, it is not clear how often such quiet time EEP occurs and the mechanism involved. In this study, we investigate EEP modulated by ULF (<5 Hz) from Observation of CondiTion of ionized Atmosphere by VLF Experiment (OCTAVE) very low frequency (VLF; 3 kHz to 30 kHz) and low frequency (LF; 30 kHz to 300 kHz) observations in geomagnetically quiet times. The OCTAVE is a worldwide network of VLF/LF signals that we established. The VLF/LF transmitter signals from four transmitters (NLK, NDK, WWVB, and NAA) in the USA were received at Athabasca (ATH; 54.7°N, 113.3°E, $L = 4.3$), Canada. There were oscillations in amplitude on the NDK-ATH and NLK-ATH paths with periods of 240 s and 270 s during magnetically quiet times from 11:20 Universal Time (UT) to 11:40 UT on October 9, 2017, respectively. The amplitudes of the VLF/LF variations were 3 dB and 1 dB on the NDK-ATH and NLK-ATH paths, respectively. Based on the wave–hop method, reflection height varied by ∼4.3 km during the VLF/LF oscillations, indicating that the electron density in the D-region ionosphere increased by ∼680 cm^{-3} (110%) at a 91 km height. The H component of ground-based magnetic field data at ATH and low latitudes showed the geomagnetic Pi2 pulsations with a similar period to that in the VLF/LF signals. The main cause of the VLF/LF oscillations could be ULF-modulated EEP due to the lowering of mirror points.

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1. Introduction

During geomagnetic storms and substorms, energetic electron precipitation (EEP; 100 keV to 1 MeV) from inner magnetosphere to lower ionosphere modulated by ultra low frequency (ULF; <5 Hz) waves were reported [1, 2]. Ionospheric modulation due to ULF Pc5 waves was observed by global positioning system total electron content, high frequency (HF; 3 MHz to 30 MHz) Doppler sounders, and Super Dual Auroral Radar Network HF radars [3]. The modifications in the lower ionosphere were reported based on riometers and X-ray observations [4]. Based on balloon-borne measurements of bremsstrahlung X-rays and simulations, the main cause of ULF-modulated EEP was reported to be lowering of mirror points [5]. Storm-time compressional ULF waves cause transport of electrons in the radiation belts toward the Earth or outward to conserve the first adiabatic invariant. When the electrons move toward the Earth, the magnetic field lines become shorter and the height of mirror points decreases. If the height of the mirror points decreased largely, the electrons would precipitate into the D-region height (60 km to 90 km).

Very low frequency (VLF; 3 kHz to 30 kHz) and low frequency (LF; 30 kHz to 300 kHz) transmitter signals reflected in the D-region ionosphere. When the electron density in the D-region ionosphere increases (decreases), the reflection height of the VLF/LF waves decreases (increases). The ground-based VLF/LF waves can monitor variations in electron density in the D-region ionosphere with a high time resolution.

There were several studies of ULF-modulated EEP during substorms, although there were few in

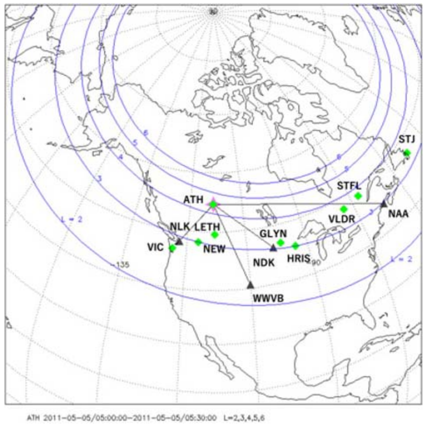

Figure 1. Location of the VLF/LF paths and ground magnetometers around the paths. The black triangles and green diamonds indicate VLF/LF transmitters and magnetometers, respectively. The blue curves indicate the L values.

geomagnetically quiet times. At present, it is not clear how often such quiet time EEP occurs and the mechanism involved. In this study, we investigate EEP modulated by ULF waves using the Observation of CondiTion of ionized Atmosphere by VLF Experiment (OCTAVE) VLF/LF transmitter signals over North America. We can estimate the location of the electron precipitation using multiple radio path networks.

2. Observations and Wave–Hop Method

Figure 1 shows the location of the VLF/LF paths. We used four transmitters in the USA, NLK (24.8 kHz), WWVB (60.0 kHz), NDK (25.2 kHz), and NAA (24.0 kHz), and one receiver Athabasca (ATH; 54.7°N, 113.3°E, $L = 4.3$), Canada. We also used ground magnetometers around the paths.

We used the wave–hop method to estimate the variation in reflection height of the VLF/LF transmitter

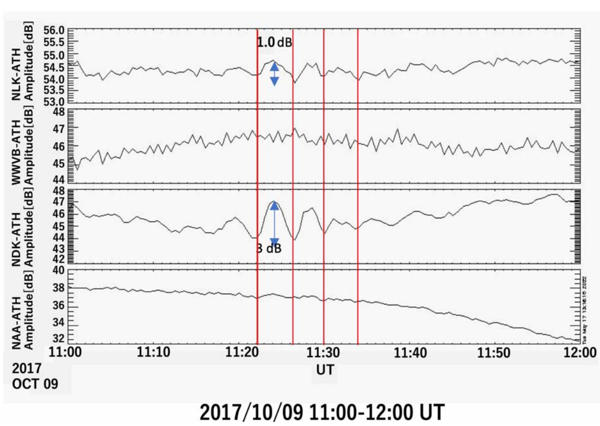

Figure 2. VLF/LF amplitudes from 11:00 UT to 12:00 UT on October 9, 2017. The red lines indicate the time with local minimum values of the oscillations, corresponding to the occurrence time of EEP.

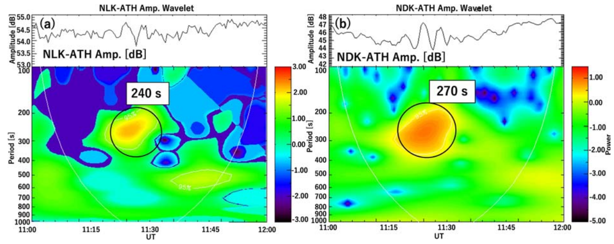

Figure 3. Wavelet spectra of VLF/LF amplitude for (a) NLK-ATH and (b) NDK-ATH paths from 11:20 UT to 11:40 UT on October 9, 2017.

signals. The synthetic electric field strength E was calculated as follows [6]:

$$E = Eg + \sum_{K=1}^{n} Es_K \tag{1}$$

where K is the number of hops, Eg is the ground wave, and Es_K is the effective field strength of transmitted sky wave. The wave–hop method is described in more detail in [6,7].

3. Results of VLF/LF Oscillations

Figure 2 shows periodic oscillations on the NLK-ATH and NDK-ATH paths during magnetically quiet times (disturbance storm time index: 20 nT to 30 nT) from 11:20 Universal Time (UT) to 11:40 UT on October 9, 2017, respectively. The red lines indicate the time with local minimum values of the oscillations, corresponding to the occurrence time of EEP. However, the oscillations were not seen on the WWVB-ATH path. Figures 3a and 3b show wavelet spectra of the VLF/LF amplitude for the NLK-ATH and NDK-ATH paths. The oscillations with the period between 200 s and 300 s were seen in both amplitudes. The main periods for the NLK-ATH and NDK-ATH paths were 240 s and 270 s, respectively.

4. Discussion of EEP

We estimated variations in the reflection height of VLF/LF waves based on the wave–hop method. The decreases in the reflection height from the 91 km height for the NLK-ATH, NDK-ATH, and WWVB-ATH paths were 4.3 km, 4.4 km, and 1.1 km, respectively. For the WWVB-ATH path, the small changes in amplitude are a cause of nonoscillations, because the amplitude has a nonlinear relation with the reflection height. Moreover, we estimated the electron density in the D-region ionosphere for the NLK-ATH and NDK-ATH paths using International Reference Ionosphere 2016 model [8]. The increases in the electron density for the NLK-ATH and NDK-ATH paths were 714 cm^{-3} (129.1%) and 654 cm^{-3} (94.5%) from the background level at a 91 km height, respectively (Figure 4). These results show that electron density in the D-region ionosphere increased by about twice during the EEP.

Figure 5 shows the oscillation in the VLF/LF amplitudes for the NLK-ATH and NDK-ATH paths and

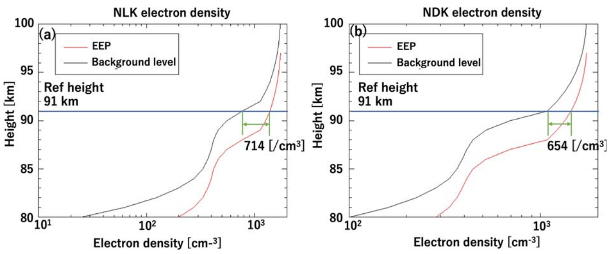

Figure 4. Estimated increases in electron density for (a) NLK-ATH and (b) NDK-ATH paths.

the H component of magnetic field variations (ΔB_H) from the mean values observed at ATH. The red and blue lines indicate the times of the local minimum value for the VLF/LF amplitude and ΔB_H, respectively. The period of the ΔB_H was 200 s to 300 s, which was similar to that of the VLF waves. The VLF oscillations for two paths were in phase, although oscillation in ΔB_H waws delayed by several tens of seconds. Figure 6 shows the ΔB_H at ATH and four sites at the low latitudes. The location of the ground-based magnetometers is shown in Figure 7. These oscillations in the ΔB_H were also seen at the low latitudes in the wide longitudes. The ΔB_H pulsations at ATH slightly preceded those at the low-latitude stations. These phenomena showed Pi2 signatures [9].

This event occurred under a geomagnetically quiet time, and solar wind speed and dynamic pressure were very low at 380 km/s and 390 nPa, respectively. When solar wind speed is low (<300 km/s), the Pi2 ULF waves with a long period of >200 s are generated by plasmaspheric resonance mode [10]. For this event, we concluded that the VLF oscillations are caused by EEP modulated by Pi2 ULF magnetic pulsation.

During the VLF oscillations, cosmic noise absorption observed by a riometer at ATH did not vary, because the energy of EEP would be larger than the detection range of the riometer. There were no VLF emissions such as whistler mode chorus waves at ATH during the oscillations. Thus, the EEP were not caused by whistler mode chorus waves. In this study, a possible

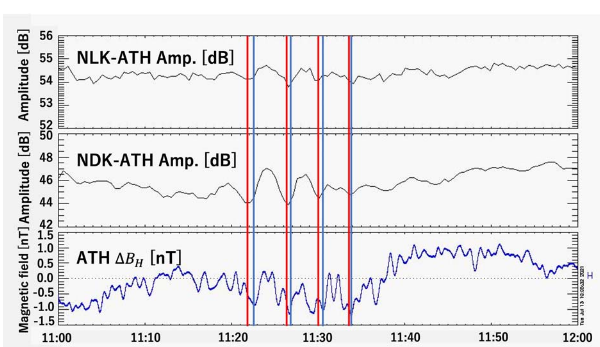

Figure 5. Oscillations in VLF/LF amplitude for the NLK-ATH and NDK-ATH paths and ΔB_H at ATH. The red and blue lines indicate the times of local minimum value for the VLF/LF amplitude and ΔB_H, respectively.

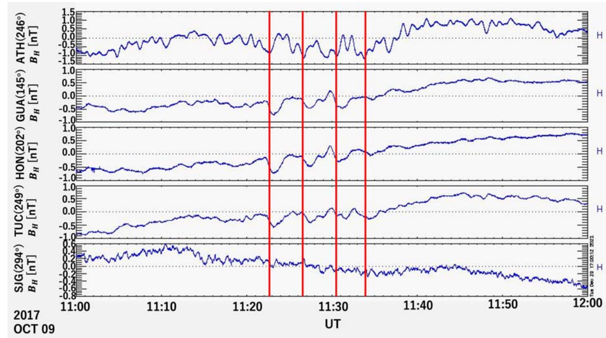

Figure 6. The ΔB_H at ATH and four magnetometers at the low latitudes.

mechanism for the EEP was considered as follows. The Pi2 ULF waves caused movement of electrons in the radiation belts toward the Earth or outward to conserve the first adiabatic invariant. When electrons moved toward the Earth, the magnetic field lines became shorter. To conserve the second adiabatic invariant, the electrons were accelerated along the magnetic field lines (Fermi acceleration) and decreased the height of mirror points. The electrons precipitated into the D-region height (60 km to 90 km).

5. Conclusions

We investigated the oscillations in amplitude of narrowband VLF/LF transmitter signals and a ground-based magnetic field during a geomagnetically quiet time from 11:20 UT to 11:40 UT on October 9, 2017. This is rare phenomenon of ULF-modulated EEP during a geomagnetically quiet time. The conclusions are summarized as follows:

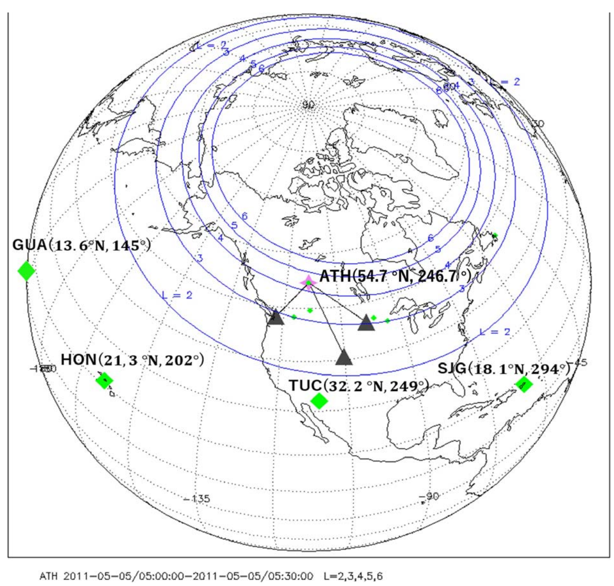

Figure 7. Location of the ground-based magnetometers at low latitudes. The black triangles and green diamonds indicate VLF/LF transmitters and magnetometers, respectively.

1) The VLF/LF amplitude oscillated with the period of 240 s and 260 s for the NLK-ATH and NDK-ATH paths, respectively.
2) The decrease in reflection height for NLK-ATH and NDK-ATH paths were estimated to be ∼4.3 km based on the wave–hop method.
3) The increases in electron density at the 91 km height for the NLK-ATH and NDK-ATH paths were estimated to be ∼680 cm^{-3} (110%) from the background level.
4) The H component of magnetic fields at ATH and low latitudes (GUA (Guam), HON (Honolulu), and TUC (Tucson)) showed similar oscillations with a period of between 200 s and 300 s, which showed that Pi2 ULF pulsations occurred.
5) This ULF-modulated EEP was caused by lowering mirror points due to shorter magnetic field lines, which was due to conservation of the first adiabatic invariant, not whistler mode chorus wave effects.

5. References

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