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SEASONAL VARIATIONS OF THE VERTICAL TOTAL ELECTRON CONTENT (VTEC) OF THE IONOSPHERE AT THE GNSS COR STATION (SEERL) UNIBEN AND THREE OTHER CORS STATIONS IN NIGERIA

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ABSTRACT

The complex environment of the Sun-Earth, which resulted in the spatial and temporal variations of the ionosphere leads to different kinds of effects on human technologies. Man's continuous increasing utilization of space technologies in addressing it's immediate and future needs demand quality research of the space environments, to understand the physics of the interaction of the environment with systems (both space and earth bound), and to develop methods of mitigating the environmental effects. This is one of the reasons Center of Atmospheric Research (CAR) set-up a GNSS monitoring station in Benin. The Vertical Total Electron Content (VTEC) time series of some selected days from the newly established Benin station together with three Cors stations (ABU, BKFP and CLBR) of OSGoF were subjected to the Lloyd seasonal classification in order to see their diurnal variation on season by season bases. The results show that there exist an interconnection(in term of their magnetic longitudes) between the ABU, CLBR and the BENIN stations even though BENIN station had the least Total Electron Content (TEC) values at all the seasons. The results also clearly showed that the BENIN station offers better advantage in terms of positional accuracy.

Keywords*: VTEC, time series, Cors stations, Lloyd seasonal classification and Positional accuracy.*

1. INTRODUCTION

The occurrence of large scale gradients in Total Electron Content (TEC) may lead to degrading in the performance of Space Based Augmentation Systems (SBAS) that provides the much needed differential corrections of the ionospheric delay to the GPS users in order to enhance the positioning accuracy [1]. The implication of these large scale gradients will be felt in the interpretation of Vertical Total Electron Content (VTEC) measurements, the complications that arise in the analysis of the GPS occultation data and the determination of the receiver biases. On the other hand, small scale gradients are associated with the scintillation of trans-ionospheric signals which are noted to have impact on communication and navigation systems. Total Electron Content (TEC) is the number of electrons in the column of $1m^2$ cross section that extends from a GPS satellite to a GPS receiver. This important by-product of GPS data is very useful in surveying the ionosphere and can therefore be used to provide an overall description of the ionosphere [2]. Total Electron Content (TEC) is known to have overbearing influence on GPS-based communication and navigation systems [3]. Ionization from Solar radiation is the dominant contributor to the diurnal variation of the TEC. Contributions from a variety of other physical phenomena such as large scale waves (associated with magnetic activity) and others are also observed. [4-6] however, emphasized that the equatorial ionosphere is noted to be highly dynamic and consequently poses serious threats to communication and navigation systems. The dominant mechanisms at the equatorial and low latitudes responsible for the generation of large scale TEC gradients include: the Appleton anomaly, equatorial electro jet (EEJ), Equatorial Spread F (ESF), geomagnetic storms among others [1, 2, 7-9]. The Appleton anomaly is as a result of the so-called fountain effect; whereby an eastward electric field at the equator gives rise to an upward ExB drift during

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the daytime [10]. Moreover, after the plasma is lifted to greater heights, it is able to diffuse downward along magnetic field lines under the influence of gravity and pressure gradient forces (± 17 magnetic equator). The net result is the formation of a plasma fountain, which produces an enhanced plasma concentration (crest) at higher latitudes and a reduced plasma concentration (trough) at the equator. This leads to the electrons being diffused along the field lines of either side of the equator to form two crests after it has lost momentum [11]. Furthermore, the occurrence of the Appleton anomaly lifts the equatorial ionosphere from 700km up to over 1000km. The development of the anomaly depends on the Zonal electric field, plasma pressure, and neutral winds which are highly dynamic with significant variability on daily, seasonal, and solar cycle time scales [12]. On the other hand, the Small scale TEC fluctuations are closely associated with ionospheric structures responsible for the scintillation of the Ultra High Frequency (UHF) and GPS satellite signals.

[7 and 9] both worked on TEC at stations (Ilorin, Nigeria and India) in low latitudes during the low solar activity period, and they showed that the diurnal characteristics of TEC depend on season, solar activity, geomagnetic activity, and latitude. [7, 8 and 13] showed that the seasonal variations in vertical TEC are higher during the equinox than the solstice during low solar activity, while [14] showed that the story was the same at high solar activity using different stations.

Quantitative study of transient variations in GPS TEC, involving simultaneously measured data from multiple stations in Nigeria, to show the diurnal and the seasonal variation of the GPS- TEC data has been done by several authors: [9, 10, 15 – 17]. This paper is not to follow suit. But, to carefully study how the diurnal variation of the TEC behaves on some selected days simultaneously across the stations on season by season bases.

1.1 Data and Method of Analysis

The locations of the 4 stations are distributed at various places in Nigeria (within the equatorial and low latitudes). The selected locations together with their details; including their respective geographical and geomagnetic coordinates, can be seen in Table 1.

The Ionospheric GPS TEC was obtained from the ground-based GPS receiver station at Benin (The GPS receiver was installed on February 9th 2017). The station is operated by Space-Earth Environment Research Laboratory under the Centre for Atmospheric Research, Anyigba, Nigeria. While the rest of the data were obtained from, the ground-based GPS receiver stations of NIGNET equipment being operated by the Office of the Surveyor General of the Federation (OSGoF) of Nigeria. However, due to the lack of availability of 2017 data on the NIGNET network during the period of this research, the authors decided to use the data of the same days of 2016 (since both year are still within the same solar activity). [18] Investigated the seasonal effects of TEC using Lloyd's seasonal classification. In this classification, the months in the year were classified into three seasons, based on the movement the sun undertakes: December Solstice or D season (November, December, January, and February), Equinox or E season (March, April, September, and October), and June Solstice or J season (May, June, July, and August). The GPS TEC data of 5 days each for the month of February (representing the D season), April (representing the E season) and May (representing the J season) were obtained from the ground GPS receiver at the Benin station (A station roughly midway between the trough and southern crest of the Appleton anomaly). The same days that were obtained at the BENIN station were also obtained at the ABU (station along the magnetic equator), BKFP and CLBR in the year 2016.

The records of slant TEC (STEC) obtained from the GPS contains satellite differential delay (b_S, satellite bias), receiver differential delay (b_R, receiver bias) together with receiver inter-channel bias (b_{RX}). This uncorrected STEC measured at every 1min interval from the GPS receiver derived from all the visible satellites at each of the 4 stations is converted to vertical TEC (VTEC). The VTEC is calculated as follows:

$$VTEC = STEC - [b_R + b_S + b_{RX}]/S(E) \qquad (1)$$

Table 1: Characteristics of the stations.

Station	Geographic Latitude	Geographic longitude	Magnetic Latitude	Magnetic Longitude
Benin(uben)	6.40^{0}N	5.62^{0}E	-8.18^{0}N	79.66^{0}E
Zaria(abu)	11.15^{0}N	7.65^{0}E	-0.13^{0}N	79.75^{0}E
Calabar(clbr)	4.95^{0}N	8.35^{0}E	-4.30^{0}N	80.09^{0}E
Binin-kebbi(bkfp)	12.47^{0}N	4.23^{0}E	0.72^{0}N	76.62^{0}E

The STEC is the uncorrected slant TEC measured by the receiver, the E is the elevation angle of the satellites in degree, S(E) is the obliquity factor with the zenith angle (z) at the ionospheric piecing point. According to [19 and 20], S(E) can be defined as:

$$S(E) = \frac{1}{Cos\,(z)} = \{1 - \left(\frac{R_E\; X \cos(E)}{R_E +\; h_S}\right)^2\}^{-0.5} \qquad (2)$$

The mean radius of the earth measured in km is taking as R_E and the height of the ionosphere from the surface of the earth is h_s, which is approximately equal to 350 km.

The STEC is converted to VTEC using the above equation which have being build-up in software developed by Institute for Scientific Research, Boston College, MA, USA. This software had being written to take into consideration the receiver bias, inter channel bias of different satellites of the receiver and also the error due to multipath by taking the minimum elevation angel at 20^0.The estimated VTEC data from this process are then subjected to two-sigma (2α) iteration. This clearly is a measure of GPS point positioning accuracy as it reveals 95% confidence level.

2. RESULTS AND DISCUSSION

The resultant TEC data obtained from the analysis done by the software are at 1minute intervals in ASCII format. Since the interest was to study the diurnal trend, the minute GPS TEC data were then scaled down to hourly values at the 4 stations used. The hourly values of GPS TEC were then plotted against the local time to examine the hourly variation. Figures 1-4 show the diurnal variation of the selected days at the 4 stations. The result is a GPS TEC with typical characteristics of the low-latitude ionosphere [7, 9, 10, 15, 21 and 22]. The spread of GPS TEC at the stations chosen for this paper revealed a minimum during the nighttime and at a maximum during the daytime, which may be attributed to the high ionization due to intense solar radiation. The characteristics of the TEC at the Pre-dawn (00:00 – 06:00hrs), Morning rise/ Afternoon (06:00 –18:00hrs) and Post sunset (18:00 – 00:00hrs) are in agreement with previous works. This is obvious by the fact that the rate of the early morning increase experienced in GPS TEC is relatively faster at all stations than the rate of the evening decrease in GPS TEC. It is clear that there exist large variations in the GPS TEC observed between the daytime and the night time and this can be attributed to the absence of solar radiation at nighttime.

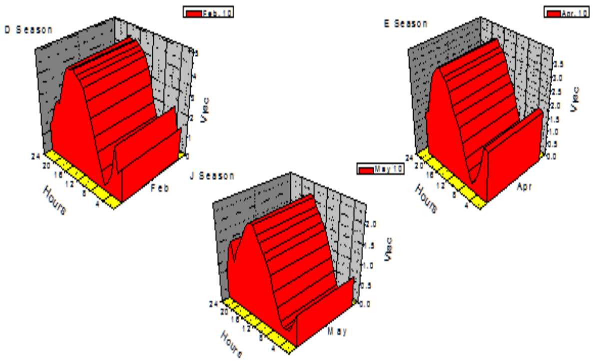

Figure 1: Diurnal variation of VTEC on the February 10th, April 10th and May 10th, 2017 at BENIN station.

It can be concluded from the Figures above that, the TEC increases as the intensity of the sun increases with the time of day. Moreover, minimum TEC occurred around the same time (which is 06:00 LT) on almost all the selected days at the stations used. This further confirms that as the Intensity of the sun decreases, TEC decreases.

Figures 5-7 show the diurnal variation of the TEC on season by season bases. Figure 5 revealed the situation during the D season. It can be seen that during the D season, the variability at the pre-dawn of the ABU station was more intensed (presence of more post sunset decrease/enhancement) than any other station. That of the CALABAR station was next, then BININ KEBBI, with BENIN station as the least. The post sunset also reflected the same in that order. [9 and 23] stated that the post-sunset decrease and enhancement could be attributed to abrupt onset scintillations, plasma bubbles, and the spread-F phenomenon. This small-scale plasma density irregularities results in ionospheric scintillations which could leads to transionospheric signal fading (potential threat to GNSS systems).

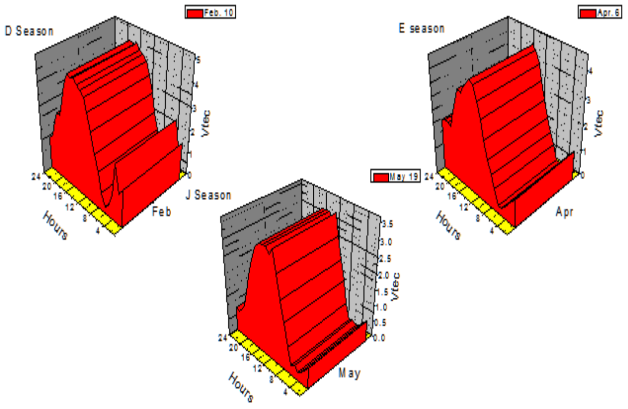

Figure 2: Diurnal variation of VTEC on February 10th, April 6th and May 19th, 2017 at CALABAR station.

[24] Revealed that a large-scale electrostatic field is produced at the low latitudes (eastward during the day and westward at night). It is the westward that is responsible for the upward drift motion while the westward at night (downward drift motion). It is this downward motion at the geomagnetic dip equator together with the southward motion of ionization that could be responsible for the nighttime enhancement of GPS TEC. There are quite a bit of similarity between the trend of the GPS TEC at the pre-dawn of ABU and CALABAR station, especially on the 21st and 27th (arrows in the graph) during the D season. Both had a depression (decrease) at 03:00hrs and at 08:00hrs at ABU station. While at CALABAR station, the two days can be termed as "days of anomaly" as the diurnal variation on these days were different from the usual. The depression was at 02:00hrs and 07:00hrs on the 21st and on the 27th at 03:00hrs and 07:00hrs. However, the depressions at the ABU were deeper than at CALABAR.

It is clear from the above, that, the "anomaly" which is most likely to be large scale wave activity from magnetic activity (because there was neither storms nor solar activity on the two days and the nature of the trend of the VTEC on the two days from 09:00hrs) was first felt at the CALABAR station because of the time of its occurrence. Even though, the effect was deeper at ABU. The activities that took place at ABU station at that time might have contributed to it being deeper there.

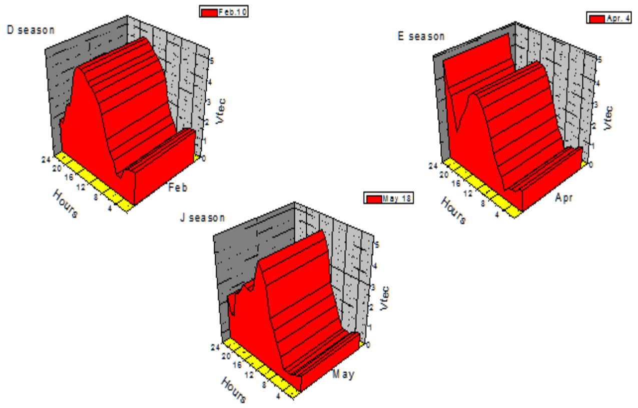

Figure 3: Diurnal variation of VTEC on the February 10th, April 4th and May 18th, 2017 at ABU station.

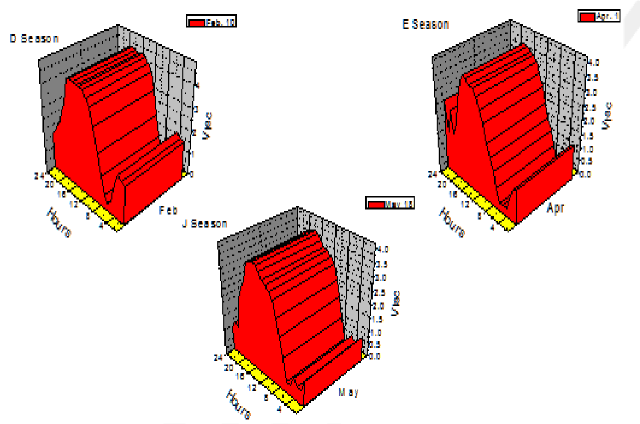

Figure 4: Diurnal variation of VTEC on February 10th, April 1st and May 18th 2017 at BININ KEBBI station.

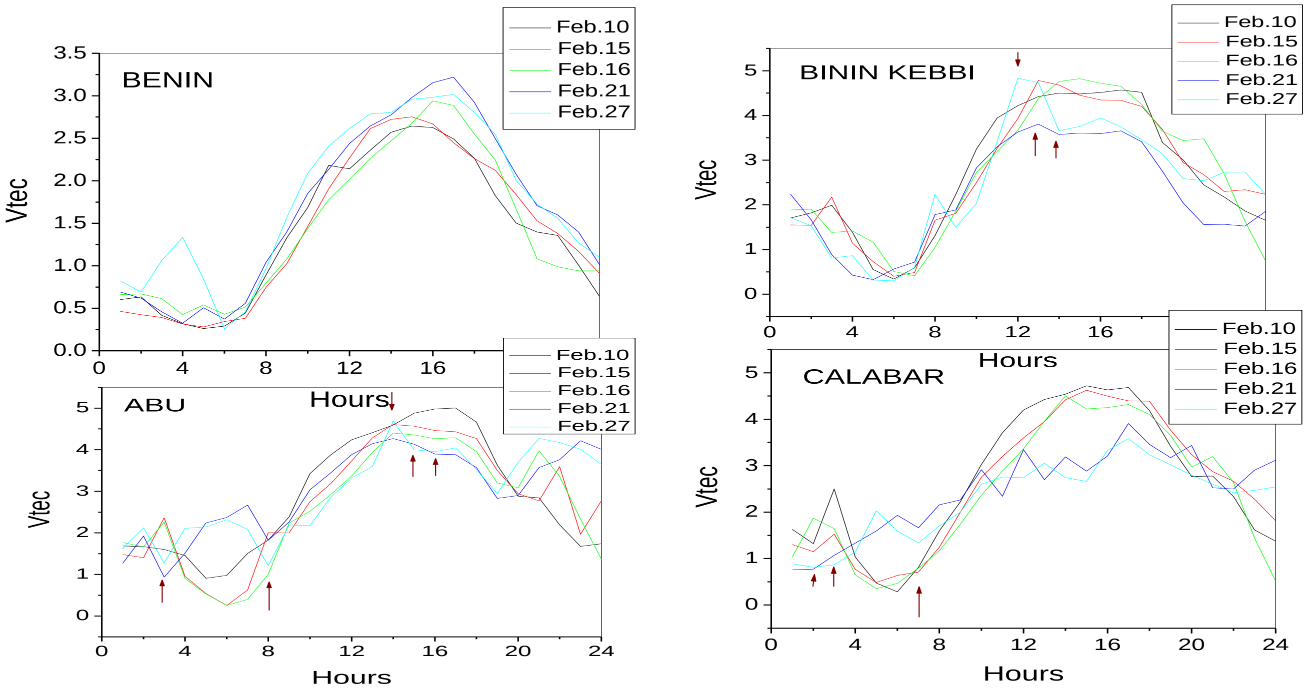

Figure 5: The diurnal variation of the Vtec on the February 10th, 15th, 16th 21st and 27th, 2016 at the ABU, CALABAR AND BININ KEBBI and of 2017 at BENIN station during the D season.

On the other hand, the morning rise/afternoon period during the D season at ABU and CALABAR station clearly showed except on the 27th day at ABU station, that the peak of the VTEC decreases as the days of the month selected increases(from 10th to 27th) at the two stations. ABU station being on the magnetic equator reflected large-scale wave activity (magnetic activity). [25] stated that magnetic equator provides unique location for thermal plasma and wave measurements.

However, the peak of the VTEC steadily increases as the days of the month increases at the BENIN station. This was unlike what took place at the ABU and CALABAR station. The time of the peak moved from 15:00hrs to 16:00hrs as the days increases at the BENIN station. While at the ABU station, the time of the peak moved from 16:00hrs to 15:00hrs. The implication of this as revealed by the results of the VTEC is that while certain similar activity might be taking place between ABU and CALABAR stations. The same cannot be said about BENIN station as the exact opposite of what took place at ABU took place there. However, at the BININ KEBBI station, the time of the peak VTEC occurred from 12:00 and 18:00hrs on the days selected. The first 3 days had the peak of the VTEC increasing as the days of the month increases (10th – 16th) just like BENIN station. The 21st and 27th day changed the pattern. There was clearly a similar trend in the VTEC of 21st and 27th at ABU and BININ KEBBI (as pointed out by the arrow on the two graphs) but the earlier days was like BENIN station.

The time of the peak of the 21st and 27th at ABU station was at 14:00hrs. While that of BININ KEBBI was at 13:00hrs and 12:00hrs respectively. The time of the subsequent decrease was at 16:00hrs on the 21st and 15:00hrs on the 27th at the ABU station. While that of both days at BININ KEBBI was at 14:00hrs. CALABAR station however also showed that the peak of the TEC on both days occurred at 15:00hrs while the depression (decrease) occurred also on both days at 17:00hrs.

The other side to this is that the BENIN station which has 2017 data still revealed the effect of the 21st and 27th day, but reflected in the VTEC in a different way (the peak of the VTEC at the 21st and 27th occurred at the same time (17:00hrs) and no decrease). This result is in agreement with [1] which stated that the degree of variability in TEC measured at a low latitude ground station depends on the location of the station with respect to the Appleton anomaly. It is clear from this that only the ABU; BENIN and CALABAR stations had the time of the peak of the VTEC on both days at the same time but with ABU station having it first then CALABAR and BENIN last.

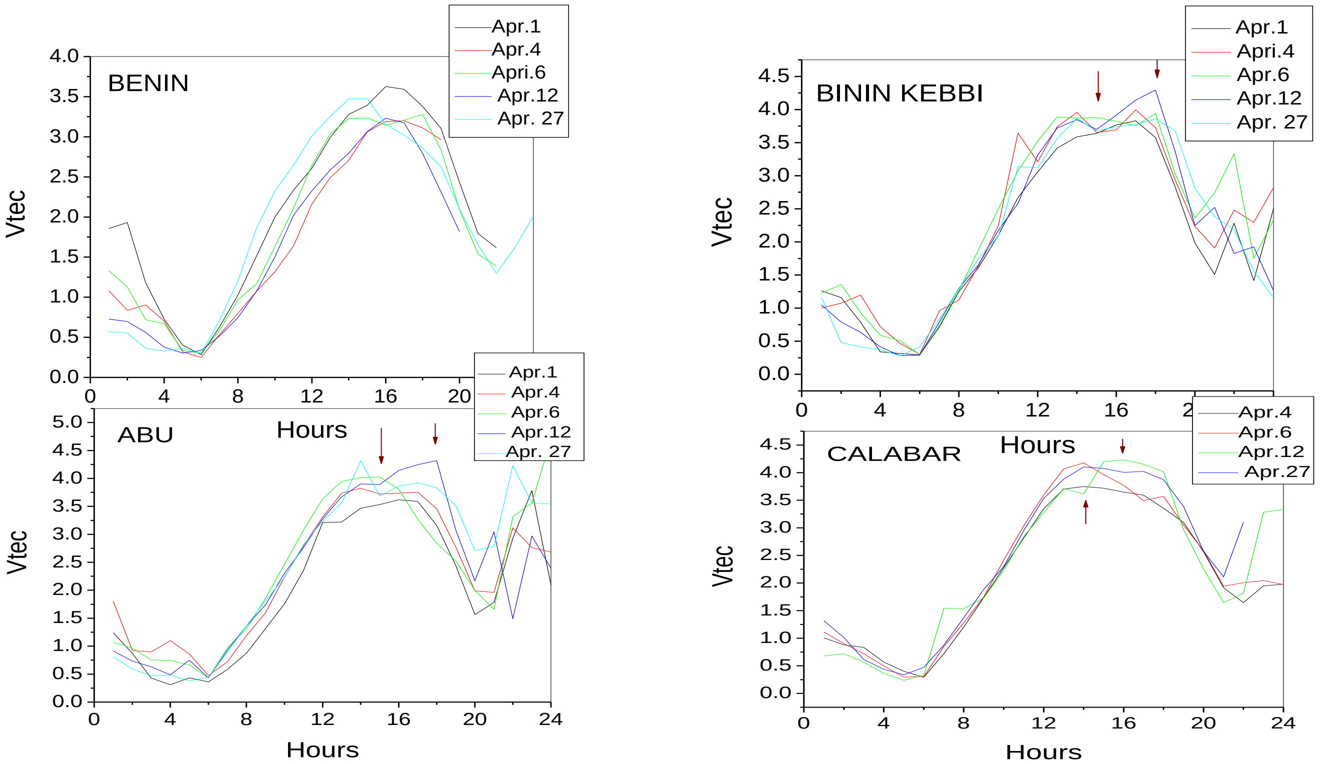

Figure 6: The diurnal variation of Vtec on the April 1st, 4th, 6th 12th and 27th, 2016 at the ABU, CALABAR AND BININ KEBBI and of 2017 at BENIN station during the E season.

The post sunset period during the D season revealed that the ABU station had the most intensed post sunset. With BENIN station having the least. The implication of this is that there were more enhancement/ decrease during the period at the ABU station than any other station. According to [9], the post-sunset decrease and enhancement could be attributed to abrupt onset scintillations, plasma bubbles, and the spread-F phenomenon. According to [23], the presence of these small-scale plasma density irregularities could result in ionospheric scintillations that cause trans-ionospheric signal fading, which is clearly a potential threat to GNSS systems.

On the other hand, during the E season, the pre-dawn period at the BENIN station was the most active, next is the ABU station, and then BININ KEBBI, with that at the CALABAR station the least active. The variability of the VTEC at the BENIN station was also the most intensed during the morning rise/afternoon period till the point of post sunset. The ABU station was next, then BININ KEBBI, with CALABAR station as the least. The time of the peaks of the VTEC varies from 14:00 till 18:00hrs at the BENIN station. All this taking place at the BENIN station is in agreement with [1] which stated that variations in the strength and location of the Appleton anomaly crests with respect to a low latitude ground station lead to a high degree of TEC variability measured at that station. Since BENIN station is roughly midway between the trough and southern crest of the Appleton anomaly, the variability was much there than other station.

The peak of the TEC increased as the days of the month increases until the 12th day of the month at the ABU station. An "anomaly" occurred on the 12th that was picked up by ABU, CALABAR and BININ KEBBI stations. CALABAR station had a depression and the peak at 14:00 and 16:00hrs respectively. While ABU and BININ KEBBI stations picked up the depression and the peak of the VTEC at the same time (15:00hrs and 18:00hrs). The depression at the BININ KEBBI was deeper than the rest, with the CALABAR next then that of ABU in that order.

On the other hand, irrespective of the depth of the depression and the time of the peak, the 12th day had the highest TEC at the 3 stations. This alone clearly revealed that the 12th day is a day of either geomagnetic or solar activity. The day was confirmed to be a day of solar activity.

However, the non availability of data for majority of the post sunset period did not allow for proper investigation of that time at BENIN station. The same period was noticed to be strongest at ABU station, when the other 3 stations were considered. This was followed by BININ KEBBI and CALABAR station as the last..

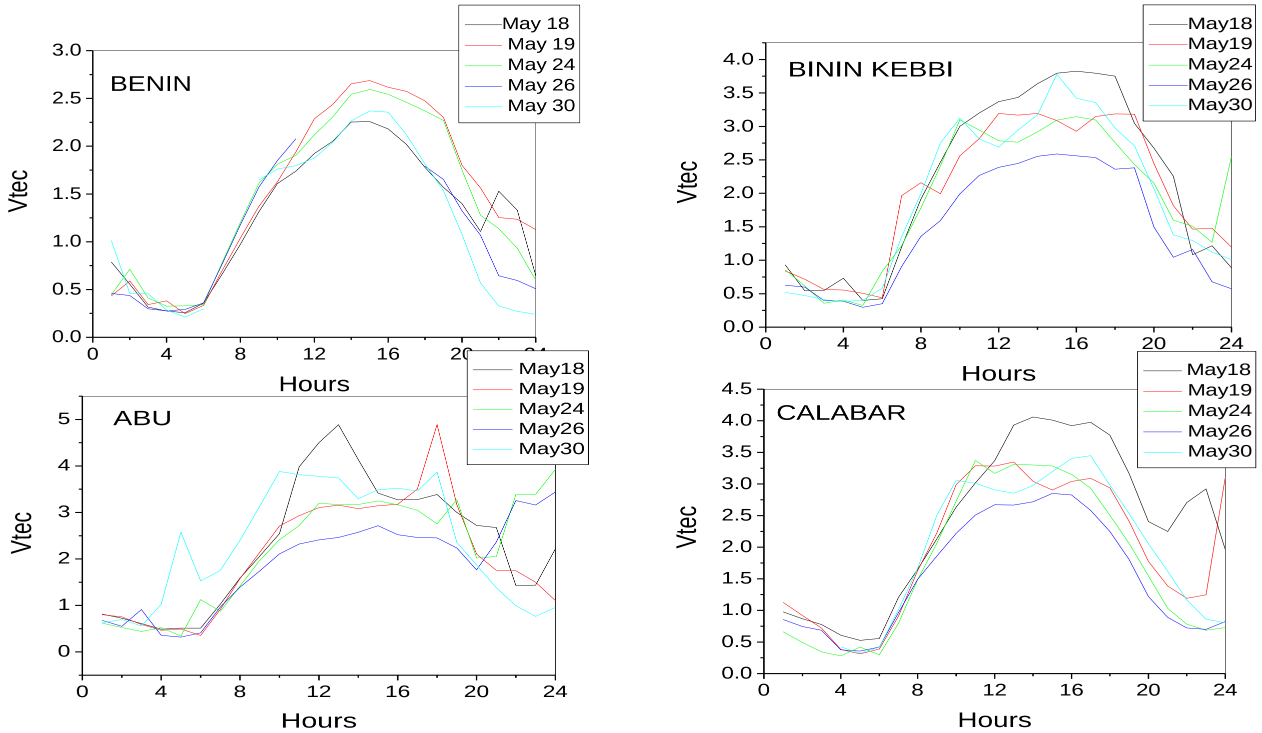

Figure 7: The diurnal variation of Vtec on the May 18th, 19th, 24th, 26th and 30th, 2016 at the ABU, CALABAR AND BININ KEBBI and of 2017 at BENIN station during the J season.

The implication of this is that, the post sunset period at ABU station experienced more decrease and enhancement (plasma turbulence) in the GPS TEC than the other two. [9, 23 and 26] attributed this to abrupt onset scintillations, plasma bubbles, and the spread-F phenomenon. The trend of the VTEC at the 4 stations during the J season revealed that the variability was not that pronounced during the pre-dawn period at all the stations (except on the 30th that showed an "anomaly" at the ABU station).The post sunset period during the J season revealed that ABU Station was the most active (had most enhancements and decrease than any other station).

This was followed by BININ KEBBI station with the BENIN station had the least. The afternoon period showed that there exists large variability in TEC across 3 of stations with the BENIN station having far lesser variability. The ABU station was highly chaotic throughout the period whether pre-dawn, morning rise / afternoon or post sunset. Another important thing that was noticed is that, in the absence of the 26th day which did not have a complete data at BENIN station. The trend experienced at the BENIN station as reflected by the VTEC during the afternoon period is of this Order: 19th, 24th, 30thand 18th. While that of CALABAR showed 18th, 30th, 24thand 19th. It is distinctively clear that the inverse of the trend at the BENIN station was seen at the CALABAR station. On the other hand, the anomaly of the 30th started from the pre-dawn period till the rest of the day at the ABU station. However, the VTEC at the other 3 stations did not reflect this from the pre–dawn period. This might likely suggest that the "source" of the anomaly might be from the magnetic equator itself since the station is along it. This anomaly was also "felt" at the other 3 stations but in different ways as expected, based on their magnetic latitude.

3. CONCLUSIONS

This study presents the diurnal variation of GPS-measured TEC (simultaneous measurements) for some selected days on season by season bases using 4 stations in Nigeria as a case study. All the stations lie within the equatorial and low latitudes which made the study interesting. The ABU station which is a station along the magnetic equator played a prominent role throughout the seasons studied. [24] emphasized in his work that large-scale electrostatic field (eastward fields during the day and westward fields during the night) are responsible for the upward plasma drift motion and the downward drift motion respectively as experience at stations within the low latitudes. This ultimately led to the plasma fountain reversing itself during nighttime hours (the northward motion of the crest of ionization experienced during the daytime reverses to a southward motion during the night). In other words, there are always activities going on at the magnetic equator. This could be the reason for the ABU station being "extremely active" at all time (pre dawn, morning rise/afternoon and post sunset) irrespective of the season.

It can be seen from Figures 5 – 7 that, irrespective of the season; the interpretations of the diurnal variation of the Vtec measurements on the days selected were far easier at BENIN station than the other 3 stations (effect of large-scale gradients). This has implication in the determination of the receiver biases and invariably positioning accuracy. BENIN station being a station that is roughly midway between the trough and southern crest of the Appleton anomaly has revealed itself out of the 4 stations, not to reflect in a significant way the impact of large scale activity, which poses a great danger to Space Based Augmentation Systems (SBAS), and are too important to be ignored by GPS users. The implication of this is that positional accuracy is greatly improved at the BENIN station than all the stations used in this study. On the other hand, the interesting interwoven relationship that exists between BENIN and ABU, BENIN and CALABAR and lastly ABU and CALABAR station as revealed by the results might be due to the fact that both BENIN and ABU stations are almost at the same magnetic longitude (difference of 0.09^0), and CALABAR is just 0.34^0 off ABU. [1, 9 and 10] all showed the longitudinal dependence of TEC. One of the most important results from this study is that the BENIN station is a station that "cannot" be ignored by surveyors and related fields alike, if accuracy of positioning is a priority.

4. ACKNOWLEDGEMENTS

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