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St. Patrick's day geomagnetic storm effect on mid-low-equatorial D-region ionosphere using very low-frequency radio waves

Ajeet K. Maurya*(1), Rajesh Singh (2)
(1) Department of Physics, Banaras Hindu University, Varanasi, India, email: ajeetphoton09@gmail.com
(2) Dr. K S K Geomagnetic Research Lab, IIG, Allahabad, India

Abstract

The amplitude of VLF signal is sensitive to change in the D-region electrical conductivity; hence the VLF diurnal signal suggested showing an imprint of space weather disturbances in the D-region. In this work, an attempt is made to study the dynamics of St Patrick 's Day severe geomagnetic storm of March 2015 using VLF diurnal signal under varying solar and geomagnetic conditions. We have used two VLF transmitter signals GBZ (19.6 kHz; L=2.38) from the Great Britten and NWC (19.8 kHz, L=1.42) from Australia recorded at low latitude station Allahabad (L=1.15), India. The D-region preparation time (DLPT), D-region evolution time (DLET), D-region reduction time (DLRT) and D-region disappearance time (DLDT) are the proposed diurnal VLF signal anomalies as the potential candidate to detect geomagnetic disturbances in the D-region. We have found that the general behavior of VLF diurnal anomalies reflects the storm effect on various time scales. In particular, DLPT and DLET show significant effect during the recovery phase. The DLRT and DLDT are effectively following storm main phase and show pronounced increase. The DLPT, DLET and DLRT also showed prolonged recovery and recovered on 28th March (3 days after storm recovery) whereas DLDT recovered before storm recovery. Significant increase is seen on a particular day in all parameters, which could be associated with solar flares caused D-region changes. The storm was associated with many flare events. The DLPT and DLET for NWC signal exhibit prolonged peaks which could be propagation path dependent.

1. Introduction

D-region (~60-90 km altitude) of the ionosphere is an important region for a sun-earth relationship. Because of its sandwich location between atmosphere and ionosphere, it plays an imperative role in atmosphere-ionosphere coupling processes [1]. Likewise, this region is also significant for the radio wave propagation, navigation, submarine communication, weather, climate and space weather processes [2]. Despite its important role, D-region remained relatively unexplored due to its low altitude and electron density, which hinders the use of traditional methods (e. g. Ionosonde, GPS etc) for ionospheric probing [1, 2]. The very low frequency (VLF: 3-30 kHz) waves from lightning discharges or powerful navigational transmitters are reflected from the lower boundary of the D-region ionosphere, and travel very long distances in the Earth-ionosphere waveguide with a very little attenuation. This property makes VLF waves one of the most important tools to study the ionosphere in the height range of ~ 60-90 km (the D-region). The space weather events can have adverse effects on the increasingly sophisticated ground and space-based technological systems as well as on the communication [2]. There are two major drivers of space weather events: Solar flares and geomagnetic storms. Solar flares affect the entire daytime ionosphere, whereas geomagnetic storms mainly affect the high-latitude ionosphere with their effects propagating toward the lower latitudes up to equatorial latitudes. The effect of solar flares on the D-region is well studied by many previous workers because of their pronounced effect (sudden increase) on the daytime VLF signals. But the geomagnetic storm effect on the VLF propagation characteristics, especially at low and equatorial latitudes, is still remained unknown.

In past few attempts have been made to study storm effect on VLF signal at mid and high latitude [3]. Kleimenova et al. (2004) [3] reported negative phase and amplitude variation of the VLF signal during the day but more pronounced effect during the night for low-mid latitude path. Recently, Choudhury et al., (2005) [4] performed correlation study between geomagnetic storms effect and VLF signal during the ionospheric sunrise time (also known as D Layer Preparation Time (DLPT) depth) for the low-equatorial path. They have reported a negative correlation between DLPT depth and A_P index of geomagnetic storm. But their study was based on minor storms. Thus, geomagnetic storm associated changes in D region parameters and its response to major to severe geomagnetic storms are still unknown.

The St. Patrick's day geomagnetic storm of March 17, 2015, is one of the severe (max Dst = -223 nT) storm of current solar cycle 24. Further, since each storm is unique in the sense that it is characterized by strength, shock impact orientation and duration of southward interplanetary magnetic field (IMF) Bz, geo-effectiveness of these storms in terms of ionospheric response are also distinctive. Thus this storm provided with an opportunity to test the hypothesis of storm effect on the subionospheric VLF signal and improve our understating of storm time dynamics over mid-low-equatorial latitude D-region ionosphere. This work utilizes various section of a diurnal variation of VLF transmitter signal at Indian low latitude station Allahabad.

2. Dataset and analysis

The VLF signal are routinely recorded with Stanford University developed Automatic Weather Electromagnetic System for Observation Modeling and Education (AWESOME) VLF receiver installed at a quiet location near Allahabad (geographic lat. 25.41N, long. 81.93E; geomagnetic lat. 16.05 N, long. 153.70 E, L = 1.15), India [5]. The Local Time (LT) of Allahabad is Universal Time (UT) + 5.5 hr. The detailed map of Indian low latitude receiving station, VLF transmitters GBZ and NWC along with Transmitter Receiver Great Circle Path (TRGCP) is shown in Figure 1. The receiver is capable of recording both narrowband and broadband VLF signals. The frequency response of the AWESOME VLF receiver is 300 Hz to 47.5 kHz [5].

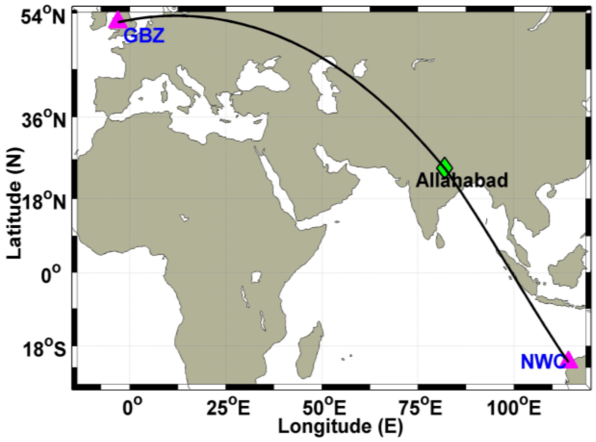

Figure 1: Depicts the receiving station Allahabad (L=1.15), two VLF transmitter locations, GBZ (L=2.38) at mind latitude and NWC (L=1.42) low-latitude.

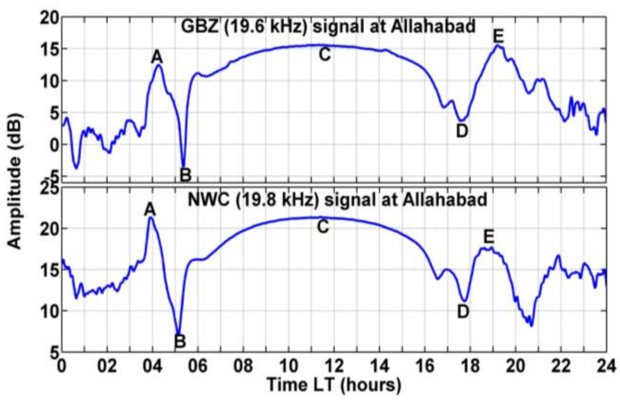

Figure 2: The upper panel GBZ (19.6 kHz), the lower panel NWC (19.8 kHz) amplitude variation at Allahabad. The Points A to E is the Sunrise Maxima, Sunrise Minima, Afternoon Maxima, Sunset Minima, and Sunset Maxima respectively.

Depending on data availability during the analysis period, we have chosen two transmitters GBZ (19.6 kHz, Geog. Lat. 54.91 N; Geog. Lon. 3.27 W; Geom. Lat. 57.07 N, L=2.38) from the Great Britten and NWC (19.8 kHz, Geog. Lat. 21.82 S; Geog. Lon. 114.17 E; Geom. Lat. Geom. Lat. 31.30 S, L=1.42) from Australia for the present analysis. The TRGCP between GBZ-Allahabad-NWC covers the mid-low-equatorial region.

The St. Patrick's day geomagnetic storm begins approximately 04:45 UT on 17th March 2015, when a double-halo CME hits the Earth's magnetic field. Initially, the IMF Bz went northward turning for a while, indicating storm sudden commencement (SSC) before turning southward. The storm reached its peak at ~00:00 UT on 18th March 2015 with minimum Dst ~ -228 nT. The storm characterized as intense category (-200 ≤ Dst<-100 nT). The details of interplanetary and geomagnetic conditions of this storm can be found in many previous works [6].

A typical clear diurnal variation of NWC and GBZ VLF signal on a geomagnetically quiet and fair weather day recorded at Allahabad is shown in Figure 2. The diurnal variation clearly shows sun's influence. As the sun rises and sets, the ionospheric electron density along the transmitter-receiver path changes, and so too does the VLF amplitude. At night, with the sun gone, the electron density is highly variable, which changes VLF propagation conditions rapidly. We have marks points A–E on the diurnal variation of VLF signal in Figure 2, which typically represents, Sunrise Maxima, Sunrise Minima, Afternoon Maxima, Sunset Minima, and Sunset Maxima as discussed by many workers [4, 7]. From the Figure 2, we designate the change in time from the points from A to B as "D Layer Preparation Time (DLPT)" and the corresponding change in decibel as "DLPT depth". The change in time between points B to C as D Layer evolution time (DLET), and from C to D as D Layer Reduction time (DLRT) and from point D and E is designated as "D-Layer Disappearance Time (DLDT)" and the corresponding change in decibel as "DLDT depth." The All four VLF diurnal anomaly parameters (VDAP) show a seasonal variation with the changing position of the Sun. We have used 30 days VLF data starting from 10 March to 10 April 2015. There are few days with no data when the transmitter was turned off.

3. Observational results
3.1 Mid-low latitude path

The Figures 3 shows daily mean variation of Ap and Dst index along with a daily variation of VLF diurnal anomalies parameters (VDAP) DLPT, DLET, DLRT and DLDT during 10 March to 10 April 2015 after subtracting each day from the mean of five international quiet days for each transmitter signals. It is interesting to see that the Ap index average show peak on 17^{th} March, (on storm day), whereas Dst average peak is on 18^{th} (the day after the storm). This is probably because of daily average mean, which increases mean on recovery day for Dst Index.

The DLPT, initially show normal variation up to 19th March, on 20th March a significant peak is visible. Further, starting from 21st March, an increasing trend is visible which become normal on 28th March. The DLET shows similar variation as of DLPT except for one prolonged peak on 17th March. The DLRT and DLDT show similar variations. Both parameters show a peak on the storm day followed by decreasing trend during recovery days. The DLRT showed long recovery (recovered fully on 28th March), whereas DLPT has fast recovery (recovered on 22 March).

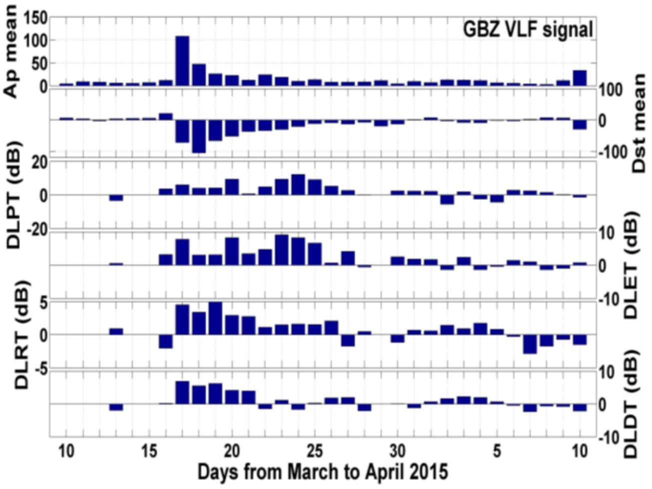

Figure 3: Showing the Ap mean, Dst mean along with DLPT, DLET, DLRT and DLDT parameters of GBZ (19.6 kHz, L=2.38) VLF diurnal signal during 10 March to 10 April 2015.

3.2 Low-equatorial latitude path

Figure 4 (similar as Figure 3) shows VLF diurnal anomaly parameters for NWC signal along with Ap and Dst daily average variations during 10 March to 10 April 2015.

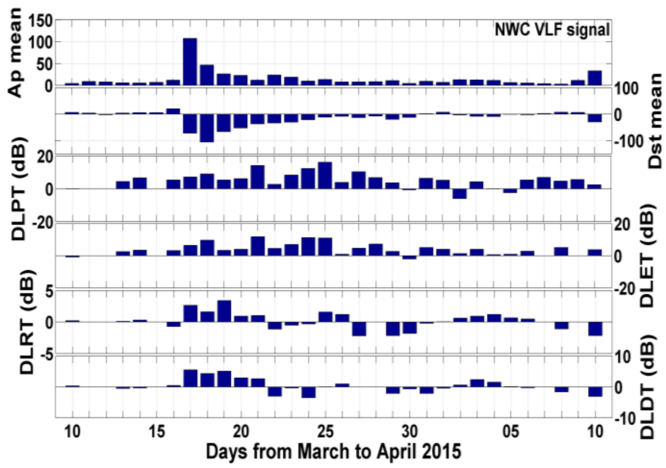

Figure 4: Showing the Ap mean, Dst mean along with DLPT, DLET, DLRT and DLDT parameters of NWC (19.8 kHz, L=1.42) VLF diurnal signal during 10 March to 10 April 2015.

The DLPT though showing more day to day fluctuations, the still trend of variation is clear. Starting from 10 with data gap on 11 and 12 shows normal trend up to 20th March, A significant peak is visible on 21st March. Further, starting from 22nd March, an increasing trend is visible which become normal on 28th March. A similar trend is seen for the DLET. For DLRT and DLDT, a significant increase is seen on the 17th March, which recovered on 22nd March.

In both cases, DLPT and DLET show pronounced effect during the recovery phase of storm whereas, DLRT and DLDT show effect during the main phase. The recovery for DLPT, DLET and DLRT completes approximately on 28th of March (3 days after storm recovery) whereas DLDT recovers on 22nd March, 3 days before storm recovery.

4. Discussion

Equations In the present work, we have attempted to study a severe geomagnetic storm effect on the D-region of the ionosphere using VLF signals passing through the mid-low-equatorial regions. The storm effect on the D-region remained not well understood probably due to the relative scarcity of investigations. Few previous works [4, 7] have attempted to study D-region by utilizing VLF signal anomalies. But their work is limited only to pure high and low latitudes. Further, Choudhury et al., (2015) [4] studied only one parameter DLPT depth during minor storms. We have used four unique parameters DLPT, DLET, DLRT and DLDT to study storm effect in the D-region.

The present observations revealed many new findings of effect of the severe geomagnetic storm on the D-region. For the first time storm effect simultaneously on mid-low-equatorial latitude path is being studied. The clear storm effects are observed on both mid-low latitude path and low-equatorial path. The effects are more pronounced in the mid-low latitude path. The DLPT and DLET parameters (from morning and forenoon sectors of diurnal variation of VLF signal) show storm effect during recovery phase or in other words, they represent negative correlation with Ap and-and Dst Index of the storm. The DLRT and DLDT parameters (during afternoon and evening sectors of diurnal variations of VLF signal) show a significant increase during storm main phase or represent positive correlations with Ap and Dst indices. The DLPT, DLET, and DLRT show prolonged recovery (3 days after storm recovery on 25th of March).

The increase in VLF diurnal anomalies parameters (VDPA) represents the decrease in VLF signal amplitude. The observation suggests that the decrease in the VLF signal amplitude is most possibly associated with the St. Patrik's day storm associated absorption on the D-region. The absorption of VLF signals due to increase in D-region electron density caused by various processes related to storm interpreted as the main processes of the decrease in VLF signal. The high and mid-latitude D- region of the ionosphere has been reported to be disturbed due to storm-induced energetic electron precipitation (EEP), which increases electron density in this region [8]. But the EEP is very unlikely to happen for low-equatorial latitude path. At the low-equatorial latitudes, prompt penetration of the high-latitude/Auroral electric fields to low latitudes during the main phase of the storm [2] is considered main source of D-region disturbance. The electric field could modify the ExB drift, causing an increase in D-region electron density. Another possible factor for D-region electron density increase is suggested by gravity waves generated during a storm at the auroral region by the auroral electrojet and Joule heating and can propagate from high latitude to mid-latitude or even to the equatorial latitudes. For GBZ-Allahabad TRGCP (mid-low latitude path), combined effect of both EEP and ExB drift could be responsible for observed effects. Whereas, for NWC-Allahabad TRGCP (low-equatorial path), only ExB might be enough to explain observed effect.

The observed long duration recovery of VLF signal or also called as "storm after effect". Spjeldvik and Thorne, (1975) [9], suggested that precipitation loss during the storm recovery is the major sources of the storm effect at the mid-latitude. A typical poststorm electron precipitation can increase D-region electron density by few orders, thus affecting VLF signal propagation during the recovery phase of the primary storm. Thus, results in an enhanced D region ionization persistent for a few days following the storm. At the low latitudes, as suggested by [10], change in the ExB drift due to prompt penetration of high-latitude electric field, to low latitudes could contribute significantly to the observed VLF signal changes during the storm. Kumar et al., (2015)[2] from the analysis of storm effect on purely low latitude path, suggested D-region composition perturbations created by prompt penetration field, recovers slowly, resulting in a long recovery in low latitude. Hence long duration storm recovery at low-equatorial latitudes could probably arise from the slow recovery of storm-associated ionization changes or redistribution due to slow molecular diffusion at D region altitudes. Further, the observed DLPT and DLET prolonged increase during storm recovery phase could be associated with slow D-region diffusion.

The DLRT and DLDT show pronounced effect starts during the main phase, which suggests that increase of D-region ionization starts along with the storm main phase. This highlights the role of prompt penetration of electric field, from high latitude to low latitude which propagates with speed of light and could show an effect even during the main phase. The observations also suggest that prompt penetration electric field is more effective during evening time than the morning time. The significant peak seen on few days is most probably associated with solar flares. As this storm also accompanied with many solar flare events ranging from C to X class, the flare induced the effect in the VLF signal are another possibility for significant peak [11]. The storm effect in the D region seems to be more complicated and required more such study using simulation. We planned such work in near future.

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