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Effects of Geomagnetic Storms on the Mid-Latitude D Region Ionosphere

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Abstract

The response of D Layer Preparation Time (DLPT) depth to geomagnetic storms during 2008-2011 is studied to investigate the effect of geomagnetic storms on the D layer of the ionosphere. The Very Low Frequency (VLF) signal at 19.6 kHz transmitted from the GBZ transmitter station Anthorn, UK (54ºN, 3ºW) and recorded by the AWESOME receiver at the Shamakhy Astrophysical Observatory named after N.Tusi, Shamakhy, Azerbaijan (40ºN, 48ºE) was used for analysis. Five geomagnetically disturbed days (Ap>26) were studied. A decrease in DLPT depth was observed for the storm day on October 11, 2008, while an increase was observed for all other storms.

Keywords: D layer preparation time; VLF wave propagation; Geomagnetic storms, AWESOME receiver.

1. Introduction

Earth's ionosphere plays a significant role in radio communication by reflecting the wave owing to electrical conductivity. Radio waves first penetrate the D layer (60-90 km) when they propagate in the ionosphere and are exposed to attenuation. Therefore, fading of signals is strongly dependent on the ionization level of this layer. Space weather events, such as Solar flares and geomagnetic storms, adversely affect radio communication, radio navigation systems, and satellite communication by increasing the ionization level of the ionosphere. Substantial enhancement of electron density, particularly in the auroral zone, during geomagnetic storms, increases radio wave attenuation, which causes the disappearance of radio signals in MH/HF ranges (Lastovicka, 1996).

VLF (3-30 kHz) remote sensing method is considered the best technique to detect space weather effects on the lower ionosphere. VLF signals are transmitted from around the world to the ionosphere and received at Sudden Ionospheric Disturbances (SID) monitoring stations. They propagate with little attenuation on the cavity called the Earth-Ionosphere Waveguide (EIWG) between ionospheric D-layer and ground (Kumar, 2018). Amplitude and phase of the waves are much sensitive to changes in the electrical conductivity of the ionosphere on the propagation path (Peter et al., 2006). EIWG height is 70 km during the daytime and 85 km during the nighttime, depending on the diurnal variation of the ionosphere (Thomson et al., 1993). The impacts of solar flares on VLF signals propagation have been discussed by many investigators (Kumar et al., 2015; Selvakumaran et al., 2014; Bouderba et al., 2016; Hayes et al., 2017; Sreckovic et al., 2017; Korsakov et al., 2018; Sharma et al., 2018). They determined that enhanced X-ray radiation when a solar flare occurs increases the ionization of the D-layer, which results in a sudden anomaly in amplitude and phase of the VLF signals. Solar flares affect the entire daytime ionosphere, while geomagnetic storms primarily affect the high-latitude ionosphere; the effect extends to low and equatorial latitudes (Kumar et al., 2018).

A geomagnetic storm is a temporary disturbance of Earth’s magnetosphere in response to changes in solar wind parameters and interplanetary magnetic field (IMF) conditions. Magnetic storms lead to energetic electron precipitation into the ionosphere associated with magnetospheric substorms. In order to penetrate below the 100 km altitude, electrons must have energies exceeding 20 keV (Spjeldvik et al., 1975). Lastovicka (Lastovicka, 1996) opined that at high latitudes, enhancement in electron density and radio wave absorption is caused by energetic electron precipitation from the magnetosphere in the storm main phase. Cummer et al. (Cummer et al., 1996) mentioned that energetic precipitating electrons penetrate the lower ionosphere, where they can cause extra ionization. Consequently, as the auroral electrojet crosses a VLF signal propagation path, this electron precipitation results in variations in amplitude and phase of the signal. Observing a decrease or increase in the amplitude at the receiving station depends on the modal mixture of the signal (Rodger et al., 2007). Clilverd et al. (Clilverd et al., 2010) observed that the amplitude of the very low-frequency signal transmitted from the NAA (24.0 kHz, 44°N, 67°W, L = 2.9) received at Sodankyla increased during geomagnetic activity. They showed ground-based electron precipitation flux (>100 keV) calculated from the NAA amplitude corresponds with the variation of electron fluxes determined by the POES satellite. From the analysis of two severe geomagnetic effects on the D-layer at low-equatorial latitudes, Kumar et al. (Kumar et al., 2018) observed that for the March 2015 storm, VLF signal amplitude decreased on the primary phase and recovered one day after the storm. For June 2015 storm, they observed amplitude decreased in the storm recovery phase.

The effect of geomagnetic storms on the lower ionosphere is characterized in terms of “primary storm effect,” “after storm effect,” “post-storm effect.” “Primary storm effect” describes signal anomaly during the main phase of the storm, whereas “after storm effect” describes anomaly during the storm recovery period and subsequent days. The “Post-storm” effect, on the other hand, is observed due to excess ionization when the magnetic perturbations have abated (Araki, 1974; Larsen et al., 1976).

In this work, the influence of geomagnetic storms during 2008-2011 on the mid-latitude D region of the ionosphere via VLF signal amplitude was studied.

2. Materials and Methods

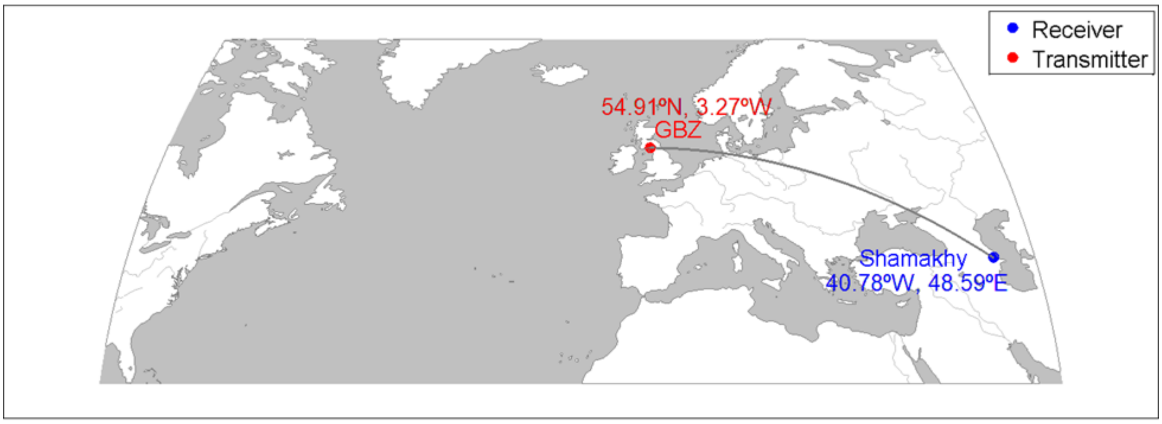

Figure 1*. Map showing the location of transmitter and receiver stations, geographical coordinates, and VLF signal propagation path along TRGCP.*

Narrowband VLF signals transmitted from the transmitter (call sign is GBZ) located in Anthorn, UK (54ºN, 3ºW) and operating at 19.6 kHz stabilized frequency, received at

Shamakhy, Azerbaijan (40ºN, 48ºE) are used for analysis. VLF signals are recorded with AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver provided by Stanford University and installed at Shamakhy Astrophysics Observatory named after Nasraddin Tusi (Figure 2). Transmitter-Receiver Great Circle Path (TRGCP) is shown in Figure 1. The distance between the GBZ transmitter and the receiver station is 5228 km.

(a) **(b)**

Figure 2. *(a) AWESOME receiver and (b) VLF antenna*

Ap index was utilized for determining geomagnetically disturbed days. A geomagnetic storm is classified as minor when the activity level is Ap<50, moderate when the storm is 50≤Ap<100, and severe when Ap≥100. Magnetic storms with Ap index above 26 were selected for analysis. Ap index data is taken from the OMNIWeb (https://omniweb.gsfc.nasa.gov/form/dx1.html). Detailed information on geomagnetic storms is given in Table 1.

The VLF DAQviewer (Data Acquisition Viewer) Matlab program was used to view VLF signal data. The DLPT depth parameter was utilized to investigate the effect of geomagnetic storms on the D-layer. A Diurnal variation of VLF signal is given in Figure 3. Sunrise Maxima, Sunrise Minima, Afternoon Maxima, Sunset Minima, and Sunset Maxima are marked with points A-E, respectively (Kumar 2018; Choudhury et al., 2015). The change in amplitude between A and B points is taken as "DLPT depth." DLPT depth was evaluated on the storm day, four days before, and four days after for each geomagnetic storm. In this way, nine days variation of DLPT depth was obtained.

Table 1. *Properties of geomagnetic storms considered in the study*

Event Date	Daily Averaged Ap index	Ap max	Start time
04 Sep 2008	31	80	04 Sep 2008 00:00 UT
11 Oct 2008	34	94	11 Oct 2008 06:00 UT
29 May 2010	28	56	29 May 2010 06:00 UT
04 Aug 2010	49	111	03 Aug 2010 18:00 UT
25 Oct 2011	38	154	24 Oct 2011 18:00 UT

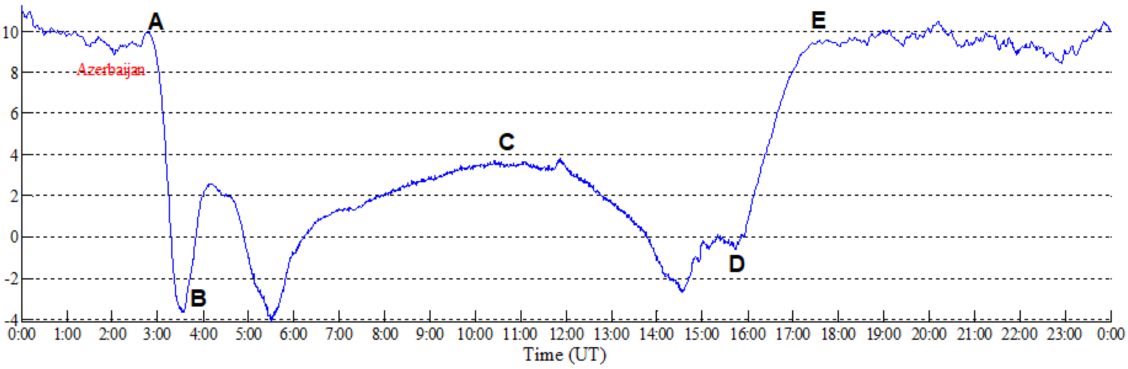

Figure 3. *A diurnal variation of GBZ signal amplitude. A-Sunrise Maxima, B-Sunrise Minima, C-Afternoon Maxima, D-Sunset Minima, E-Sunset Maxima*

3. Observational Results

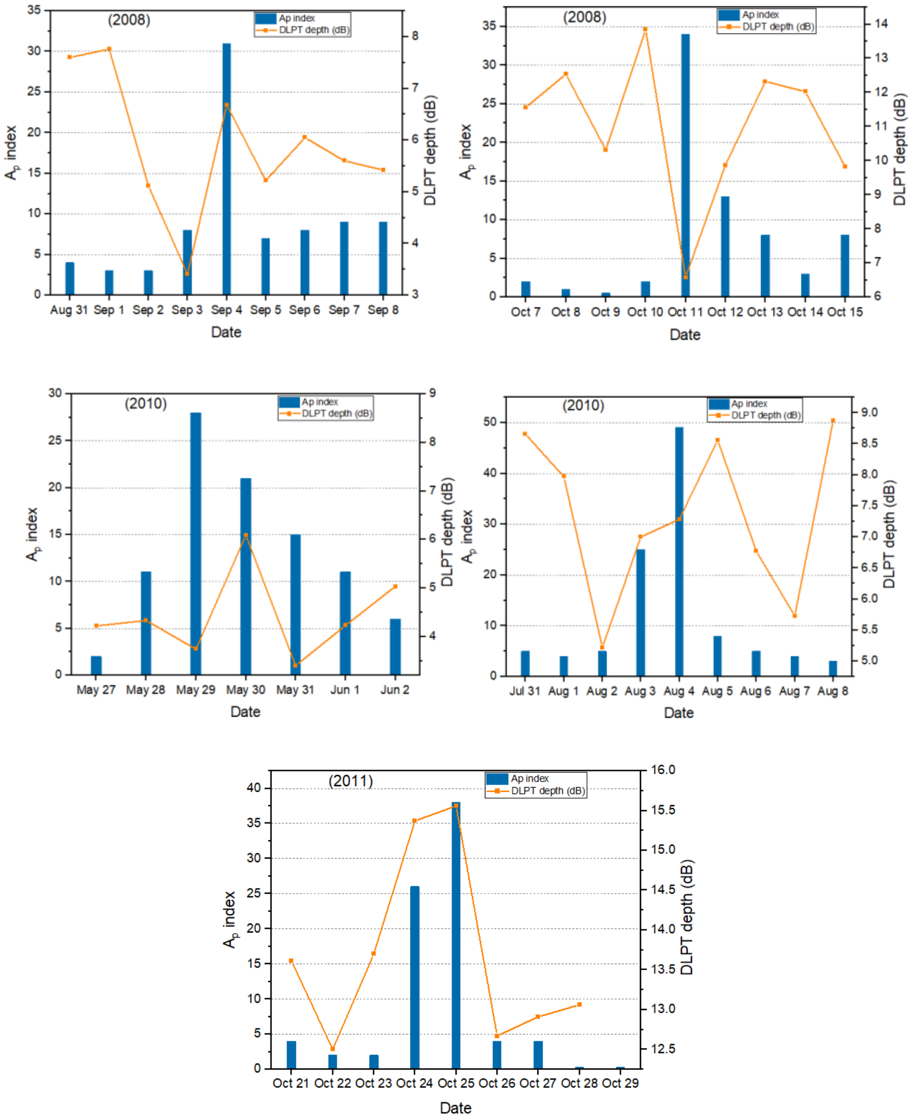

Figure 4. *Nine days variation of DLPT depth and Ap index values for all geomagnetic storms considered in the study.*

Figure 4 represents the variation of DLPT depth with bars and Ap index values with lines for all events. There was an increase in DLPT depth on the storm day for the September 2008 and October 2011 events, whereas there was an increase in the storm recovery period for the August 2010 and May 2010 events. Only for the October 11, 2008 storm, a dramatic decrease by 7dB was observed in DLPT depth

4. Discussion and Conclusions

The present paper investigated the effect of geomagnetic storms on the D layer of the ionosphere using the DLPT depth parameter of the VLF signal. The “primary storm effect” was observed on the DLPT depth parameter for three magnetic storms, but the “after-storm effect” was observed for the remaining two storms. Clilverd et al. (Clilverd 2008) found that phase advance on signal recorded at mid-latitudes is associated with magnetospheric substorms. They suggested that the phase advance is related to triggering energetic electron precipitation during the substorm, concerning electromagnetic ion cyclotron (EMIC) wave-particle interaction. Additionally, the cause of the after-storm effect at mid-latitudes is the loss of energetic electrons from Earth's radiation belt during the recovery phase of the storm (Spjeldvik et al., 1975; Larsen et al., 1976).

In this study, DLPT depth showed an increase for all geomagnetic storms, apart from one storm. An increase in DLPT depth resulted from decreased amplitude during the morning terminator with respect to the previous day. This depression of amplitude can be related to a storm-induced increase in electron concentration of the D-layer, which is to say more electron-molecule collisions and consequently leads to absorption of the signal. In the previous works, researchers discussed geomagnetic storm effects on DLPT depth. Kumar and Singh (Kumar 2018) studied a severe geomagnetic storm effect on the D region for the mid-equatorial-low path using VLF signals transmitted from GBZ and NWC transmitters. They observed that DLPT shows an increase during the recovery phase of the storm. Naidu et al. (Naidu et al., 2020) investigated the change of DLPT depth during intense magnetic storms for mid-latitude path and observed an increase in DLPT depth on the storm day, except for one event. They explained that an increase in DLPT depth could be due to a reduction in the reflection height of VLF waves resulting from the enhanced electron concentration of the D layer. Nevertheless, from the study of DLPT depth variation for low-latitude path, Choudhury et al. (Choudhury et al 2015) reported that during long-duration geomagnetic storms, DLPT depth decreases due to decreased day-night asymmetry caused by increased electron density.

Obtained results showed that the response of the D region to geomagnetic storms varies from storm to storm. We will investigate separately the influence of geomagnetic storms on the D region originating distinct solar and interplanetary sources in the near future.

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