Indian Journal of Radio & Space Physics
Vol 44, September 2015, pp 138-146

GNSS positioning accuracy over Nigeria during geomagnetic storm of 24-27 October 2011 and 7-10 October 2012

Omojola Joseph[$,*] & Abimbola Oladiran Johnson

Department of Physics, Federal University Lafia, P M B 146, Lafia, Nigeria

[$]E-mail: omojola.josef@gmail.com

Received 6 April 2015; revised 6 July 2015; accepted 20 July 2015

The present work investigates the positioning error of five Nigeria GNSS network stations during the geomagnetic storm of 24-27 October 2011, a sudden storm commencement (SSC) with disturbance storm time (Dst) minimum of -134 nT; and 7-10 October 2012, a gradual storm commencement (GSC) with Dst minimum -105 nT. Satellite data were obtained from Nigeria GNSS network stations and Dst values were obtained from World Data Center (WDC) for Geomagnetism Kyoto, Japan while the quiet period was selected with Ap index of zero (0) and one (1) for the two storms, respectively from the same World Data Center. RTKLIB (version 2.4.2), a GNSS analysis software, was used to determine the positioning of the stations during the selected storm period and quiet period and the results were analyzed using MATLAB. This investigation revealed that during the selected storm period, the positioning error of the stations increase; though the two storms do not show the same characteristics on GNSS positioning. The GSC of 7-10 October 2012 showed a latitudinal effect, which may be as a result of local variation in the electron density and enhancement of ionospheric irregularity during the storm. This was not clearly depicted in the SSC of 24–27 October 2011.

Keywords: Positioning error, Geomagnetic storm, Disturbance storm time

PACS Nos: 94.20.Vv; 95.40.+s

1 Introduction

Global Navigation Satellite Systems (GNSS) is a generic name, which refers collectively to all the satellite navigation systems being developed around the world, namely Global Positioning System (GPS) of the United States of America, the Global Orbiting Navigation Satellite System (GLONASS) of the Russian Federation, GALILEO of the European Union, and COMPASS/BeiDou of China[1]. Two of these systems, namely GPS and GLONASS are fully developed and are already providing services.

GNSS has become part of all applications, where mobility plays an important role. This technology has a wide spread of applications in Automatic Vehicle Location (AVL), tracking systems, Pedestrian Navigation Systems (PNSs), intelligent transportation systems, ionosphere study, precise positioning, navigation and emergency callers. Positioning and timing also play critical role in telecommunications, land surveying, law enforcement, emergency response, precision agriculture, mining, banking, and space research. GNSS signals propagate through the ionosphere and are affected by its dynamism.

A geomagnetic storm is a temporary disturbance of the earth's magnetosphere caused by adverse space weather associated with solar activity[2]. The dispersive nature of the ionosphere results in phase advances and group delay of radio wave propagating through it, thereby, inducing range error in positioning and navigation. Nigeria falls within the equatorial anomaly region (between 0° and 20° latitude on either side of the geomagnetic equator). The equatorial ionosphere behaves very differently under different solar, geomagnetic, and atmospheric conditions[3]. Geomagnetic storms induce plasma redistribution and large scale disturbances in the equatorial ionosphere, which increases GNSS positioning error.

This study investigates the positioning error by estimating the error in the five Nigeria GNSS stations during the storm period and the selected quiet day as reference for comparison. The two storms chosen for this study occur in the same season though not in the same year; both the storms are of class I type according to standard classification[4].

The observed variation in the effect of the storms on GNSS positioning could be as a result of the nature of the two storms over the stations. The present work supplements the existing knowledge on the dynamism of the equatorial ionosphere of African sector and also helps in better prediction of positioning accuracy for GNSS users in this region.

2 Experimental Procedure and Method

2.1 Research data

Five (5) GNSS stations in Nigeria have been selected for the study. The selected storms can be classified as intense. Standard nomenclature for intense storms usually has disturbance storm time (Dst index) minimum or less than -100 nT (Ref. 4). The Dst index data for storm period was downloaded from World Data Centre for Geomagnetism (WDC) Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/dst), which was corroborated by the international quiet day (IQD) and international disturbed days (IDD) data from Geosciences Australia website (www.ga.gov.au/oracle/geomag/igd_form.jsp).

Daily RINEX file data for the selected quiet day and storm days were downloaded from Nigeria GNSS stations website (http://server.nignet.net/data). The stations are located in Nigeria as shown in Fig. 1 are: Zaria (ABUZ), Birnin-Kebbi (BKFP), Abuja (OSGF), Lagos (ULAG), and Enugu (UNEC). The five stations have a known International Terrestrial Reference Frame (ITRF) coordinates (Tables 1 and 2).

All the stations are fixed with TRIMBLE NETRS receiver (Table 2). The stations receive both the GPS and GLONASS signals through their TRM59800.00 antenna. More information on the Nigerian GNSS network is available at http://www.nignet.net.

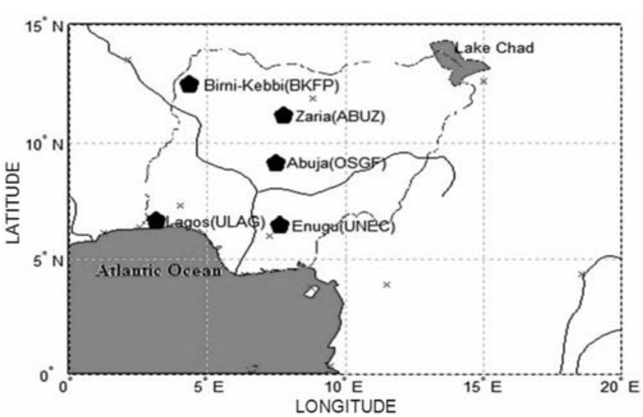

Fig. 1 — Map of Nigeria showing the stations coordinates

2.2 Data analysis

Real Time Kinematic Library (RTKLIB) software version 2.4.2 (2013) was used in the analysis to compute the positioning errors for both the storm and quiet period. RTKLIB is an open source program package, which supports standard and precise positioning algorithm for GNSS systems. It can run on various positioning modes and supports several GNSS proprietary messages (NovAtel, Superstar II, OEM3, etc.)[5]. RTKLIB also supports many standard formats and protocols, like RINEX 2.10, 2.11, 2.12; IONEX, ANTEX, RINEX 3.01, 3.02, etc. RTKLIB can be used both in real time positioning and post processing positioning estimation. Several authors have validated the usefulness and accuracy of RTKLIB in the real time and post processing analysis of GNSS positioning[5,6].

The positioning output of RTKLIB was analyzed using MATLAB software. MATLAB was used in the analysis of the 30 seconds epoch by epoch 24 hourly post processing data of the RTKLIB to determine the average and the instantaneous positioning error over the stations during the storm period and the quiet period.

Since the International Terrestrial Reference Frame (ITRF) position of the stations used in this study are

Table 1 — ITRF coordinates of the selected stations (m)

Stations	Coordinates, m
ABUZ	X:6203493.8286
	Y:833088.6899
	Z:1225614.6117
BKFP	X: 6211960.3543
	Y:459365.4671
	Z:1368115.0245
OSGF	X:6246471.2622
	Y:820848.7319
	Z:994267.9084
ULAG	X:6326097.3068
	Y:375576.0951
	Z:719131.6690
UNEC	X:6284298.3153
	Y:827900.5052
	Z:708988.5652

Table 2 — Latitude, longitude and receiver type of the selected stations

Station	Latitude	Longitude	Elevation (m, ellipsoid)	Receiver type
ABUZ	+11°09′06″.02632	+007°38′55″.02740	706.1	TRIMBLE NETRS
BKFP	+12°28′06″.08757	+004°13′45″.02713	251.0	TRIMBLE NETRS
OSGF	+09°01′39″.05965	+007°29′10″.08300	533.6	TRIMBLE NETRS
ULAG	+06°31′02″.03751	+003°23′51″.04439	45.5	TRIMBLE NETRS
UNEC	+06°25′29″.03010	+007°30′17″.09682	255.4	TRIMBLE NETRS

known, it is easier to compare the coordinates with the ones obtained during both the quiet period and geomagnetically disturbed period. The positioning output of each epoch was subtracted from the given ITRF position of the stations for the selected storm and quiet period to determine the positioning error of the stations for both the storm period and the selected quiet day chosen as reference. The average percentage error was then computed using Eq. (1) below.

$$Percentage\ error = \frac{|error|}{ITRF\ \ Coordinate} \times 100 \qquad \ldots (1)$$

2.3 Storms description

The storm of 24–27 October 2011 (Fig. 2) started with sudden storm commencement on 24 October 2011 at 24:00 hrs UT. This was followed by initial phase, which lasted for 3 hours (i.e. 25 October between 01:00 and 02:00 hrs UT). The main phase occurred on 25 October with minimum Dst of -134 nT at 02:00 hrs UT. The recovery phase commenced on 26 October through 27 October.

The storm of 7-10 October 2012 (Fig. 3) was a two step gradual storm commencement (GSC), which began towards the end of 7 October at 22:00 hrs UT. The storm's first main phase occurred at 13:00 hrs UT with minimum Dst of -95 nT on 8 October, after which it began a recovery phase which was short-lived. The second main phase occurred on 9 October with minimum Dst of -105 nT at 09:00 hrs UT before beginning the recovery phase which lasted through 10 October. The four days, 7-10 October 2012 and 24–27 October 2011 were considered the storm period consecutively in this work.

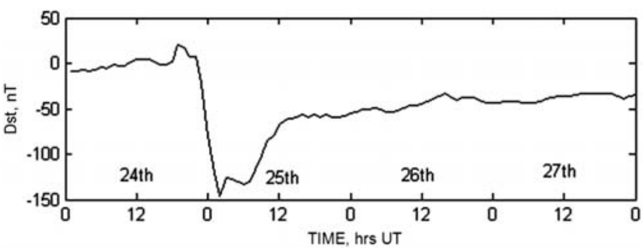

Fig. 2 — Dst plot for 24-27 October 2011

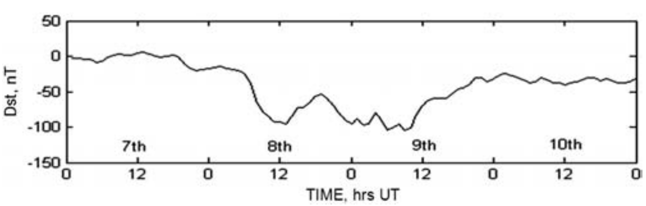

Fig. 3 — Dst plot for 7-10 October 2012

3 Results

Tables 3-5 present the average errors (deviation from ITRF) during the geomagnetic storm of 24-27 October 2011 and Figs (4–8) show the instantaneous positioning error over the five stations. The storm period was 24-27 October 2011 while the quiet day was 28 October 2011. It may be noted that 24-27 October are represented as storm day 1-4, respectively in the tables.

Figures 4-8 represent four panel plots of the instantaneous positioning error of the stations, the first panel is the Dst plot and the other panels are the coordinates error plots of the SSC during 24–27 October 2011 for the stations. day 1–day 4 represent the storm period 24–27 October, 2011 respectvely. Thick line represent the plot of the storm period while the thin line represent the quiet day superimpose on the storm period in the plots.

Tables 7-9 are the average error (deviation from ITRF) during the geomagnetic storm of 7-10 October 2012. The

Table 3 — Average error for the quiet day and storm period of the X-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day 4
ABUZ	0.90791	0.88206	1.35554	0.69493	1.31828
BKFP	1.45613	1.10493	1.47633	1.17726	1.96779
OSGF	0.68582	0.77817	1.46704	0.66097	1.50029
ULAG	0.75425	0.70778	1.23071	1.10299	1.53770
UNEC	0.46976	0.96968	1.05033	0.55143	1.45721

Table 4 — Average error for the quiet day and storm period of the Y-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day 4
ABUZ	-0.04391	-0.24522	0.033756	0.301059	0.048416
BKFP	-0.10297	-0.40515	0.011598	0.182397	-0.34638
OSGF	0.058151	-0.23285	-0.02919	0.33738	0.004838
ULAG	0.086079	-0.10115	0.027311	0.320126	-0.12446
UNEC	0.099546	-0.31876	0.026472	0.428521	0.009269

Table 5 — Average error for the quiet day and storm period of the Z-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day4
ABUZ	-0.096928	-0.480994	-0.3045	-0.283225	-0.098872
BKFP	-0.277367	-0.92355	-0.287736	-0.5166	-0.464208
OSGF	0.44283	0.08686	0.04914	0.40177	0.51703
ULAG	1.00516	0.97315	0.56614	1.17572	1.16628
UNEC	1.01381	0.94755	0.36448	1.15851	1.24012

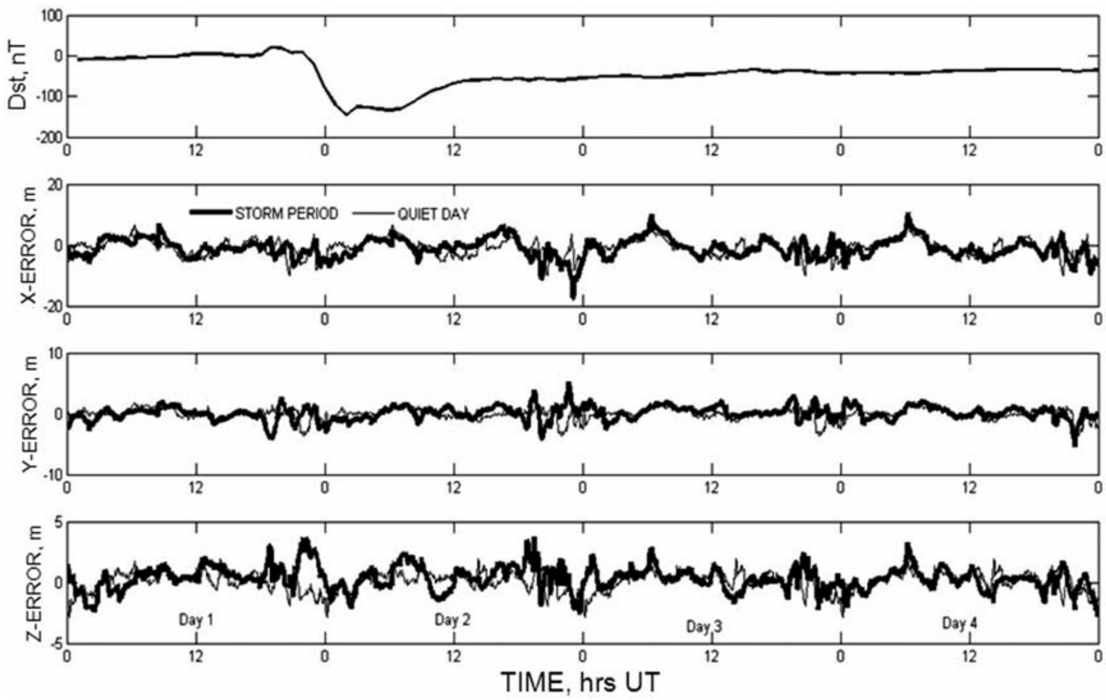

Fig. 4 — Coordinate error plots of ABUZ during the storm of 24-27 October 2011

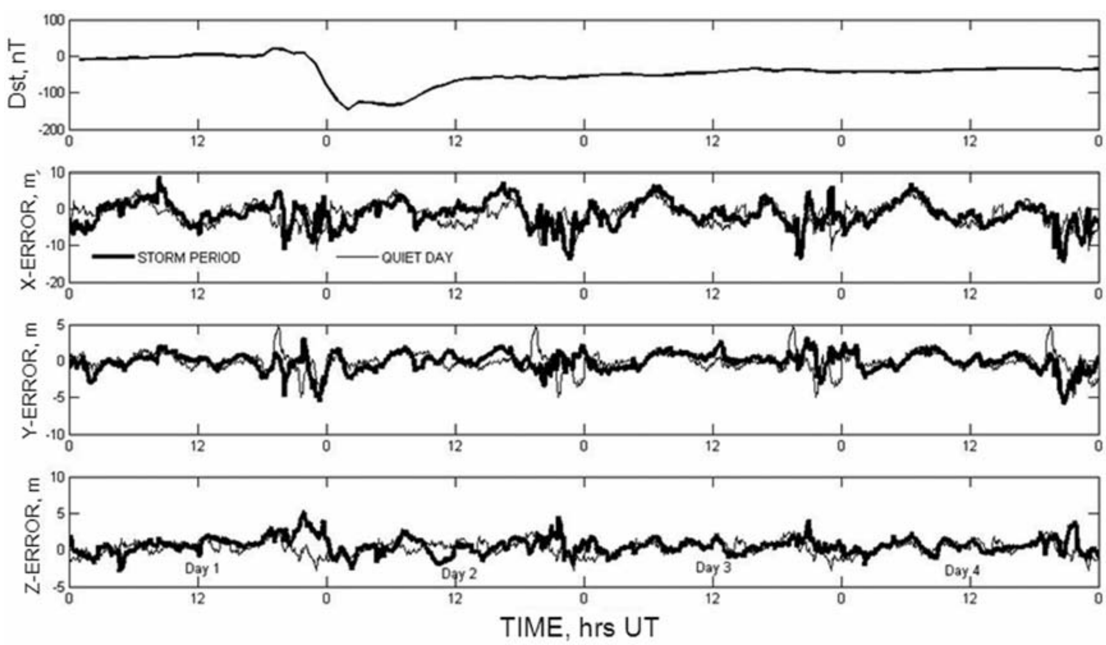

Fig. 5 — Coordinate error plots of BKFP during the storm of 24-27October 2011

storm period is 7-10 October 2012, respectively while the quiet day is 4 October, 2012. Days 7-10 are depicted as storm day1- storm day4, respectively in the table of results.

Figures 9-13 represent panel plots of the instantaneous positioning error, the first panel is the Dst plot and the other panels are the coordinates error plots of the GSC of October 2012 for the stations. Day 1 – Day 4 represent the storm period during 7-10 October 2012, respectively. Thick line represent the plot of the storm period while the thin line represent the quiet day superimpose on the storm period.

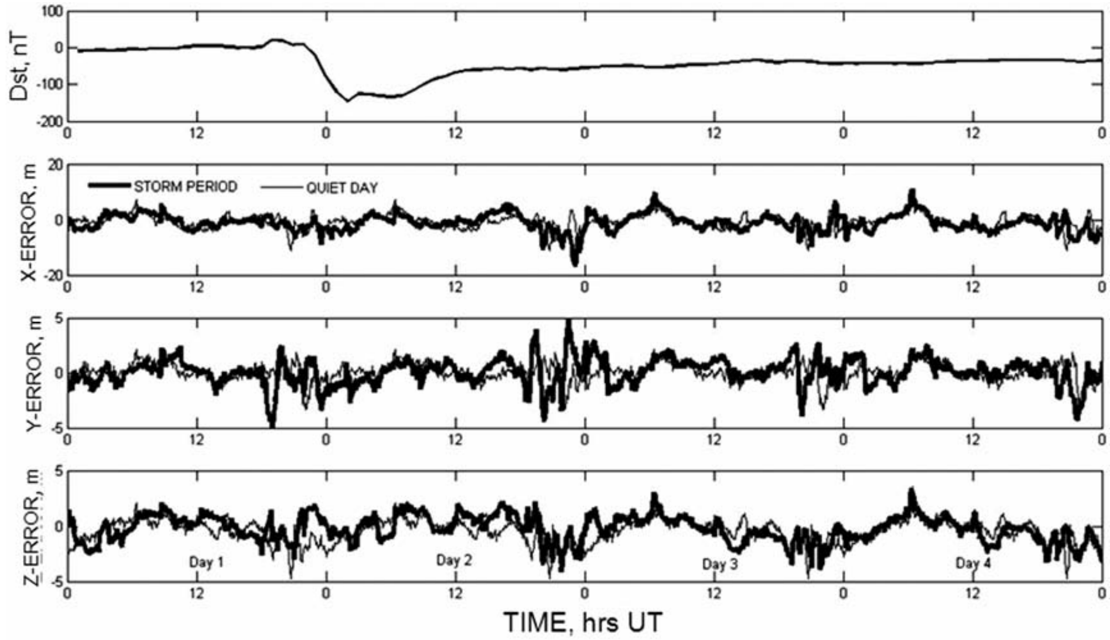

Fig. 6 — Coordinate error plots of OSGF during the storm of 24-27October 2011

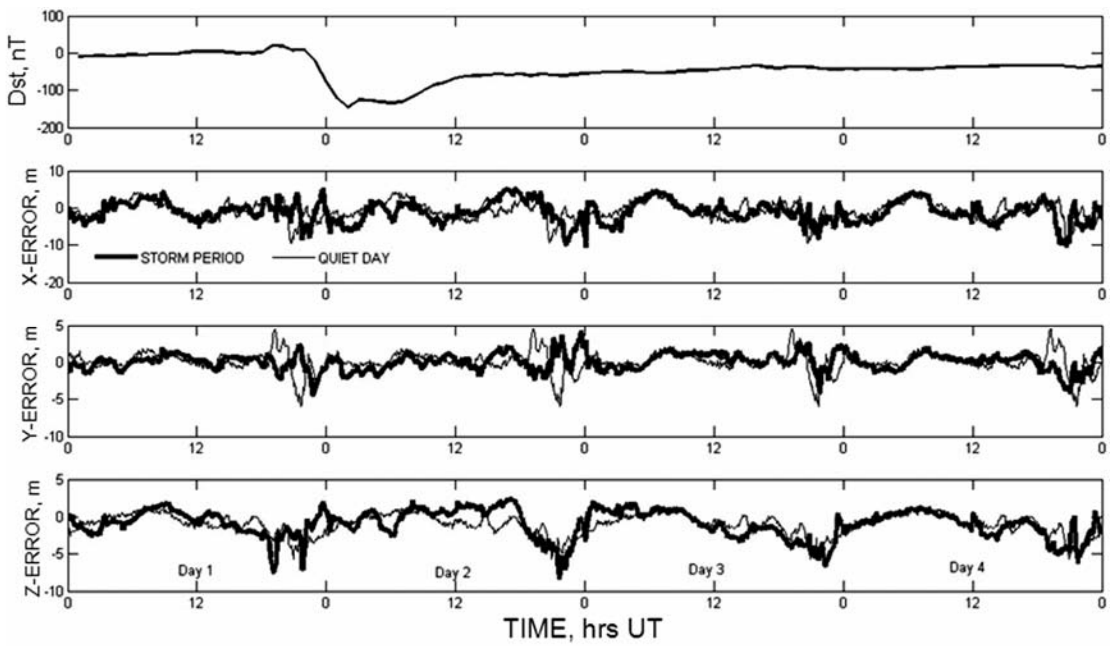

Fig. 7 — Coordinate error plot of ULAG during the storm of 24-27October 2011

4 Discussion

4.1 Storm during 24-27 October 2011

The storm shows a minimal effect on GNSS positioning (Tables 3-5), this is in agreement with Li *et al.*[9] that not all storms pose a significant positioning error. The X-coordinates error of the stations is less than 1.5 m during the period of peak minimum Dst index (storm day 2), the instantaneous positioning error do not show any significant storm signature for all the stations [Figs (4–8)]. The Y and Z coordinates error are both less than 1 m during the same period. The percentage errors also show no significant effect of the storm on the X and Y coordinates of the stations (Table 6). The Z-coordinate error is higher in stations with low latitude than the stations with higher latitude. This could be as a result of variation in the

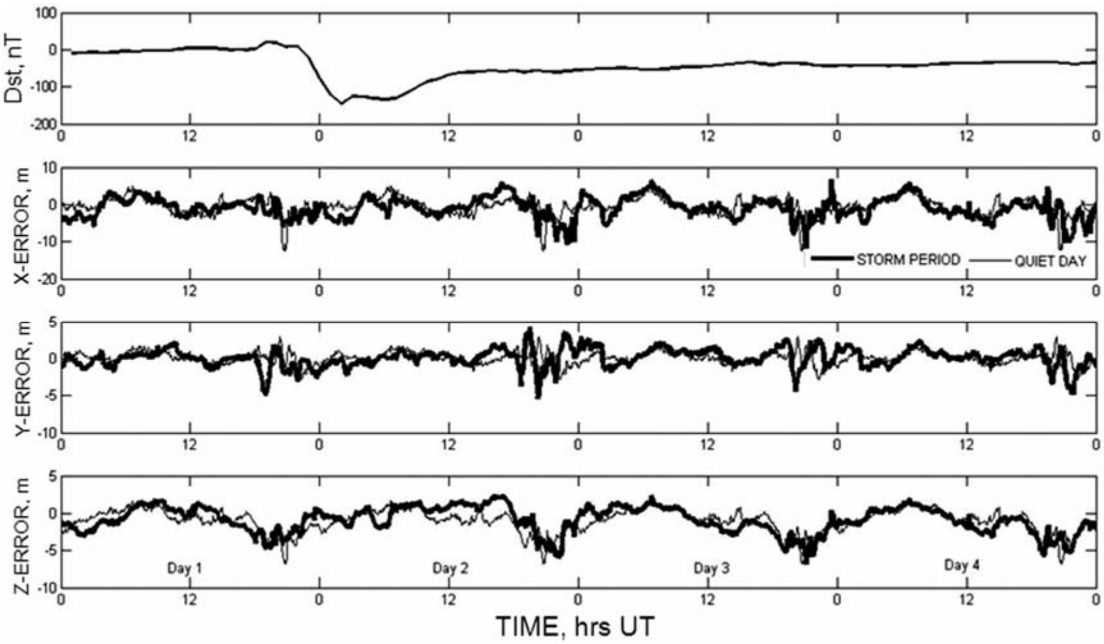

Fig. 8 — Coordinate error plots of UNEC during the storm of 24-27October 2011

Table 6 — Percentage error average over the stations during the storm of 24-27 October 2011

Station	X (%)	Y (%)	Z (%)
ABUZ	1.7×10^{-5}	4.1×10^{-6}	2.4×10^{-5}
BKFP	2.3×10^{-5}	3.0×10^{-5}	4.0×10^{-5}
OSGF	1.8×10^{-5}	2.4×10^{-6}	2.7×10^{-5}
ULAG	1.8×10^{-5}	8.1×10^{-6}	1.4×10^{-4}
UNEC	1.6×10^{-5}	2.7×10^{-6}	1.3×10^{-4}

Table 7 — Average error for the quiet day and storm period of the X-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day 4
ABUZ	1.961589	3.109947	4.034717	4.147458	4.265781
BKFP	1.706928	3.294481	4.118372	4.943881	4.488572
OSGF	1.917872	3.218226	3.811012	4.034983	3.902386
ULAG	2.005344	2.919936	3.299603	4.396258	3.883567
UNEC	1.971917	3.286358	3.194061	3.819583	3.037436

Table 8 — Average error for the quiet day and storm period of the Y-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day 4
ABUZ	-0.01058	-0.1011	0.294966	0.136243	0.115554
BKFP	-0.09024	-0.14142	-0.07898	-0.47605	-0.1502
OSGF	-0.12079	-0.16238	0.200477	0.116541	0.029296
ULAG	-0.25212	-0.22666	-0.54997	-0.44731	-0.22351
UNEC	-0.13637	-0.11089	0.176027	0.150312	0.103603

Table 9 — Average error for the quiet day and storm period of the Z-coordinates of the stations (m)

Station	Quiet day	Storm day 1	Storm day 2	Storm day 3	Storm day 4
ABUZ	0.225919	0.699036	0.617469	0.728472	0.464286
BKFP	-0.08196	0.388392	0.641592	0.497897	-0.3324
OSGF	0.712207	1.226761	0.802833	1.197399	0.636893
ULAG	1.354838	1.439675	0.893668	1.692954	-0.974681
UNEC	1.302946	1.756502	0.844174	1.699247	0.620974

local distribution of electron density in the equatorial region. The sudden commencement storm discussed in this work may not have enhanced the equatorial electrojet at the equatorial ionosphere of African sector.

4.2 Storm during 7-10 October 2012

The geomagnetic field causes GNSS trans-ionospheric signal delay to vary and often results in increased positioning error[4]. There is an increase in the positioning error at the stations during the storm period (Tables 7-9), which is in agreement with other authors[4,7-10].The effect of the storm is more pronounced on the X-coordinates, which resulted in higher positioning error throughout the storm period (Table 7). This error has a positive correlation with the period of minimum Dst for all the stations on the X–coordinates. This is also observed in the instantaneous positioning error plots [Figs (9–13)]. It could be inferred that during the gradual storm commencement reported in this study, the equatorial ionospheric irregularity is enhanced, which account for the increase in the positioning error of the stations.

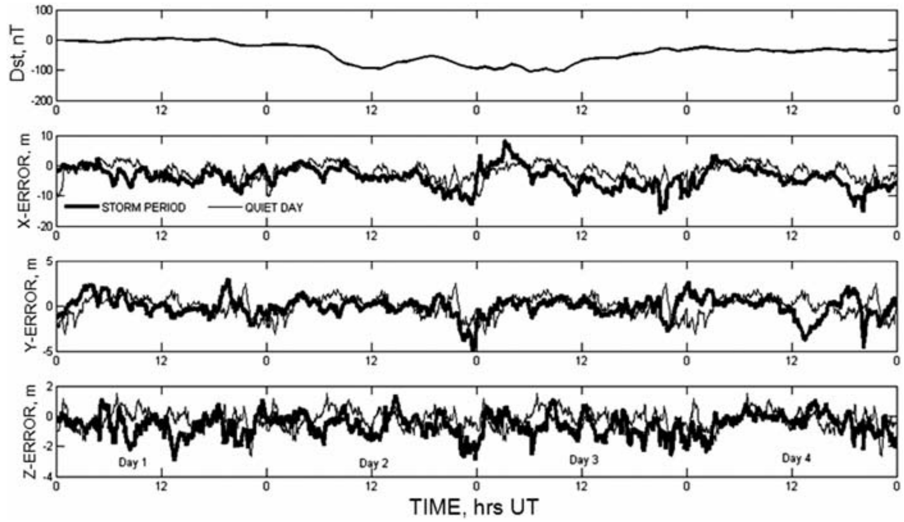

Fig. 9 — Coordinate error plots of ABUZ during the storm of 7-10 October 2012

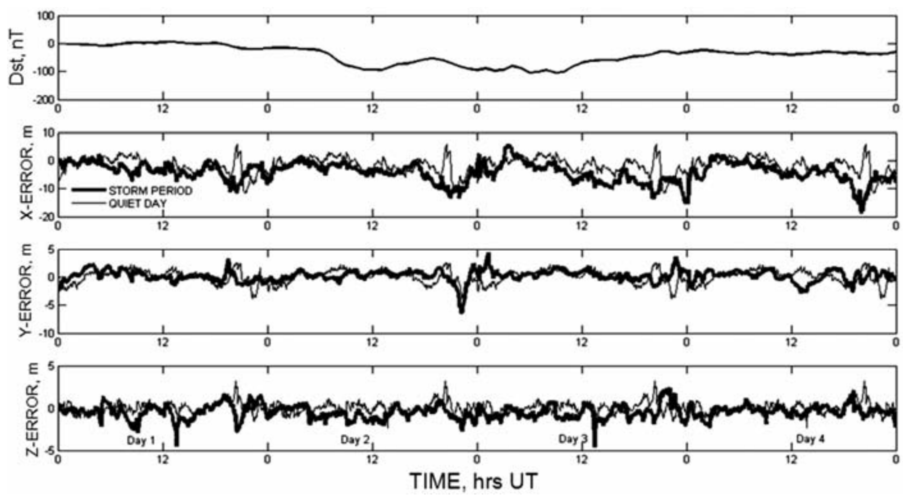

Fig. 10 — Coordinate error plots of BKFP during the storm of 7-10 October 2012

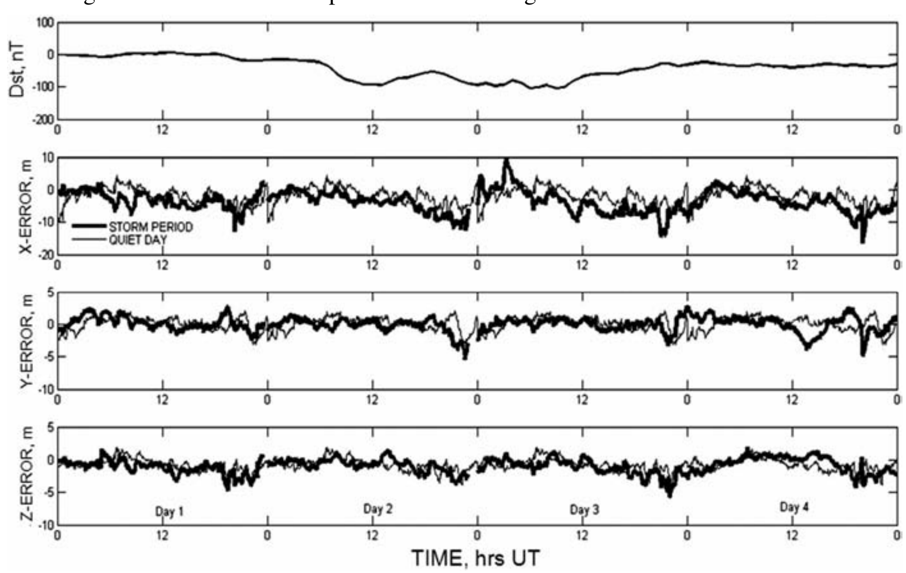

Fig. 11 — Coordinate error plots of OSGF during the storm of 7-10 October, 2012

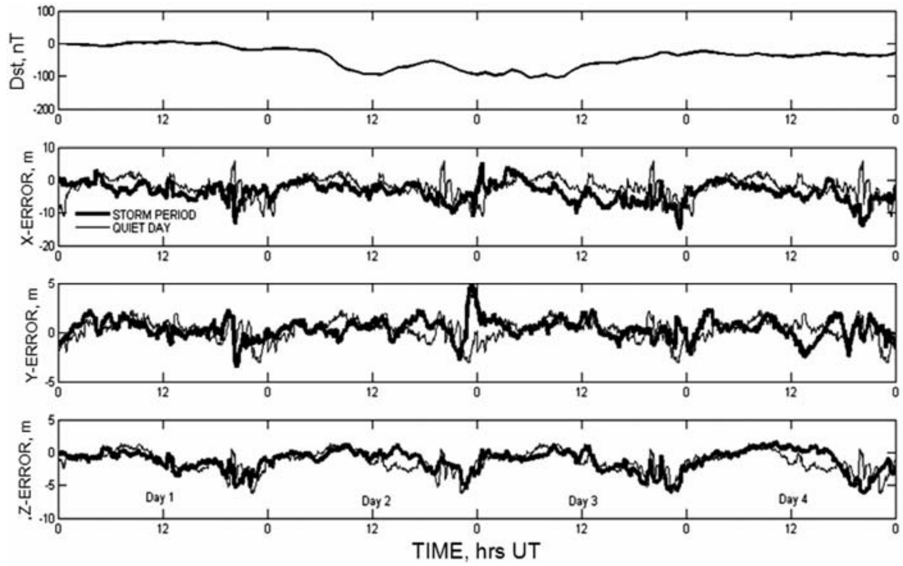

Fig. 12 — Coordinate error plots of ULAG during the storm of 7-10 October 2012

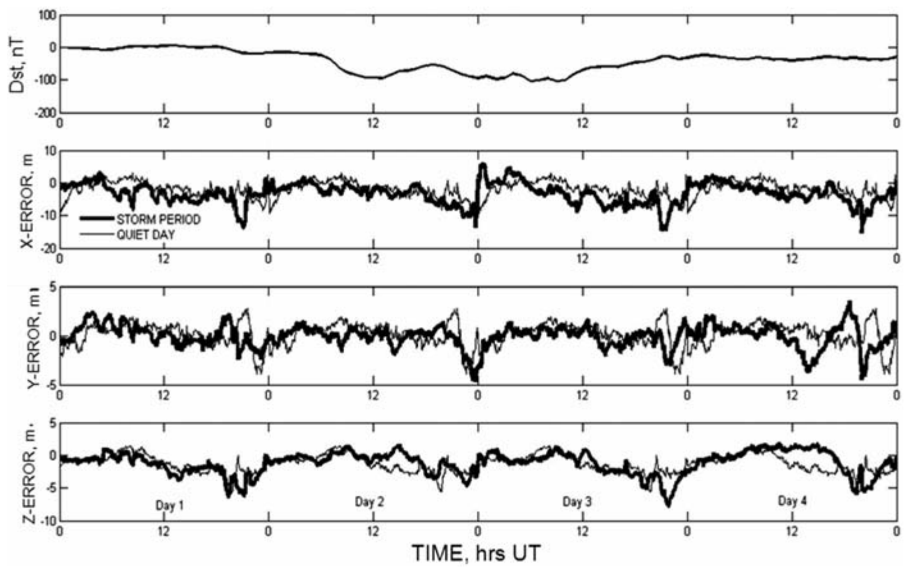

Fig. 13 — Coordinate error plots of UNEC during the storm of 7-10 October 2012

Table 10 — Percentage error average over the stations during the storm of 7-10 October 2012

Station	X (%)	Y (%)	Z (%)
ABUZ	6.3×10^{-5}	1.3×10^{-5}	5.1×10^{-5}
BKFP	6.8×10^{-5}	4.6×10^{-5}	3.4×10^{-5}
OSGF	6.0×10^{-5}	5.6×10^{-5}	9.7×10^{-5}
ULAG	5.7×10^{-5}	9.6×10^{-5}	1.7×10^{-4}
UNEC	5.3×10^{-5}	9.6×10^{-6}	1.7×10^{-4}

The average percentage error shows a latitudinal effect of the storm on the X and Z coordinates, which may be as a result of latitudinal enhancement of the equatorial ionization anomaly during the storm as reported by Amit *et al.*[10]. The percentage error increases with increase in latitude on the X-coordinates and decreases with increases in latitude on the Z-coordinates (Table 10). This latitudinal effect is not depicted clearly on the Y-coordinates of the stations.

5 Conclusion

The response of GNSS signals to two intense storms of 7–10 October 2011, a SSC and 24–27 October 2012, a GSC over Nigeria is studied from five GNSS network stations. Nigeria is situated within equatorial ionospheric anomaly region and the ionosphere in this region is highly dynamic. The positioning error increases during the storm over the five stations examined, which is in agreement with previous studies. The X-coordinates error is higher than the other coordinates for all the stations examined during the storm.

The percentage error shows a latitudinal effect on both X–coordinates and Z-coordinates during the gradual commencement storm of 7–10 October 2012, which could be a signature of local variation in the electron density of the equatorial ionosphere and enhancement of its irregularity. The percentage error shows no significant effect and no observable latitudinal effect on both X-coordinates and Y-coordinates during the sudden commencement storm of 24-27 October 2011, which shows that ionosphere respond differently during different storm categories and not all storms pose a significant GNSS positioning error. It is found that although both storms occur in the same season they do not have the same signature on GNSS over the five stations.

Further studies need to be carried out to ascertain if SSC poses no significant positioning error to GNSS user as compared to GCS for GNSS user in the equatorial region of African sector. This will further enhance better prediction of GNSS positioning accuracy in the region.

Acknowledgement

The authors wish to express their gratitude to World Data Centre for Geomagnetism, Kyoto, Japan; and Nigeria GNSS network (NIGNET) for the data used in this study. They also wish to thank the reviewers for their suggestions in improving the content of the paper.

References

1 United Nation Office for Outer Space Affairs (UNOOSA), *Curriculum for GNSS Education,* (UNOSA, New York), 2012, http://www.unoosa.org/pdf/icg/2010.

2 Adekoya B J, Chukwuma V U, Bakare N O & David T W, Effects of geomagnetic storm on middle latitude ionosphere F2 during storm of April 2–6, 2004, *Indian J Radio Space Phys,* 41 (2012) pp 606-616.

3 Comberiate J, Kelly M, Dyrud L & Weaver G, *Space Weather Effects on GPS Systems: Conference Proceeding* (Applied Physics Laboratory, USA), 2012.

4 Stankov S M, Stegen K & Warnant R, Seasonal variation of Storm time TEC at European middle latitudes, *Adv Space Res (UK),* 46 (2010) pp 1318-1325.

5 Takasu T, *RTKLIB Version 2.4.2 Software Manual*, (Free and Open Source Software for Geospatial (FOSS4G), Japan), 2013.

6 Wisniewski B, Bruniecki K & Moszynski M, Evaluation of RTKLIB's positioning accuracy using low-cost GNSS receiver and ASG-EUPOS, *Int J Mar Navig Safety Sea Transp (Poland),* 7 (2013) pp 79–85, http://www.transnav.eu/Ars_Positioning_25,412.html.

7 Warnant R, Kutiev I, Marinov P, Bavier M & Lejeune S, Ionospheric conditions during periods of degraded GPS positioning accuracy, *Adv Space Res (UK),* 39 (2007) pp 875-880, doi: 10.1016/j.asr.2006.03.044.

8 Afraimovich E L, Demyanov V V & Kondakova T N, *Degradation of GPS performance in geomagnetically disturbed conditions, 2002,* e-print archive: http://xxx.lanl.gov/abs/physics/0211015.

9 Li J, Ma G, Maruyama T & Li Z, Mid-latitude ionospheric irregularities persisting into late morning during the magnetic storm on 19 March 2001, *J Geophys Res (USA)*, 2012; doi: 10.1029/2012JA017626.

10 Amit J, Sunita T, Sudhir J & Gwal A K, TEC response during severe geomagnetic storms near the crest of equatorial ionization anomaly, *Indian J Radio Space Phys,* 39 (2010) pp 11-24.