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Prompt Penetration Electric Field and the Ionospheric Effects of Major Geomagnetic Storms in Low Latitude Stations

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***Abstract* - The effect of prompt penetration electric field of high latitude origin during geomagnetic storms on total electron content (TEC) has been analyzed using GNSS data. The major storm events that occurred in 2015, with particular emphasis to events on 17 March, 22 – 23 June and 5 July was the subject of consideration. The storms started with Storm Sudden Commencement (SSC) and happened during the daytime of about 06:00, 19:00 and 16:00 UT respectively. The effects of penetration electric field during the main phase of the storms was evidence in the low latitude TEC data, as it resulted in the enhancement in TEC in Cotonou and Addis Ababa and subsequent uplift of F-layer. The penetration of electric field to Lagos low latitude resulted in depletion of TEC during the day and night enhancement. The variations in TEC were dependent on time of the day, location and the time of occurrence of the storm. Addis Ababa recorded the highest variation in TEC, followed by Cotonou station. Lagos low latitude consistently recorded the least variations in all the days considered.**

Keywords: Electric Field, Geomagnetic Storms, Low-Latitude Ionosphere, Total Electron Content.

I. INTRODUCTION

The modern society is becoming ever increasingly dependent on space technology for daily routine functions, such as communication, navigation data transmission, global surveillance, e.t.c. The Ionosphere however is that part of space environment that affects space borne and ground based technological systems. The variations of ionospheric parameters during geomagnetic storms are very complex phenomena and not yet fully understood. Continuous investigation, especially the low-latitude ionosphere where complexities have been recorded due to Equatorial Ionization Anomaly (EIA), Equatorial Electro jet (EEJ) and the likes, is required. Geomagnetic storm is a temporary disturbance of the earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field. The interaction of the Earth's magnetic field and Solar wind magnetic field causes an increase in movement of plasma through the magnetosphere and an increase in electric current in the magnetosphere and ionosphere.

According to Sugiura and Kamei (1991), the disturbance in the interplanetary medium which drives the geomagnetic storm may be due to a solar coronal mass ejection or a high speed stream of the solar wind originating from a region of weak magnetic field on the Sun's surface.

In this work, the GPS data from three low-latitude stations has been analyzed to ascertain the effects of prompt penetration electric field on ionospheric total electron content. The result will be helpful to monitor for possible space weather impacts in low latitudes.

II. METHODOLOGY

Total electron content (TEC) data were obtained from GPS NovAtel GSV4004B receivers located at Addis Ababa, Ethopia (GeographicLat. 8.98^{o}N, Long. 38.76^{o}E), Cotonou, Benin (Geographic Lat. 6.37^{o}N, Long. 2.39^{o}E) and Lagos, Nigeria (Geographic Lat. 6.52^{o}N, Long. 3.38^{o}E). The GPS SCINDA is a real-time GPS data acquisition and ionospheric analysis system, and computes ionospheric parameters of TEC among others, using the full temporal resolution of the receiver.

The TEC is computed from the combined L_1 (1575 MHz) and L_2 (1228 MHz) pseudo ranges and carrier phase. The differential instrumental bias was removed to ensure accuracy of the estimated ionospheric TEC (Sardon, *et al.*, 1994).Also, the TEC data obtained was the slant TEC (STEC), which is dependent on the ray path geometry through the ionosphere.

It is therefore desirable to calculate an equivalent vertical value of TEC, which is independent of the elevation of the ray path. This is best done by taking the projection from the slant to vertical using a thin shell model, assuming a height of 350 km following the techniques given by Klobuchar (1986).

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$$VTEC = STEC \times Cos[Sin^{-1}\left(\frac{R_E \ Cos\ e}{R_E + h_{max}}\right)] \quad (1)$$

Where the radius of the Earth, R_e = 6378km, the height to the pierce point, h_{max} = 350km, and e = elevation angle at the ground station, as depicted in Fig. 1.

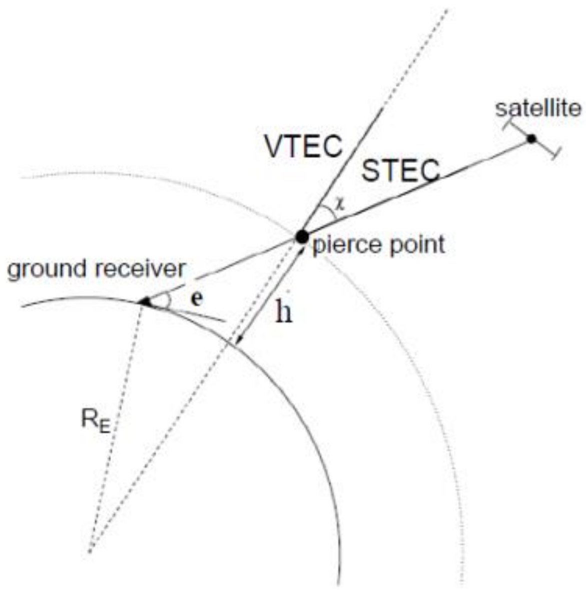

Figure 1: Geometry for the conversion of slant TEC to vertical TEC

The analysis of the TEC data from the three stations was carried out using the GPS-TEC analysis application software developed by Gopi Semeela. The application gives plots of vertical TEC on the screen and writes ASCII output files which are used for further analysis of the data. It calculates TEC from the observation data of GPS Rinex, Novatel (reads only ID43 records), SCINDA (scn files) and Leica binary files.

The magnetospheric indices of Dst and Kp for the identification and classification of storm events are obtained from World Data Center (WDC) for Geomagnetism, Kyoto, Japan. The Dst values show the hourly Equatorial Dst values and represents the signature of magnetopause electric currents during the compression phase of magnetic storm and that of the ring current during the main phase and the recovery phase of a storm. The Kp index in the other hand quantifies geomagnetic disturbances in the horizontal component of earth's magnetic field. It provides a measure of the general level of geomagnetic activity and is used as an indicator of electrodynamics in the post-sunset equatorial ionosphere. The interplanetary magnetic field (IMF-Bz) and solar wind plasma speed (Vp) data were obtained from OMNI Web of National Aeronautics and Space Administration (NASA).

III. RESULTS AND DISCUSSION

3.1 Classification of Geomagnetic Storms

The major geomagnetic storms that occurred in 2015 are classified based on their size and level of severity following Gonzale *et al*, 1994. The geomagnetic storms are grouped into two: intense and moderate storm as shown in Table 1.The geomagnetic indices of Disturbance storm time (Dst) and Planetary index (Kp) were used to identify and classify respectively the geomagnetic activities, with Dst_{min} values indicating the magnitude of the storms and the Kp values showing the severity of the storm. The values of ionospheric parameters of interplanetary magnetic field of z-component (IMF-Bz) and plasma speed (Vp) reveal the conditions of the ionosphere during the period under consideration.

3.2 Solar Interplanetary conditions during the Storms

Here, the plots of Dst, Kp, IMF-Bz and Vp are used to ascertain the severity of storms and the condition of the ionosphere before and after the storms, as well as during the three phases of the storm events. To investigate the condition of the ionosphere before, during and after the storms, the interplanetary condition for range of days to include the day of the storms are used.

Fig. 2 shows the solar wind parameters of IMF-Bz and plasma speed and the magnetospheric indices of Dst and Kp for the intense storm events during March 16 – 19 and June 21 – 24, 2015. The solar wind parameters describe the conditions of the ionosphere, while the magnetospheric parameters identify and measure the severity of the storms. For the storm events during March 16 – 17, the Dst plot shows a sudden decrease in value from about 50 nT at about 06:00 UT on March 17 to about -223 nT at about 22:00 UT on the same day. During the initial phase of the storms, the Dst values increased owing to the compression of the magnetosphere. The storm was preceded by storm sudden commencement (SSC), which was positive. During the main phase of the storms, the Dst value decreased, peaking at about -223 nT, relative to prestorm values. This decrease was because magnetic storms are associated with a southward interplanetary magnetic field, which allows for an efficient energy coupling of the solar wind and magnetosphere. It thereafter recovers more slowly. During the recovery phase, the Dst gradually increased to its prestorm value. This occurs because the source of the enhanced ring current subsides and the excess particles are lost via several different mechanisms. The Kp index that measures the severity of the storm indicates a moderate maximum value of about 77 during the main phase of storm.

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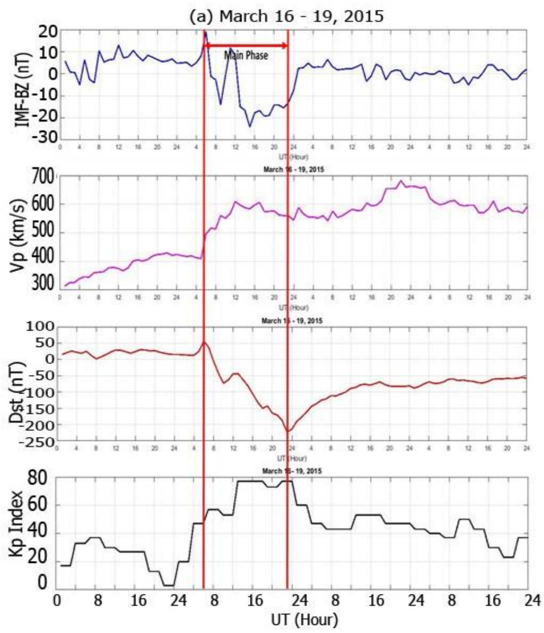
Table 1: The Major Geomagnetic Storms in 2015

Class	Day/Date	UT (Hour)	Dst_{min}(nT)	Kp index	Plasma Speed (km/s)	IMF-Bz (nT)
Intense storm(-250 <Dst< -100 nT)	76 (17 March)	22:00	-223	77	558	-12.3
	77 (18 March)	00:00	-190	60	588	2.5
	173 (22 June)	20:00	-121	83	630	12.1
	174 (23 June)	04:00	-204	77	703	-20.8
	280 (7 October)	22:00	-124	60	744	0.9
	354 (20 Dec.)	22:00	-155	63	415	-17.8
	355 (21 Dec.)	01:00	-148	67	414	-16.1
Moderate storm (-100 <Dst< -50 nT)	49(18 Feb)	00:00	-64	50	418	2.7
	55 (24 Feb)	07:00	-56	40	472	0.2
	61 (2 March)	08:00	-55	53	583	-1.1
	101 (11 April)	09:00	-75	33	346	-4.9
	106 (16 April)	23:00	-79	60	670	2.4
	186 (5 July)	05:00	-67	50	487	1.9
	204 (23 July)	07:00	-63	53	434	-9.3
	228 (16 August)	07:00	-84	57	506	-4.9
	239 (27 August)	20:00	-92	40	341	-8.2
	253 (9 Sept)	09:00	-94	10	415	0.7
	311 (7 Nov)	06:00	-89	60	599	-4.2

The main phase of the storm is characterised by the build-up of the intensified ring current by high energetic particle injection and energisation. The IMF-Bz turned sharply downward at about 06:00 UT on March 17 and attained a maximum negative value of about -15 nT at about 09:00 UT and thereafter turned northward to attain a maximum value of about 11 nT at about 10:00 UT. It descended again southward to attain a maximum negative value of about -25 nT at about 15:00 UT. This reveals both under shielding and over shielding condition during the main phase of the storm. The rapidly decreasing IMF-Bz causes the sudden increase in polar cap potential, resulting in the generation of sudden region-1 currents.

The region-2 currents cannot respond at the same rate. Thus, the high latitude electric potential, normally shielded by the region-2 currents, then reached much lower latitudes (Peymirat *et al*., 2000). The under-shielding results in prompt penetration of interplanetary electric fields to low latitudes and equator. However, after a steady southward configuration, the IMF-Bz turns northward again and the over-shielding condition occurs. In this case, the existing region-2 electric field penetrates the equatorial and low latitudes (Kelly *et. al.*, 1979; Sastri *et. al.,* 1992a, b; Kikuchi *et. al.,* 2008).When there is a positive phase before the SSC, it implies compression in the field. This is an indication that the factors generating the positive phase have a bearing on the southward turning of the IMF-Bz. The sudden southward turning of the IMF-Bz from steady northward configuration produces a dawn to dusk convection electric field at high latitude.

The storm event during June 21 – 24 (Fig. 2) has similar features with that during March 16 – 18. Both over- and under- shielding conditions occurred during the main phase of the storm. The plasma speed was as low as about 400 km/s during the SSC and rose sharply attaining a maximum value of about 600 km/s during the main phase of the storm. It remained high even during the recovery period. The plasma speed rose from about 460 km/s, which marked the commencement of the storm to about 700 km/s, the end of the main phase of the storm. The Kp index maximum value was about 77 during the main phase, a Dst minimum of about -204 nT at about 04:00 UT was observed.



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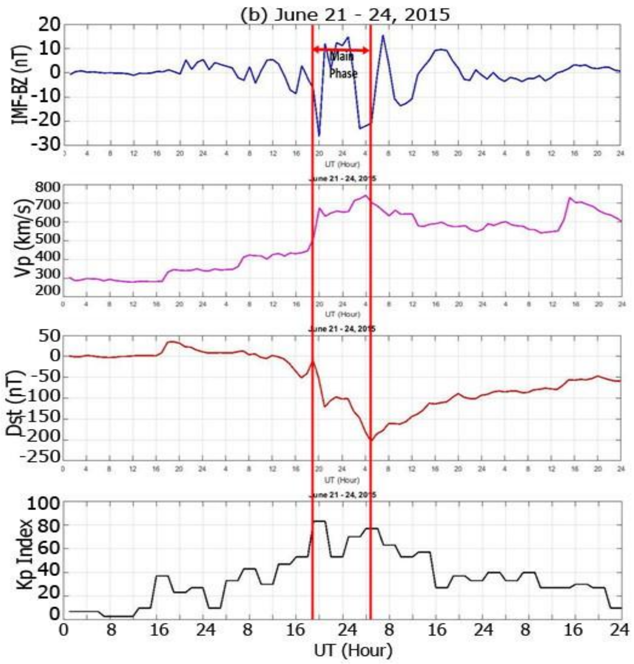

Figure 2: Interplanetary Condition during the Intense Storms on (a) March 16 -18 and (b) June 21 -24, 2015

Fig. 3 shows the moderate storm event on July 4 – 5. The storm started on July 4at about 16:00 UT and ended at about 05:00UT on July 5, with a minimum Dst value of about -68 nT. The Kp maximum value during the main phase of the storm was about 53, this means a moderate storm event. The plasma speed rose from about 475 Km/s from the commencement of the storm to about 570 Km/s during the main phase of the storm. There were numbers of storms during the main phase as evidenced from the Dst values. This was corroborated by the IMF-Bz plot during the main phase.

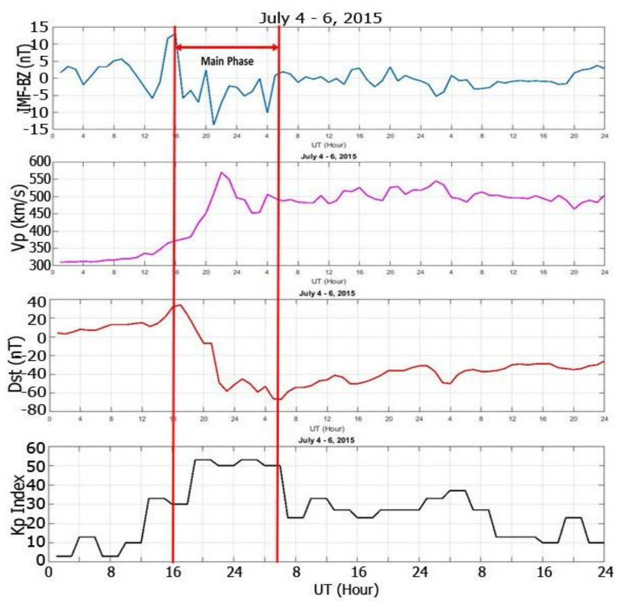

Figure 3: Interplanetary Condition during the Moderate Storm on July 5, 2015

3.3 Mean TEC variations during the Storm Events

Here, the mean diurnal TEC variations before, during and after the storms in the three stations are investigated to ascertain the effects of prompt penetration electric field on ionospheric TEC in the stations.

Considering the TEC variation during storms (Fig. 4), Cotonou and Addis Ababa stations perfectly exhibited the pattern expected of a low-latitude: TEC minimum at pre-dawn and gradual increase with the time of the day, attaining a maximum in the afternoon and a gradual decrease after sunset. However, Lagos low-latitude fails to adhere to this pattern in most of the days considered. In terms of TEC magnitude, Cotonou and Addis Ababa consistently recorded higher TEC during the daytime plateau than that in Lagos. In all the days considered, there was no much effect of storm on TEC variations, considering post- and pre-storm periods.

On 17 March storm event, there was no enhancement in TEC in Cotonu and Addis Ababa stations. The penetration electric field only resulted in multiple peaks in the two stations. In Lagos station, night enhancement in TEC was observed during the storms. This may be due to pre reversal enhancement which Galav *et al.*, 2010 attributed to variation of the vertical F region drift. They found this to be true for variations during Equinox season. This was not the case in this study, the enhancement was also observed during the summer month of June 22 – 23 storm events.

During the moderate storm events, observation showed that Lagos low latitude exhibited the pattern expected of a low-latitude, alongside the other two stations, unlike that observed during intense storms. Considering the July 4 – 5 storm events, there was enhancement in TEC in Cotonu and Addis Ababa, while depletion occurred in Lagos low latitude. Night enhancement in TEC was also observed in Lagos station. It can then be said that the occurrence of storm affects the expected pattern of Lagos low latitude, as it tends to assume the normal pattern when the storm is moderate and even goes better at quiet periods (Olatunbosun *et al*, 2019).

Still, the TEC magnitude in Lagos was consistently lower than that observed in Cotonou and Addis Ababa. Comparing the TEC magnitude in the two stations of Cotonou and Addis Ababa, Addis Ababa recorded highest TEC in all the days considered. The effect of storm on TEC variation was also minimal, as the days before and after storms was not too different from what was observed on the day of the storms.

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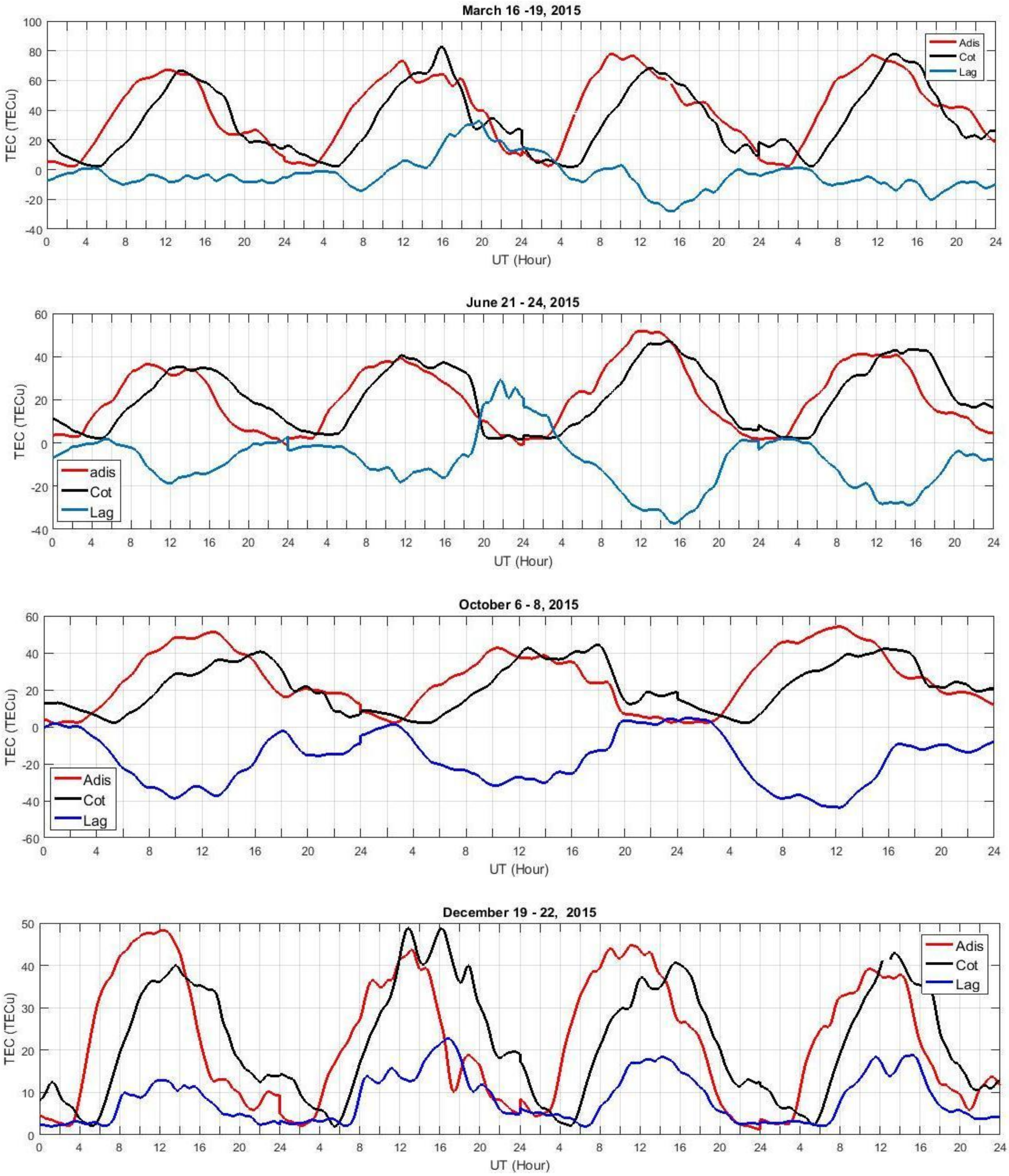
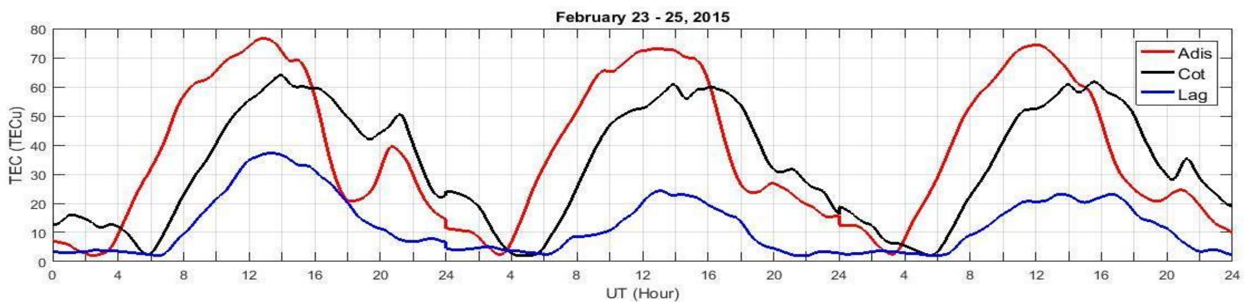


Figure 4: TEC Variation during Intense Storms: (a) March 16 – 19 (b) June 21 – 24 (c) Oct 6 – 8 and (d) Dec 19 - 22, 2015



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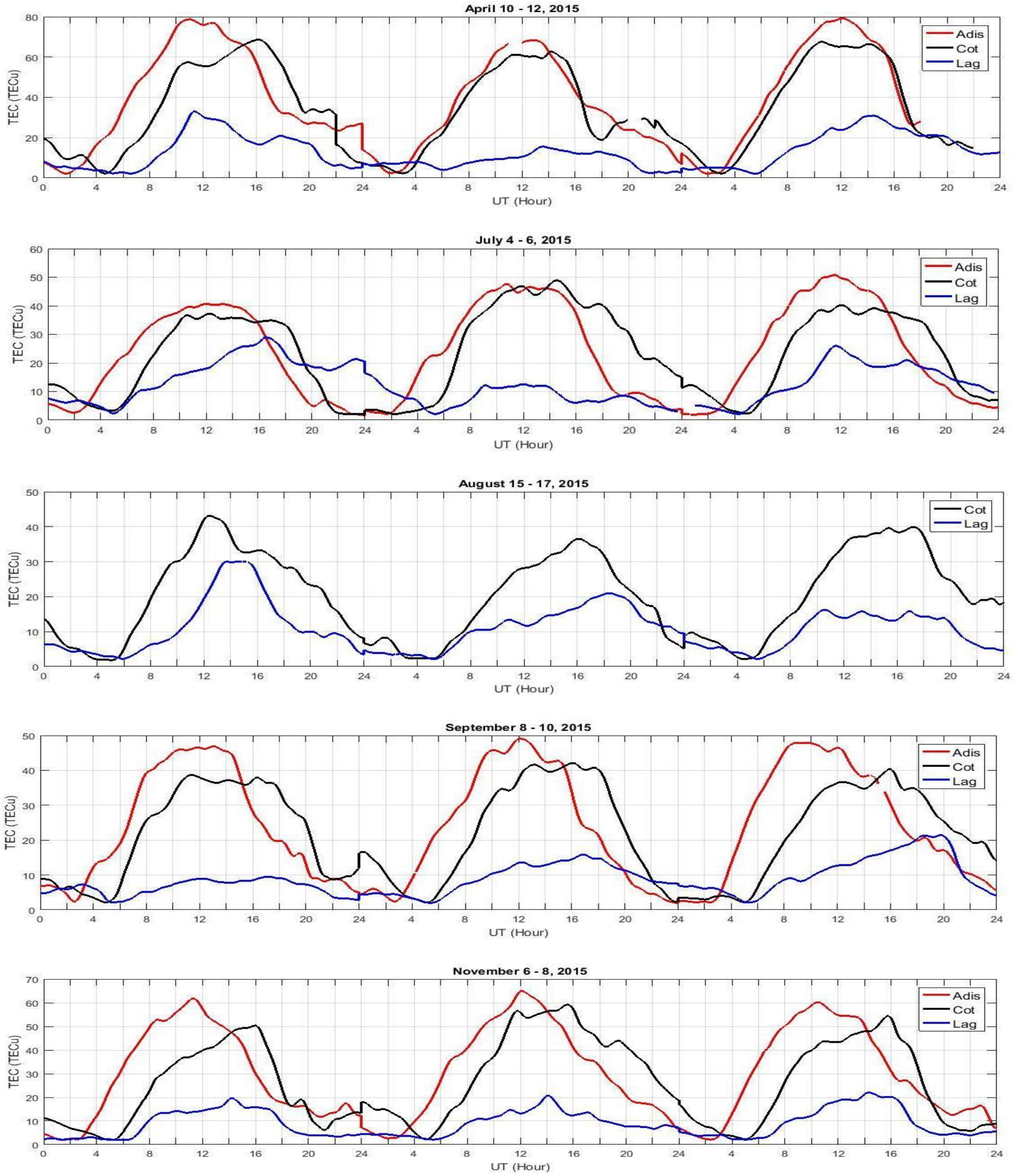

Figure 5: TEC Variation during Moderate Storms: (a) Feb 23 – 25 (b) Apr 10 – 12 (c) Jul 4 – 6 (d) Aug 15 – 17 (e) Sep 8 – 10 and (f) Nov 6 – 8, 2015

IV. CONCLUSION

In this study, GPS data from three independent stations located within the EIA region has been used to study the effects of prompt penetrate ionelectric field on TEC variations. Results showed that there was significant role played when there is prompt penetration electric field of high latitude origin into the low latitude ionosphere. From the three stations considered, disparities were observed in their ionospheric response to the prompt penetration electric field. The ionospheric responses of Cotonu and Addis Ababa are very much similar, while Lagos station responded differently. The penetration electric field into the low latitude caused the ionospheric TEC in Lagos to deplete during the day and get enhanced during the night. Also, when the storm is intense, Lagos station fails to exhibit the pattern expected of low latitude. In Cotonu and Addis Ababa, there was no significant enhancement, nor depletion in TEC as a result of the prompt penetration; rather it resulted to multiple peaks.

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The findings in this work further suggest and confirm the complexities of the EIA morphology. The low latitudes of Lagos and Cotonu are very close to each other, yet respond to effects of storms in entirely different ways.

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