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AN ASSESSMENT OF SEASONAL VARIATIONS IN THE CREF CORS AT THE UNIVERSITY OF LAGOS

Peter Chigozie Nwilo, Emmanuel Gbenga Ayodele, Chukwuma John Okolie, Michael Joseph Orji, Mnguhenen Funmilayo Marve, Esther Abidemi Oyelade, Olagoke Emmanuel Daramola

Summary

Continuously Operating Reference Stations (CORS) are reference stations of the Global Navigation Satellite System (GNSS), providing fundamental positioning infrastructure that is accurate and reliable. As such, CORS are designed to meet the needs of a wide range of users requiring high three-dimensional (3D) positional accuracy. The Continuously Operating Reference Station at the Engineering Faculty (CREF), University of Lagos was set up in order to support research applications in Surveying, Mapping and Geodesy. This study evaluates the seasonal variations in the 3D coordinates of CREF using metrics such as coordinate differences, Standard Deviation (SD) and Standard Error (SE). The Canadian Spatial Reference System (CSRS), known as CSRS – Precise Point Positioning (CSRS-PPP) was used to compute the station's daily coordinates over a three-year period from 2016 to 2018. In the analysis, the daily coordinates were divided into two seasons - the wet and the dry. The results obtained show that the dry and the wet seasons had SDs (5.4 mm, 3.9 mm, and 2.0 mm) and (5.2 mm, 18.6 mm and 14.4 mm) in the x, y and z-directions respectively. Generally, the dry season presents a better result than the wet season as revealed by the accuracy metrics. These results have led to an increased understanding of the seasonal variability inherent in the data acquired by GNSS CORS, and must be taken into consideration: in particular, for GNSS applications such as the weather prediction and water vapour estimation. This study concludes that more needs to be done regarding the maintenance of CREF to ensure data continuity and reliability for geodetic studies.

Keywords

GNSS • CORS • CREF • CSRS-PPP • seasonal variation

1. Introduction

Global Navigation Satellite System (GNSS) base stations operating from permanent and stable locations with an all-weather capability are referred to as Continuously Operating Reference Stations (CORS). Winstead et al. [2009] define CORS as static, survey-grade GNSS receivers permanently mounted on places of known geographic locations, otherwise referred to as reference stations. CORS are active reference stations, which can replace traditional base stations used in differential positioning; and they form the international geodetic reference infrastructure, as well as the national geodetic reference framework for most countries. CORS comprises of permanent stations that are strategically mounted in places satisfying the required standards such as a stable location with least obstruction so as to continually collect data throughout the day. They can also be mounted on top of buildings, in areas of easy accessibility for continuous day and night data acquisition and transmission of corrections to users over the Internet. These reference stations provide GNSS measurements that can support three-dimensional (3D) positioning with relatively higher accuracy than GNSS differential positioning due to its dense network and robust geodetic requirements. For example, CORS is greatly enhanced, because more than one reference station is used to correctly fix the position of a single point, which is a safeguard against possible false initialization of a single base station. CORS can give an instant position to an accuracy of ±20mm required by many industries [UNSW 2017 in: Ayodele et al. 2017].

It is important to note that the primary purpose of geodetic CORS is to collect data for measuring and monitoring the movement of continents so as to define and improve the reference frame and datum, and also to maintain geo-scientific and spatial datasets [ICSM 2014]. With the use of CORS network, position and velocity associated with a given site can easily be monitored. The concept of CORS can be used in the study of natural phenomena due to geophysical processes such as ground water recharge and discharge cycle, varying atmospheric processes (ionospheric cycles) and changing multi-path effects [Nwilo et al. 2013].

CORS provide the necessary infrastructure required to meet the needs of geodesy, geosciences, and professional GNSS users in different areas of application such as surveying, mapping and navigation [Rizos 2007]. A hierarchy for classifying CORS was proposed by Rizos [2008] and adopted by the Intergovernmental Committee on Survey and Mapping (ICSM). CORS are categorised into three (3) tiers based on the primary purpose for which the CORS was established, and the expected stability and accuracy of a station monument. The Tier 1 CORS is expected to be of the highest accuracy with highly stable monuments that can support geo-scientific research and can also be used for global reference frame realisation. The Tiers 2 and 3 CORS are intended for defining a national geodetic datum. It is worthy to note that the classification by Rizos has been expanded to include Tiers 4 and 5, which are established by smaller government agencies and private business groups to support the satellite positioning needs of these agencies and for the purpose of research.

Already, the Office of the Surveyor General of the Federation (OSGOF) has set up some CORS in Nigeria referred to as the Nigerian GNSS Reference Network (NIGNET). More details can be obtained from the following literature: Jatau et al. [2010], Dodo et al. [2013], Ayodele et al. [2017] and Ayodele et al. [2019]. Apart from NIGNET, there are other CORS established by various state government and private organisations within the country that include the Continuously Operating Reference Station at the Engineering Faculty (designated CREF) at the Department of Surveying and Geoinformatics, University of Lagos, Nigeria. While the NIGNET has been investigated by different researchers, most of the newly established CORS such as CREF are yet to be examined both for stability and accuracy.

It is well established that the quantity of atmospheric water vapor is typically higher in the rainy season, and lower in the dry season, thus leading to higher tropospheric delays impacting GNSS signals [Mayaki et al. 2018]. Due to the critical role played by CORS in providing positioning services to GNSS users, it is important to account for any displacement arising from the shift in their positions; as well as seasonal variability in the data acquired. Therefore, the present study computed the 3D coordinates of CREF using the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) software, and went further to investigate the seasonal variation in the coordinates to determine its reliability for research and scientific applications. The understanding of the station's reliability is critical for monitoring its temporal stability in order to detect any changes in its 3D coordinates. The coordinate differences in the rainy (wet) and dry season were explored using both exploratory and quantitative analysis techniques such as the Tukey's method of outlier detection and filtering (Crawley, 2005), Standard Deviation (SD) and Standard Error (SE). Also, Analysis of Variance (ANOVA) was used to test for any significant variation in the 3D coordinates obtained in both the wet and dry seasons. The assessment is conducted in the Cartesian Earth-centred Earth-fixed (ECEF) coordinate system.

1.1. Precise Point Positioning (PPP)

A brief overview of the principle of Precise Point Positioning (PPP) is provided here given that it is already well explained in the existing literature [e.g. Zumberge et al. 1997, Grejner-Brzezinska 2009, Ayodele et al. 2017]. PPP is a positioning technique that makes use of only one GNSS receiver to accurately fix the position of points, using satellite-based positioning techniques in real-time or post-processed mode. It is an enhanced form of single point positioning for code or phase measurements using undifferenced dual frequency pseudo-range and carrier phase observations, along with precise orbit and clock products instead of broadcast data [Cai 2009]. The positioning accuracy, availability and reliability are dependent on the number of satellites visible at the time of observation.

Several online and research software products that implement PPP processing have been developed by government agencies, universities, and the industry, and are well-documented in the literature [e.g. Leandro et al. 2007, 2010, Seredovich et al. 2012, Urquhart et al. 2014, Dach et al. 2015, Ocalan 2016, Okolie et al. 2019]. Some of the online PPP products include the AUSPOS online GPS Processing Service by Geoscience Australia, the Automatic Precise Positioning Service (APPS) by the United States Jet Propulsion Laboratory and CSRS-PPP by Natural Resources Canada (Ocalan 2016). Several researchers [e.g. Iyiola et al. 2013, Ayodele et al. 2019] have adopted the PPP technique for the determination of station coordinates when testing the reliability of CORS in Nigeria. The adoption of PPP for this purpose is due to its proven, cost-effective and timely capability for determining station coordinates, and it is accordingly adopted in this study.

1.2. CSRS-PPP

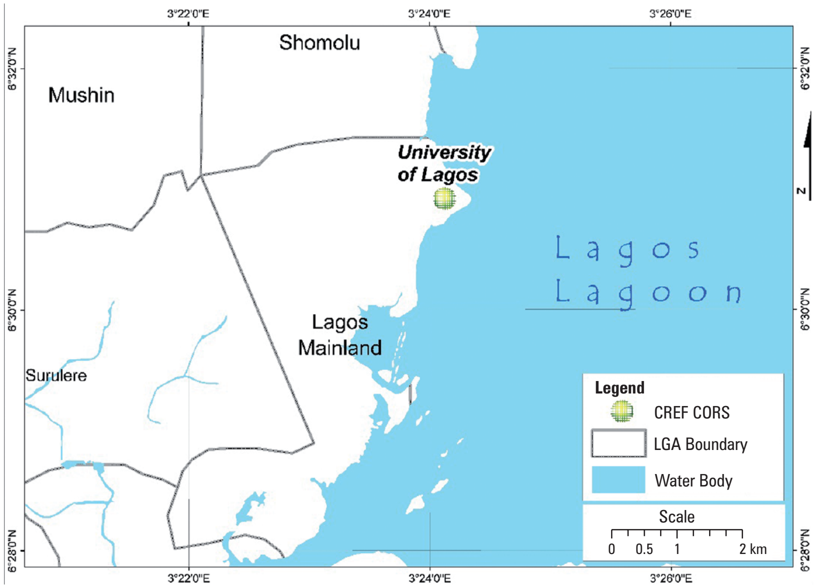
In October 2003, the Geodetic Survey Division (GSD) of Natural Resources Canada introduced an online service for GPS users with easy access to the CSRS-PPP. This PPP service allows GPS users in Canada (and abroad) to achieve accurate positioning by submitting GPS observations from a single receiver over the Internet, and the resultant precision is comparable to phase-differential GPS [Tétreault et al. 2005]. According to Mireault et al. [2008], the GSD improved the timeliness of CSRS-PPP service by introducing the use of near-real-time precise GPS orbits and clocks at 30-second intervals. This enabled absolute positioning worldwide as early as 90 minutes after data collection with centimeter or sub-decimeter accuracy level, depending on user dynamics (static or kinematic). Mireault et al. [2008] also reported improvements to CSRS-PPP modelling in the aspects of antenna phase variations and tropospheric delay mapping. More recently, in October 2019, the Canadian Geodetic Survey updated the CSRS-PPP outputs with the addition of uncertainties related to epoch transformation [NRCan 2019]. However, experience has shown that PPP software have limitations in terms of the file sizes that can be handled for processing. The choice of CSRS-PPP for this study was due to its capability for handling files with sizes significantly larger than what some other online PPP software could handle.

2. Methods

2.1. Description of CREF CORS and its location

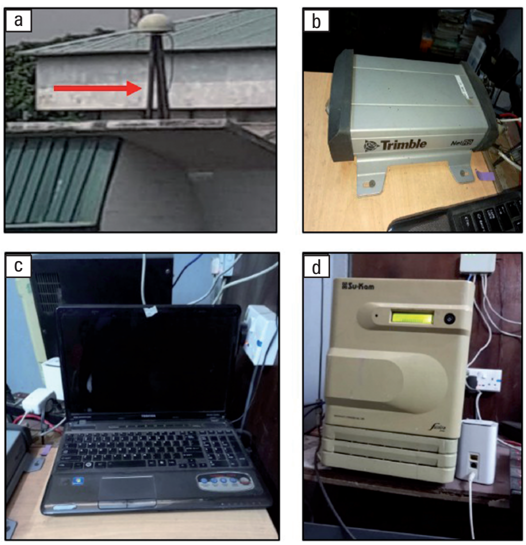
The CREF Continuously Operating Reference Station is located in the Lagos State metropolitan area at the Department of Surveying and Geoinformatics in the Faculty of Engineering, University of Lagos, South-Western Nigeria. Figure 1 presents a map of part of Lagos State showing the location of CREF CORS. CREF is a donation to the Department by the Japanese Aerospace Agency (JAXA) and was installed in 2014. The station components comprise of an antenna, Trimble Net R9 receiver, Internet facility, a router and a personal computer attached to the receiver. Some of these components are shown in Figure 2.

The antenna was installed on the roof of a one-storey building which houses the Departmental laboratories and some Faculty workshops. The location of the CREF was selected having been considered to adequately satisfy all the requirements of the establishment of a CORS. The receiver and power source are housed within the building where the antenna is mounted. Table 1 shows the station antenna information while Table 2 shows the components of the receiver. Since installation, the CREF station has logged a large volume of daily observation data. However, the data is yet to be analysed to assess its reliability for geodetic and mapping purposes; and as such provided an opportunity to investigate the data acquired overtime at the station for variability. Interestingly, there are two seasons in Nigeria: a rainy/wet season from April to October, and a dry season from November to March [Fasona et al. 2005 in: Ojeh et al. 2016].



Source: Authors' own study

Fig. 1. Map showing the location of CREF CORS at the University of Lagos, Nigeria



Source: Authors' own study

Fig. 2. CREF station components: (a) Antenna, its position being indicated by the red arrow (b) Trimble Net R2 Receiver (c) Toshiba Satellite A665 Computer (d) Su-Kam Inverter

Table 1. CREF Antenna Information

Manufacturer	Type	Serial number
Ashtech	701945D_Mw/SCIS dome	462

Table 2. Components of the Trimble Net R9 Receiver

Item	Quantity	Notes
Receiver	1	Trimble Net R9 P/N: 67668-10
AC power adaptor	1	P/N:68650 100-240VAC
Power code	1	P/N:78656
Power jack	1	P/N:59044
BNC cable	1	P/N:11517
Serial cable	1	P/N:19309-00
Ethernet cable	1	P/N:50150-00
USB cable	4	P/N:74399-00 (MiniBP – A) P/N:74404-00 (MiniBP – MiniB) P/N:74406-00 (MiniBP – Ap) P/N:74408-00 (MiniBP – B)

2.2. Data Acquisition

The daily coordinates of the CREF station were acquired by downloading the GNSS observation data (in .T02 format) directly from the station's receiver. The downloaded data covered the period from August 2016 to August 2018. The average size of each .T02 file downloaded from CREF was 30 megabytes. A massive data gap was observed from April 2017 to April 2018, spanning a year; and again in the month of June 2018, due to the problems of Internet and power supply. This problem was addressed through the installation of a battery inverter as a backup power supply. Summarily, eleven (11) months of data had been acquired for this study. The missing month in the year is June. Nevertheless, the acquired data is considered representative of the weather conditions in both the wet and dry seasons to be investigated.

2.3. Data Conversion

The Trimble receiver recorded data in the proprietary, compressed ".T02" format. In order to ensure compatibility with the CSRS online post-processing service, the Trimble ConvertToRINEX utility version 3.08 was used to convert the files from .T02 format to RINEX (Receiver INdependent EXchange) format version 2.11. After the conversion to RINEX, the average size of each .T02 file increased to 200 megabytes.

Hence, the RINEX files were compressed to an average size of 50 megabytes before uploading to CSRS-PPP.

2.4. Determination of Station Coordinates using CSRS-PPP

Users of CSRS-PPP have the option of submitting GNSS files directly online using the CSRS-PPP online service found at https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en. Using the online service, parameters such as processing mode and file format are set in addition to entering an email address to upload the results. Alternatively, the files can be submitted without the use of a web browser using a Windows utility, PPP direct v2.1. In this study, the downloaded files were submitted directly using the online tool. Table 3 shows the configurations settings used during the processing. The results were made available in the processing reports via the URL links delivered to the user email provided. The daily geocentric coordinates (X, Y, Z) were extracted from the reports and tabulated in a Microsoft Excel 2013 worksheet.

Table 3. Configuration settings used in CSRS-PPP

Processing mode	Static
Reference frame	ITRF2014
RINEX Observation file	.zip

2.5. Exploration of Station Coordinates

Following the processing of the coordinates using CSRS-PPP, an initial exploration was conducted in order to remove outliers from the data selected, which was to be used for computing the station's initial coordinates. To this end, the Tukey's method of outlier detection was used to explore the distribution of the daily coordinates in Microsoft Excel. The Tukey's method defines outliers as values greater than $Q3 + 1.5 \cdot \mathrm{IQR}$ and values less than $Q1 - 1.5 \cdot \mathrm{IQR}$, where $Q1$, $Q3$ and IQR are the lower quartile, upper quartile, and inter-quartile range respectively [Crawley 2005]. The run of Tukey's method returned no outliers in the data. This implies that all the computed coordinates can be used in further analyses. This furthermore suggests that CSRS-PPP has the capability to remove outliers in the computed coordinates before returning the final output to be uploaded. This is considered a significant advantage in the use of the service, given that data cleaning is a key aspect of data analysis if we are to achieve any meaningful result. The next step considers the computation of the initial station coordinates and seasonal variations.

2.6. Computation of the most probable initial coordinates and seasonal variations

Following the computation of the station coordinates using CSRS, the next step was the selection of the periods of observation for the analysis. The first thirty-one (31) days of the observation from August 14 to September 13, 2016 were selected, and averaged for use in determining the station's most probable initial coordinates. Besides the April 7th 2017–April 12th 2018 period, it was observed that there were very little or no gaps in the first seven days of the observation of every month at each station. Consequently, for the analysis of seasonal variations, the first 7 (available) days of each subsequent month were selected. This consideration helped reduce the data archive to a manageable size, and this translated to a reduction in the overall processing time.

The approach consisting of averaging the daily coordinates of the first months of observation in order to determine the initial coordinates of the stations remains in line with the recommendation of Janssen (2009), who suggested the use of coordinates determined during installation, after six months and eighteen months and every two years thereafter as reference marks for Tiers 1 and 2 CORS. For the assessment in different seasons, the daily station data was divided into two sets corresponding to the dry and the wet season in Lagos State. The following parameters were computed for the evaluation of the data: coordinate differences, the SD and SE of the coordinate differences. Next, using the IBM Statistical Package for the Social Sciences (SPSS) version 20, a one-way ANOVA test was conducted to explore the differences in the *X*, *Y* and *Z*-coordinates of both seasons. The null hypothesis (H_0) is that there is no significant difference in the mean values of the 3D coordinate differences for both seasons. The converse forms the alternative hypothesis (H_1). H_0 is rejected if the p-value is less than the significance level of 0.05.

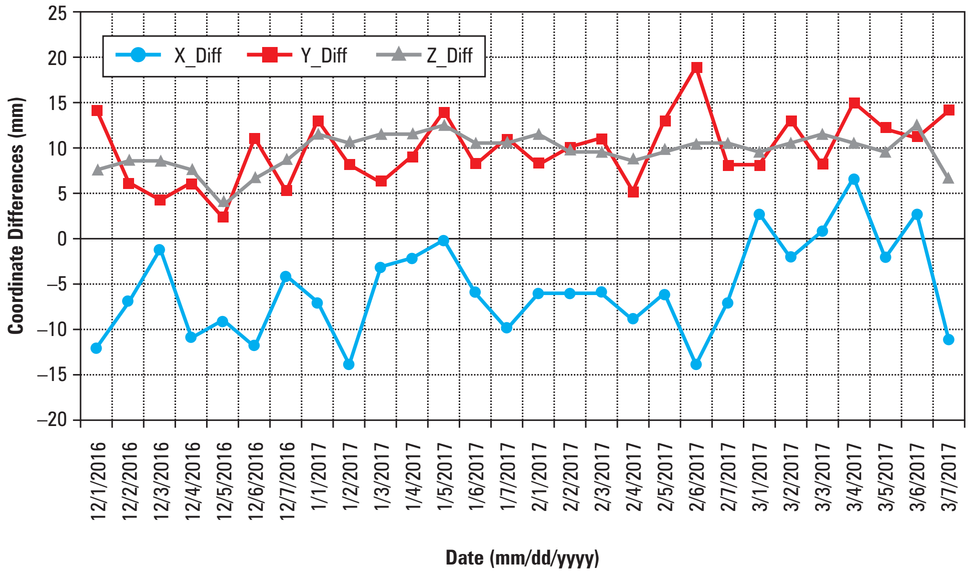
3. Results presentation and analysis

3.1. Presentation of the initial station coordinates

The initial coordinates in the *x*, *y* and *z* directions are denoted by X_i, Y_i and Z_i respectively, while the daily observed coordinates are denoted as X_o, Y_o and Z_o. After averaging, the mean initial station coordinates were obtained as follows: $X_i = 6326075.690$ m, $Y_i = 375786.473$ m and $Z_i = 719178.760$ m. These initial coordinates were used as reference values for computing the coordinate differences to be considered in the next Section 3.2.

3.2. Analysis of the daily coordinate differences – wet season versus dry season

Figure 3 presents the daily coordinate differences for twenty-eight (28) days in the dry season (months of November–March), while Figure 4 presents the daily coordinate differences for fifty-six (56) days in the wet season (months of April–October). The absolute minimum and maximum coordinate differences in the dry season are as follows: *X* [min: 0.3 mm (Jan 2017); max: 13.7 mm (Jan and Feb 2017)], *Y* [min: 2.7 mm (Dec 2016); max: 19.7 mm (Feb 2017)] and *Z* [min: 4.2 mm (Dec 2016); max: 13.2 mm (Jan and Mar 2017)]. In the wet season, the absolute minimum and maximum coordinate differences are as follows: *X* [min: 0.3 mm (Apr 2018); max: 24.7 mm



Authors' own study

Fig. 3. Daily coordinate differences at CREF – dry season

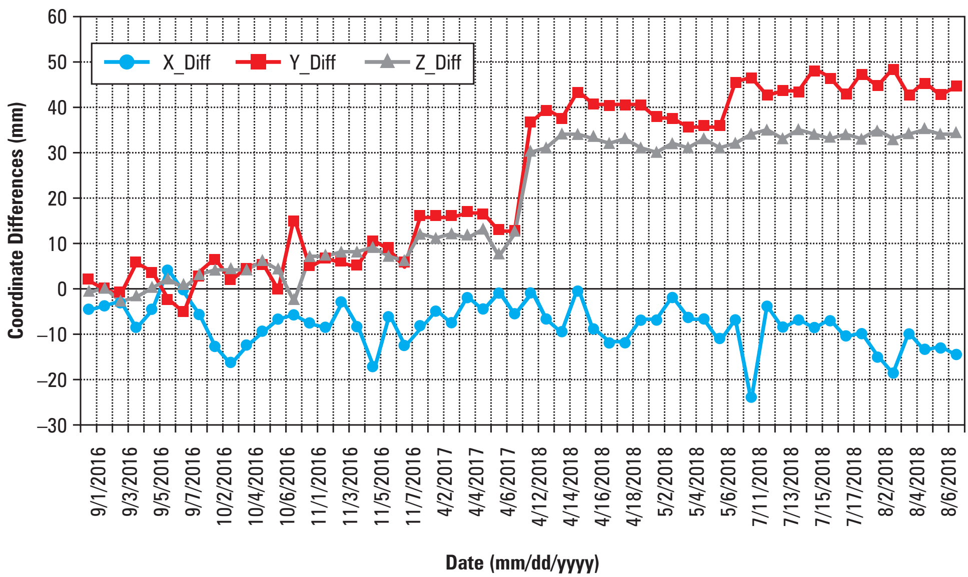


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Fig. 4. Daily coordinate differences at CREF – wet season

(Jul 2018)], *Y* [min: 0.3 mm (Sep and Oct 2016); max: 48.7 mm (Jul and Aug 2018)] and *Z* [min: 0.2 mm (Sep 2016); max: 35.2 mm (Jul and Aug 2018)]. The highest daily coordinate differences in all the three directions occurred in the wet season. This signifies the season with a higher variability and consequently a lower level of reliability. Also, from Figure 3, the differences in the *X*-coordinates remain the most variable, and are consistently lower than the *Y* and Z-coordinate differences. On the other hand, the *Z*-coordinate differences remain the least variable, and by extension, the most reliable estimate. Overall, the total variability between the *x*, *y*, and z difference is about 25 mm overtime. However, from Figure 4 in the wet season, there is a sharp variation in the total variability between the three coordinate differences as observed over the months of heavy rainfall from the 2018 data. Interestingly, the trend in the *x*-coordinate differences is uniform. As a result, this might necessitate a further investigation into the seasonal variability given this observation in order to arrive at a firm conclusion.

Table 4. SD and SE of the *X*, *Y* and *Z* coordinate differences in both seasons

	Season	N	Mean (mm)	S.D (mm)	S.E (mm)	95% C.I for mean		Min (mm)	Max (mm)
						Lower Bound (mm)	Upper Bound (mm)		
$X_0 - X_i$ (mm)	Dry	28	−5.21	5.38	1.02	−7.29	−3.12	−13.74	7.26
	Wet	56	−8.06	5.17	0.69	−9.45	−6.68	−24.74	4.26
	Total	84	−7.11	5.38	0.58	−8.28	−5.94	−24.74	7.26
$Y_0 - Y_i$ (mm)	Dry	28	10.46	3.90	0.74	8.95	11.97	2.74	19.74
	Wet	56	24.55	18.58	2.48	19.57	29.52	−5.26	48.74
	Total	84	19.85	16.68	1.82	16.23	23.47	−5.26	48.74
$Z_0 - Z_i$ (mm)	Dry	28	10.27	2.03	0.38	9.48	11.05	4.16	13.16
	Wet	56	19.29	14.41	1.93	15.43	23.15	−2.84	35.16
	Total	84	16.28	12.54	1.37	13.56	19.00	−2.84	35.16

For an analytical and holistic overview of the variations in the station's coordinates in both seasons, all the months were summarised into just two classes corresponding to the dry and the wet season. Table 4 presents the SDs and SEs of coordinate differences for both the dry and the wet season. In terms of the mean coordinate differences, the dry season months had mean coordinate differences of −5.2 mm, 10.5 mm, and 10.3 mm in the *x*, *y* and *z*-directions, respectively, while the wet season months had mean coordinate differences of −8.1 mm, 24.5 mm and 19.3 mm in the *x*, *y* and *z*-directions, respectively. In terms of the SDs, the dry season months had SDs of 5.4 mm, 3.9 mm, and 2.0 mm in the *x*, *y* and *z*-directions, respectively, while the wet season months had SDs of 5.2 mm, 18.9 mm and 14.4 mm in the *x*, *y* and *z*-directions, respectively. In terms of the SEs, the dry season months had SEs of 1.0 mm, 0.7 mm, and 0.4 mm in the *x*, *y* and *z*-directions, respectively, while the wet season months had SEs of 0.7 mm, 2.5 mm and 1.9 mm in the *x*, *y* and *z*-directions, respectively. Generally, the lowest coordinate differences, SDs and SEs are associated with the dry season months while the highest coordinate differences, SDs and SEs are associated with the wet season months. These findings are in agreement with the submission of Mayaki et al. [2018] that higher levels of Zenith Tropospheric Delay (ZTD) typically occur within the days of year (DoY) 100–300, which coincides with the wet season months of April to October while the lower ZTD estimates, which mean lower amounts of atmospheric water vapor, are typically found in the dry season months November to March (around DoY 300–365/366 and 1–100).

3.3. Analysis of variance in station coordinates

The results of the one-way ANOVA test in Table 5 shows that there are significant differences in the *X*, *Y*, *Z* coordinates differences in both wet and dry seasons. This suggests that the data logged by the station in both the wet and the dry seasons may not have an equal level of reliability. Further analysis would be required to confirm this in order to be sure that the outcome is not merely random. For example, more than a year data would be required to ascertain the magnitude the variability between the dry and the wet seasons. Accordingly, this result should be applied considering some of the limitations in the study.

Table 5. Results of ANOVA Test

		Sum of squares (mm)	df	Mean square (mm)	F	Sig.
$X_0 - X_i$	Between Groups	152.38	1	152.38	5.55	0.02
	Within Groups	2253.18	82	27.48		
	Total	2405.56	83			
$Y_0 - Y_i$	Between Groups	3705.48	1	3705.48	15.66	0.00
	Within Groups	19398.55	82	236.57		
	Total	23104.04	83			
$Z_0 - Z_i$	Between Groups	1518.01	1	1518.01	10.79	0.00
	Within Groups	11534.80	82	140.67		
	Total	13052.81	83			

4. Conclusions

The seasonal variability in CREF CORS at the University of Lagos was assessed using the data downloaded from the station and processed with CSRS-PPP software. The analysis performed suggests that CREF possesses good data quality with standard deviations that were generally less than 20 mm in all the coordinate differences. It was noted that the least errors occurred in the *z*-direction suggesting the direction having the most accurate coordinates. It was also noted that the differences in the *z* and *y* directions are more correlated than the differences in *x*. Also, the seasonal variability test conducted using one-way ANOVA showed that statistically, there is a significant difference between the observations in the dry and the wet season. This means that the two data sets may have differing levels of application, and must be considered as an important factor. Summarily, this study has enabled the computation of the initial coordinates of CREF and the understanding of its performance, particularly on a seasonal basis. More importantly, this study has also enabled the understanding of whether the station is fulfilling its main goal. That is, the provision of data for research and scientific purposes at the Department of Surveying and Geoinformatics. Currently, more needs to be done to ensure its continuous tracking and transmission of data in order to achieve this objective. Therefore, the following recommendations should be considered to fully harness the potential of the station:

1. A lightning protector should be provided to curb any possible destruction of the antenna by lightning and thunderstorm.
2. The station has been configured to log data at an interval of 1 second. This poses the challenge of consuming large memory, hence an external drive with a large storage capacity should be acquired for regular data archiving.
3. Positioning data from CREF should be well marketed to public users. This is to generate funds to maintain the station.
4. Lastly, the upgrade of CREF to a real-time kinematic GNSS network should be considered.

Acknowledgments

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References

Ayodele E.G., Okolie C.J., Ezeigbo C.U., Fajemirokun F.A. 2017. Evaluation of Continuously Operating Reference Stations (CORS) Data for the Definition of Nigerian Geodetic Reference Frame. Paper presented at the Nigerian Association of Geodesy 2017 General Assembly/Conference, Port-Harcourt, Nigeria. DOI: 10.13140/RG.2.2.17375.82085/1

Ayodele E.G., Okolie C.J., Mayaki O.A. 2019. An Assessment of the Reliability of the NIGNET Data. Nigerian Journal of Environmental Sciences and Technology, 3(1), 18–29. https://doi.org/10.36263/nijest.2019.01.0097

Cai C. 2009. Precise Point Positioning using Dual-Frequency GPS and GLONASS Measurements. M.Sc.E. thesis. Department of Geomatics Engineering, Technical Report No. 20291, University of Calgary, Alberta, Canada.

Crawley M.J. 2005. Statistics: An Introduction using R. John Wiley and Sons Ltd, West Sussex, England.

Dach R., Lutz S., Walser P., Fridez P. 2015. Bernese GNSS Software Version 5.2. User manual of the Bernese GNSS Software, Version 5.2. http://www.bernese.unibe.ch/docs/DOCU52.pdf

Dodo J., Yakuba T., Ojigi L., Tsebeje S. 2013. Determination of the best-fit tropospheric delay model on the Nigerian Permanent GNSS Network (NigNet). GNSS Positioning and Measurement II and Remote Sensing, 6525, 6–10.

Fasona M., Omojola A., Odunuga S., Tejuoso O., Amogu N. 2005. An appraisal of sustainable water management solutions for large cities in developing countries through GIS: The case of Lagos, Nigeria. Proceeding of the Symposium S2 Held during the 7th IAHS Scientific Assembly, Foz do Iguaçu, Brazil, 3–9 April 2005, 49–57.

Grejner-Brzezinska D.A. 2009. Mapping and Surveying. Presented at the First Workshop on Satellite Navigation Science and Technology for Africa. Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, March 31, 2009.

ICSM 2014. Guideline for Continuously Operating Reference Stations. Intergovernmental Committee on Surveying and Mapping, P.C.O.G. (ed.).

Iyiola F., Ogundele R., Oluwadare C., Kufoniyi O. 2013. Integrity Check on Ground Control Points Using NIGNET's Continuously Operating Reference Stations. FIG Working Week, Abuja, Nigeria.

Janssen V. 2009. Precision Rules! How to Establish an AusCORS Site, Position Magazine, Intermedia Group, Pyrmont, NSW, 44.

Jatau B., Fernandes R.M., Adebomehin A., Gonçalves N. 2010. NIGNET – The new permanent GNSS network of Nigeria. Proceedings of FIG Congress, 2010.

Leandro R.F., Santos M.C., Langley R.B. 2007. GAPS: The GPS Analysis and Positioning Software – A Brief Overview. ION GNSS 20th International Technical Meeting of the Satellite Division. Fort Worth, TX, 1807–1811. http://gaps.gge.unb.ca/publications/iongnss2007.leandro.gaps.pdf

Leandro R.F., Santos M.C., Langley R.B. 2010. Analysing GNSS data in Precise Point Positioning Software. GPS Solutions. DOI: 10.1007/s10291-010-0173-9

Mayaki A.O., Nikolaidou T., Santos M., Okolie C.J. 2018. Comparing the Nigerian GNSS Reference Network's Zenith Total Delays from Precise Point Positioning to a Numerical Weather Model. [In:] International Symposium on Advancing Geodesy in a Changing World. International Association of Geodesy Symposia, 149, eds. J. Freymueller, L. Sánchez. Springer, Cham.

Mireault Y., Tétreault P., Lahaye P., Héroux P., Kouba J. 2008. Online Precise Point Positioning. A New, Timely Service from Natural Resources Canada. GPS World, September 2008.

NRCan. 2019. Precise Point Positioning. https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en (accessed: 4th November, 2019).

Nwilo P.C., Dodo J.D., Edozie R.U., Adebomehin A. 2013. The Nigerian Geocentric Datum (NGD2012): Preliminary Results. FIG Working Week 2013 Environment for Sustainability, 6–10.

Ocalan T. 2016. Accuracy Assessment of GPS Precise Point Positioning (PPP) Technique using different Web-Based Online Services in a Forest Environment. Prethodno priopćenje – Preliminary communication, Šumarski list, 7–8, 357–368. https://doi.org/10.31298/sl.140.7-8.4

Ojeh V.N., Balogun A.A., Okhimamhe A.A. 2016. Urban-Rural Temperature Differences in Lagos. Climate 2016, 4, 29. DOI:10.3390/cli4020029

Okolie C.J., Ayodele E.G., Mayaki O.A., Daramola O.E. 2019. Assessing the Position Accuracy of NIGNET using Precise Point Positioning Technique. Manuscript under review.

Rizos C. 2007. Alternatives to current GPS-RTK services and some implications for CORS infrastructure and operations. GPS Solutions, 11(3), 151–158.

Rizos C. 2008. Multi-Constellation GNSS/RNSS from the Perspective of High Accuracy Users in Australia. Journal of Spatial Sciences, 53, 29–63.

Seredovich V.A., Ehigiator-Irughe R., Ehigiator M.O. 2012. PPP Application for estimation of precise point coordinates – case study of a reference station in Nigeria. FIG Working Week, Rome, Italy, 6–10 May 2012. https://www.fig.net/resources/proceedings/fig_proceedings/fig2012/papers/ts02b/TS02B_seredovich_ehigiatorirughe_et_al_5496.pdf

Tétreault T., Kouba J., Héroux P., Legree P. 2005. CSRS-PPP: An Internet Service for GPS User Access to the Canadian Spatial Reference Frame. Geomatica, 59, 1, 17–28. https://doi.org/10.5623/geomat-2005-0004

UNSW. 2017. What is a CORS Network? The University of New South Wales website. http://www.sage.unsw.edu.au/currentstudents/ug/projects/Gowans/Thesis/What_is_it.html/ (accessed: 28 August, 2017).

Urquhart L., Santos M.C., Garcia C.A., Langley R.B., Leandro R.F. 2014. Global Assessment of UNB's Online Precise Point Positioning Software. [In:] Earth on the Edge: Science for a Sustainable Planet, eds. C. Rizos, P. Willis. Springer-Verlag, Berlin, Heidelberg, 585–589. http://gaps.gge.unb.ca/publications/GlobalAssessmentUNBsPPP.pdf. DOI: 10.1007/978-3-642-37222-3.

Winstead A., Norwood S., Fulton J.P., Harbuck T. 2009. Application of CORS in Agriculture. Precision Agriculture Series. Timely Information Web publication.

Zumberge J.F., Heflin M.B., Jefferson D.C., Watkins M.M., Webb F.G. 1997. Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from large networks. Journal of Geophysical. Research, 102(B3), 5005–5018.

Prof. Peter Chigozie Nwilo
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: pcnwilo@unilag.edu.ng
ORCID: 0000-0002-1740-8008

PhD Emmanuel Gbenga Ayodele
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: eayodele@unilag.edu.ng
ORCID: 0000-0003-2684-2276

MSc/MA Chukwuma John Okolie
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: cokolie@unilag.edu.ng
ORCID: 0000-0003-4542-7051

MSc/MA Michael Joseph Orji
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: morji@unilag.edu.ng
ORCID: 0000-0002-1971-4367

MSc/MA Mnguhenen Funmilayo Marve
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: shan4pepe@gmail.com
ORCID: 0000-0003-2809-8196

MSc/MA Esther Abidemi Oyelade
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: estheroyelade@ymail.com
ORCID: 0000-0002-5493-1252

Olagoke Emmanuel Daramola
University of Lagos
Department of Surveying and Geoinformatics
Lagos, Nigeria
e-mail: eodaramola@unilag.edu.ng
ORCID: 0000-0001-5350-194X