Comparing the Nigerian GNSS Reference Network's Zenith Total Delays from Precise Point Positioning to a Numerical Weather Model

A. O. Mayaki, T. Nikolaidou, M. Santos, and C. J. Okolie

Abstract

As a pivotal infrastructure for the socio-economic development of Nigeria, the Nigerian Global Navigation Satellite Systems (GNSS) Reference Network – NIGNET – can serve as a tool for weather and climate monitoring, by obtaining and analyzing the neutral atmospheric Zenith Total Delays (ZTD) from processed GNSS data. With the use of surface meteorological measurements, the ZTD can be transformed to the integrated water vapor content in the neutral atmosphere, which is an essential parameter in weather forecasting, and climate change and variability analysis. The focus of this research is to assess the adaptability of the NIGNET for meteorological applications using the global positioning system precise point positioning (PPP) derived ZTD at the stations. ZTD estimates are derived from daily data obtained from the NIGNET and International GNSS Service (IGS) stations spanning the years 2011–2016. These estimates are compared with ray-traced delay estimates from the National Centre for Environmental Prediction Reanalysis II (NCEP II) global Numerical Weather Model (NWM) and the IGS zenith path delay products. A comprehensive analysis is performed to assess the level of agreement of the different ZTD estimates and to identify possible systematic effects from the different sources. Comparisons between the PPP and NCEP II NWM ZTD estimates show a range of mean offsets from −6.4 to 23.9 mm, and standard deviations from 33.1 to 44.9 mm. With the PPP and IGS ZTD estimates, mean offsets of −2.4 and −0.1 mm, and standard deviations of 9.9 and 13.8 mm are obtained.

Keywords

Global Positioning System · Nigerian GNSS Reference Network · Numerical Weather Model · Precise Point Positioning · Zenith Total Delay

1 Introduction

Dry gases and water vapour affect the accuracy of point positions on Earth by delaying the Global Navigation Satellite Systems (GNSS) signals propagating through the neutral atmosphere (UCAR 2011) to ground receivers. This delay, called the neutral atmospheric or total delay, depends on the neutral atmosphere's refractive index which is a function of temperature, pressure and humidity. In GNSS analysis, the neutral atmospheric delay consists of a modelled hydrostatic delay and an estimated wet delay. At the line of sight, these

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delays are usually referred to the zenith direction by means of mapping functions used to convert the slant delays at the actual elevation angle of satellite observations to the zenith (Isioye et al. 2015).

Many countries in the world employ networks of Continuously Operating Reference Stations (CORS) for multi-disciplinary applications such as surveying, mapping, navigation and meteorology (Isioye et al. 2016). In Nigeria, the Nigerian GNSS Reference Network (NIGNET) CORS serve as the fiducial network that defines the national spatial reference framework based on modern space geodesy techniques. NIGNET also contributes to the African Geodetic Reference Frame (AFREF) project (Jatau et al. 2010; Farah 2009). However, NIGNET can also be used as a weather and climate monitoring tool through the processing of its data and the analyses of the derived neutral atmospheric parameters, such as the zenith total delay (ZTD), the zenith wet delays (ZWD) and the gradients. The ZTD and the integrated water vapor (which is derived from the ZWD) can be assimilated into local/regional and global numerical weather models (NWM), to improve weather forecasting and climate monitoring (Ahmed et al. 2014, 2015). This would aid, for example, in the identification of potential severe weather activity in the country and the tracking of weather fronts. In this work, however, we concentrate on the ZTD.

Precise Point Positioning (PPP) is a well-known technique that utilizes precise satellite orbit and clock information in the processing of observations produced by a single GNSS receiver, to determine its 3-D position along with other parameters such as the receiver clock error, the ambiguities and the ZTD (Zumberge et al. 1997; Leandro et al. 2010). Therefore, this technique renders GNSS suitable for meteorological studies by providing information about the atmospheric water vapour from the determined ZTD (Isioye et al. 2016).

In this chapter, we compare the ZTDs obtained from the GNSS PPP technique with those from an NWM and from the International GNSS Service (IGS). GNSS observations for 16 NIGNET and IGS stations in and around Nigeria were obtained. These observations were processed with the GNSS Analysis and Positioning Software (GAPS) PPP package of the University of New Brunswick (Urquhart et al. 2014). We calculated ZTD using the National Centre for Environmental Prediction Reanalysis II (NCEP II) global NWM (Kanamitsu et al. 2002) for all the stations employed in the study. NCEP II was chosen because of its quality and tested performance for geodetic applications[1] (Urquhart and Santos 2011) as well as its free data availability.[2] We also used the zenith path delay (ZPD) products, as generated by the IGS for its stations (Byun and Bar-Sever 2009), for the validation of the GAPS ZTD estimates of those stations. For simplicity, in this work, the ZTD estimates from GAPS, IGS and NCEP II NWM are referred to as "GAPS", "IGS" and "NCEP II", respectively.

The chapter is structured as follows. The data used, and the methodology employed are discussed in Sect. 2. Section 3 presents the results with discussion and analysis about the statistical and graphical comparisons between the GAPS, IGS and NCEP II ZTD estimates. Conclusions finalize the chapter.

2 Data and Methodology

A map of the study area and the distribution of the stations is shown in Fig. 1. Daily NIGNET and IGS observation files, spanning the years 2011–2016, with a data logging interval of 30 s, of 14 CORS and 2 IGS stations, were processed using GAPS. The observations used are the ionosphere-free linear combinations of the GPS undifferenced L1 and L2 carrier-phase and pseudo range measurements. For the processing, which was done in static mode, the IGS final orbit (sampled at 15-min intervals) and 30-s clock products were utilized in a sequential least-squares filter, with the Vienna Mapping Functions 1 – VMF1 – (Boehm et al. 2006) as the a priori hydrostatic delay model and mapping function, and an elevation angle cut-off of 10°. Satellites and receivers' antennae were corrected for phase centre offsets and phase centre variations. The coordinates of the stations were determined based on the International Terrestrial Reference Frame (ITRF) 2008 solution (Altamimi et al. 2011), and the ambiguities were estimated as real numbers. The ZTD estimates, together with their horizontal gradients, were estimated at every epoch. The horizontal gradients model the asymmetry of the delay in the north-south and east-west directions, and its estimation has shown to improve the position of stations (Balidakis et al. 2018) especially under the presence of extreme weather events (Nikolaidou et al. 2018). It should be noted that the use of the final orbit and clock products is to ensure high quality ZTD estimation useful for climate monitoring but not for weather forecasting due to its latency.

The ZPD products of the IGS stations are also produced through PPP with the same process noise as used in GAPS but sampled at 5-min intervals. The full list of the processing options is given in Byram and Hackman (2014). These ZPDs have a nominal accuracy of 4 mm and a latency of less than 4 weeks (www.igs.org/products).

The NCEP II ZTD estimates were retrieved from ray-tracing using the University of New Brunswick's in-house software developed by Nievinski and Santos

[1] http://unb-vmf1.gge.unb.ca/About.html.

[2] https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html.

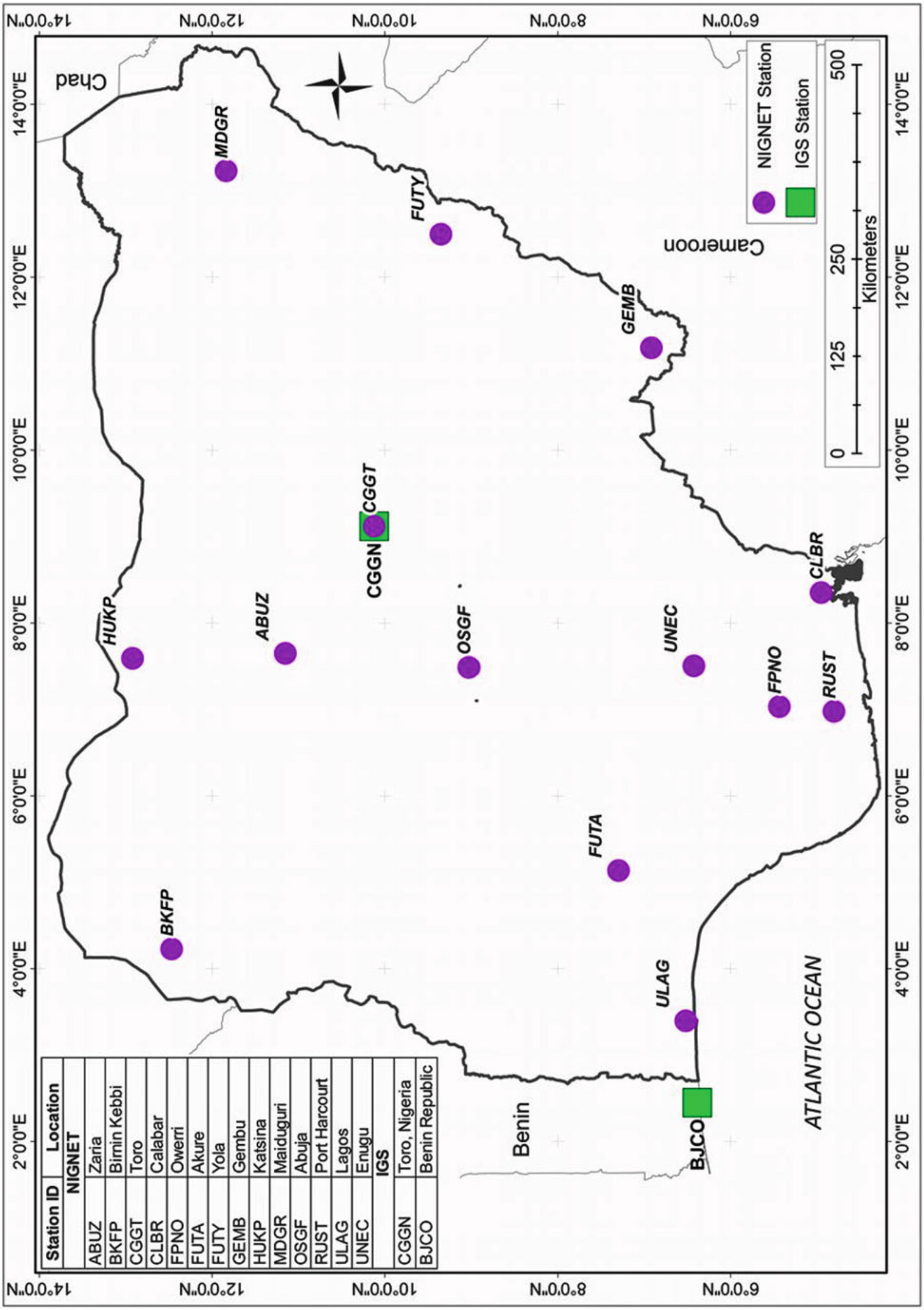

Fig. 1 Map of study area with GNSS reference stations

(2010), with computed station-specific zenith hydrostatic and wet delays, and horizontal gradients. A 2-D ray-tracing was performed at the initialization intervals of 0, 6, 12, and 18 h (temporal resolution) of the NCEP Reanalysis II global NWM, with a horizontal resolution of 2.5° × 2.5°.

In PPP static post-processing, it takes the first few hours for the 3-D coordinate of a point to become accurate to the centimetre level (Abdallah 2015; Bolbol et al. 2017). Because of this, the initial 2 h of the GAPS estimates were not considered for the analysis. Consequently, the first daily estimates (0-h ZTD estimates) of the NCEP II, and the initial 2 h of the IGS ZPDs were also neglected in the analysis. For comparing GAPS with NCEP II, daily 6-, 12- and 18-h GAPS values, averaged over 5-min windows centred around the exact 6-, 12- and 18-h estimates, were used. The same 5-min averaging was done for the comparison between GAPS and the IGS ZTDs to match the IGS interval. Statistic of values (the mean offsets (μ), standard deviations (σ) and root mean square (rms) values of the differences) of GAPS with respect to NCEP II and IGS values for each station, were determined.

3 Results and Discussion

3.1 Comparison Between GAPS and NCEP II

In this section, the quality of the ZTD estimates from GAPS is evaluated in comparison to those from NCEP II. Figure 2a–f show the GAPS and NCEP II estimates for six stations across the country in the year 2012. As shown in the plots, GAPS is generally in agreement with NCEP II; the statistics for the six stations (CLBR, ULAG, ABUZ, FUTY, BJCO and CGGN) is given in Table 1. The other stations in other years show a similar behaviour.

According to Eludoyin et al. (2014), the two major seasons in Nigeria are the rainy season (April to October) and the dry season (November to March). The quantity of atmospheric water vapor is typically higher in the rainy season, and lower in the dry season. Disregarding altitude, higher amounts of atmospheric water vapor are related to higher ZTD estimates and vice versa. Examples of these are seen in Fig. 2a–f; higher ZTD estimates typically occur within the days of year (DOY) 100–300, which coincides with the months April to October. 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). Studies by Olusola et al. (2015) and Willoughby et al. (2002) indicate that because the southern part of Nigeria is closer to a coastline of the Atlantic Ocean, its atmosphere is more humid (more water vapor content) than the atmosphere in the northern part of the country. In both the GAPS and the NCEP II plots, the southern stations have estimates as high as 2.75 m (Fig. 2a, b, e). However, the estimates in the northern stations (Fig. 2c, d, f) generally do not exceed 2.65 m.

Portrayed within DOY 200–250 (mid of July to early September), is a decrease in the GAPS estimates for the stations ULAG and BJCO (Fig. 2b, e). This decrease coincides with a phenomenon known as the "August break" (Ogungbenro et al. 2014), which is characteristic of the precipitation pattern in the southern part of the country and is consistent with the findings of Willoughby et al. (2002). Rapid changes in the GAPS and NCEP II estimates can be attributed to rapid changes in the humidity around the stations. Observed gaps at certain epochs in the plots are due to the non-availability of observations from the NIGNET stations.

Overall, for all the years combined, and for each NIGNET and IGS station, the differences between GAPS and NCEP II have mean offsets varying between −6.4 and 23.9 mm, and standard deviations between 33.1 and 44.9 mm. Table 2 gives the overall statistics for all the stations for all the years of study.

3.2 Comparison Between GAPS and IGS

In this comparison, the year 2016 is considered because of the substantial amount of ZPD products available for the station CGGN. Figure 3a, b show the 2016 GAPS and IGS estimates for the stations CGGN and BJCO, indicating very good agreement. The observed gaps at certain epochs in the plots are due to the non-availability of observations from the NIGNET station and the non-availability of ZPD products from the IGS.

For the combination of all years, Table 3 gives the statistics of the comparison between GAPS and IGS for the stations BJCO and CGGN.

3.3 Comparison Between GAPS, IGS and NCEP II

The comparisons here are only done for the IGS stations and are restricted to the epochs which have ZTD estimates from all three sources between 2011 and 2016. Figure 4a–c show the histograms for the offsets between NCEP II and GAPS, NCEP II and IGS, as well as IGS and GAPS.

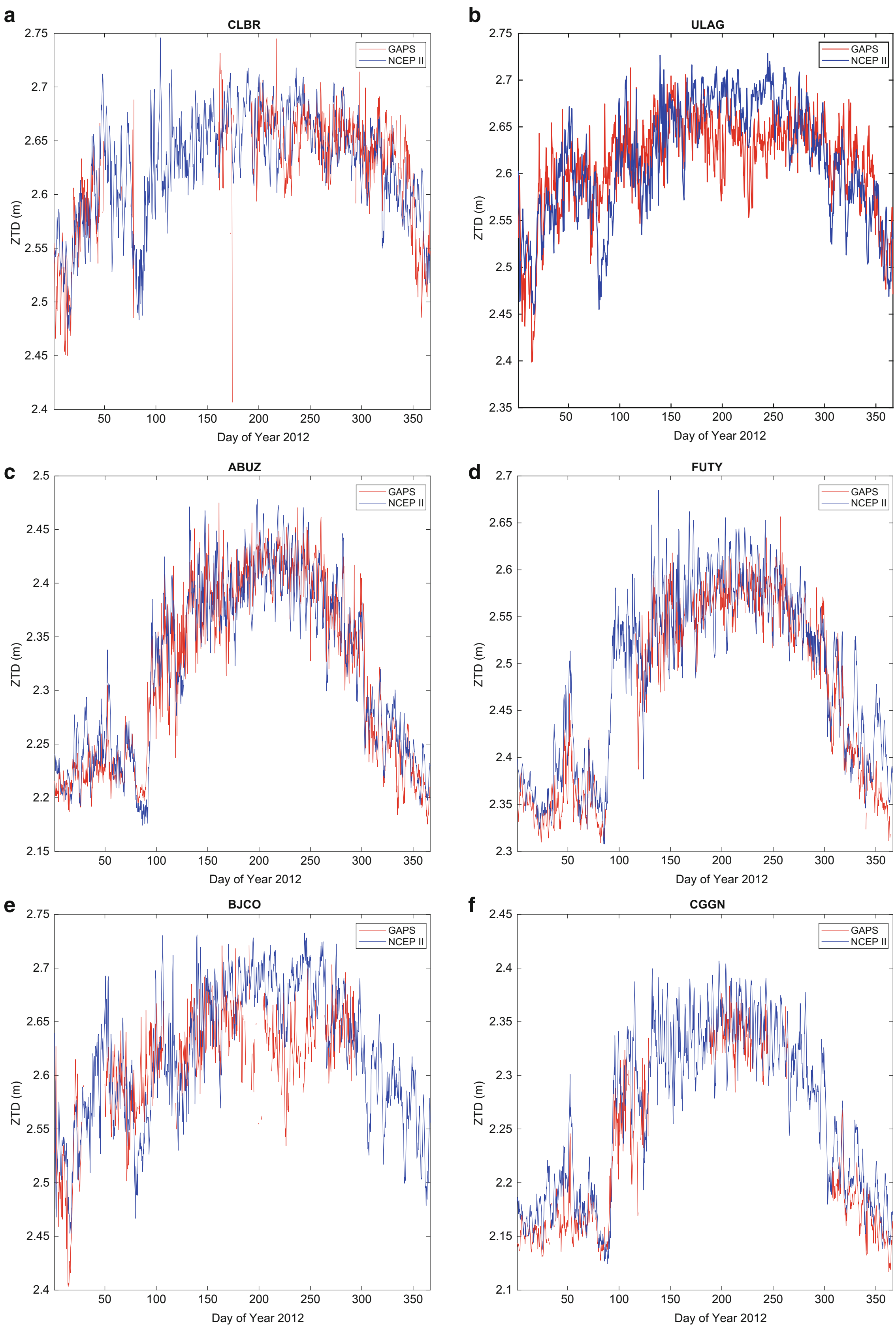

Fig. 2 (**a**) GAPS and NCEP II ZTD for CLBR in 2012. (**b**) GAPS and NCEP II ZTD for ULAG in 2012. (**c**) GAPS and NCEP II ZTD for ABUZ in 2012. (**d**) GAPS and NCEP II ZTD for FUTY in 2012. (**e**) GAPS and NCEP II ZTD for BJCO in 2012. (**f**) GAPS and NCEP II ZTD for CGGN in 2012

Table 1 2012 ZTD difference between GAPS and NCEP II

Stations	μ (mm)	σ (mm)	rms (mm)
ABUZ	4.9	31.3	31.7
BJCO	17.9	48.2	51.4
CGGN	20.8	29.3	35.9
CLBR	3.1	39.4	39.5
FUTY	17.5	37.3	41.2
ULAG	2.5	45.9	46.0

Table 2 ZTD difference between GAPS and NCEP II (NIGNET and IGS stations)

Stations (years of data used)	μ (mm)	σ (mm)	rms (mm)
ABUZ (2011–2014, 2016)	3.4	36	36.2
BKPF (2011–2016)	17.7	41.7	45.3
CGGT (2011–2013)	9.5	38	39.2
CLBR (2011–2016)	−6.4	40.2	40.7
FPNO (2012–2014, 2016)	16	34.6	38.1
FUTA (2012–2013)	23.9	38.2	45.1
FUTY (2011–2016)	16	44	46.8
GEMB (2012–2013, 2015)	−4.3	33.1	33.3
HUKP (2012–2015)	10.1	35.8	37.2
MDGR (2011, 2013–2014)	18.3	36	40.3
OSGF (2011–2014, 2016)	14.1	44.4	46.6
RUST (2011–2013)	−3	40.9	41
ULAG (2011–2013)	4.5	37.7	38
UNEC (2011–2014, 2016)	3.9	43.8	44
BJCO[a] (2011–2016)	6.6	40.9	41.4
CGGN[a] (2011–2016)	11.9	44.9	46.5

[a]IGS stations

Table 3 ZTD difference between GAPS and IGS (IGS stations)

Stations (years of data used)	μ (mm)	σ (mm)	rms (mm)
BJCO (2011–2016)	−2.4	13.8	14
CGGN (2015–2016)	−0.1	9.9	9.9

For the comparisons of NCEP II between GAPS and IGS (Fig. 4a, b), the large standard deviations may be attributed to the variability and the higher concentration of atmospheric water vapour at the lower latitudes/equatorial regions as stated in Li et al. (2015) and Dousa and Bennitt (2013). It could also be due to insufficient amounts of atmospheric observations assimilated into the NCEP II NWM from this part of the world, resulting in estimations with larger errors than in, for example, North America and Europe. The closer agreement between IGS and GAPS (Fig. 4c) can be attributed to both being obtained through the same technique, except for differences in the elevation cut-off angles (10° for GAPS and 7° for IGS) and a priori tropospheric models and mapping functions (VMF1 for GAPS and Niell model and Global Mapping Functions for IGS) used. The precision of the IGS and GAPS comparison agrees well with the result of Guo (2015).

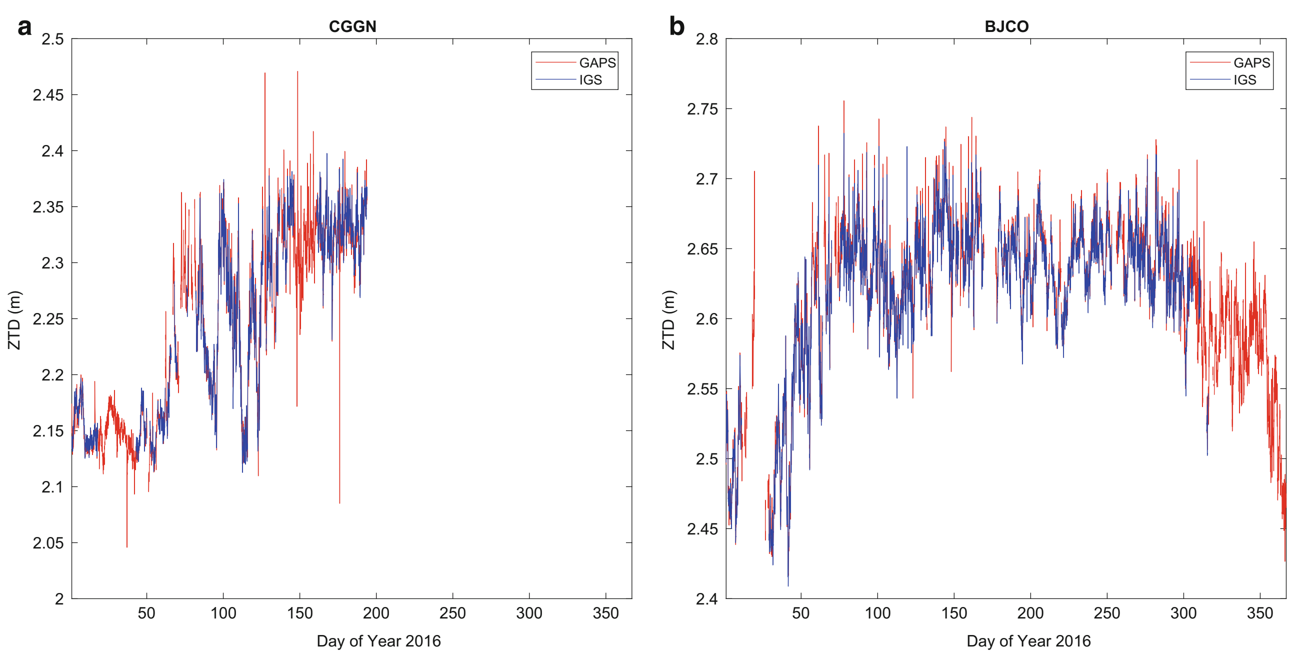

Fig. 3 (**a**) GAPS and IGS ZTD for CGGN in 2016. (**b**) GAPS and IGS ZTD for BJCO in 2016

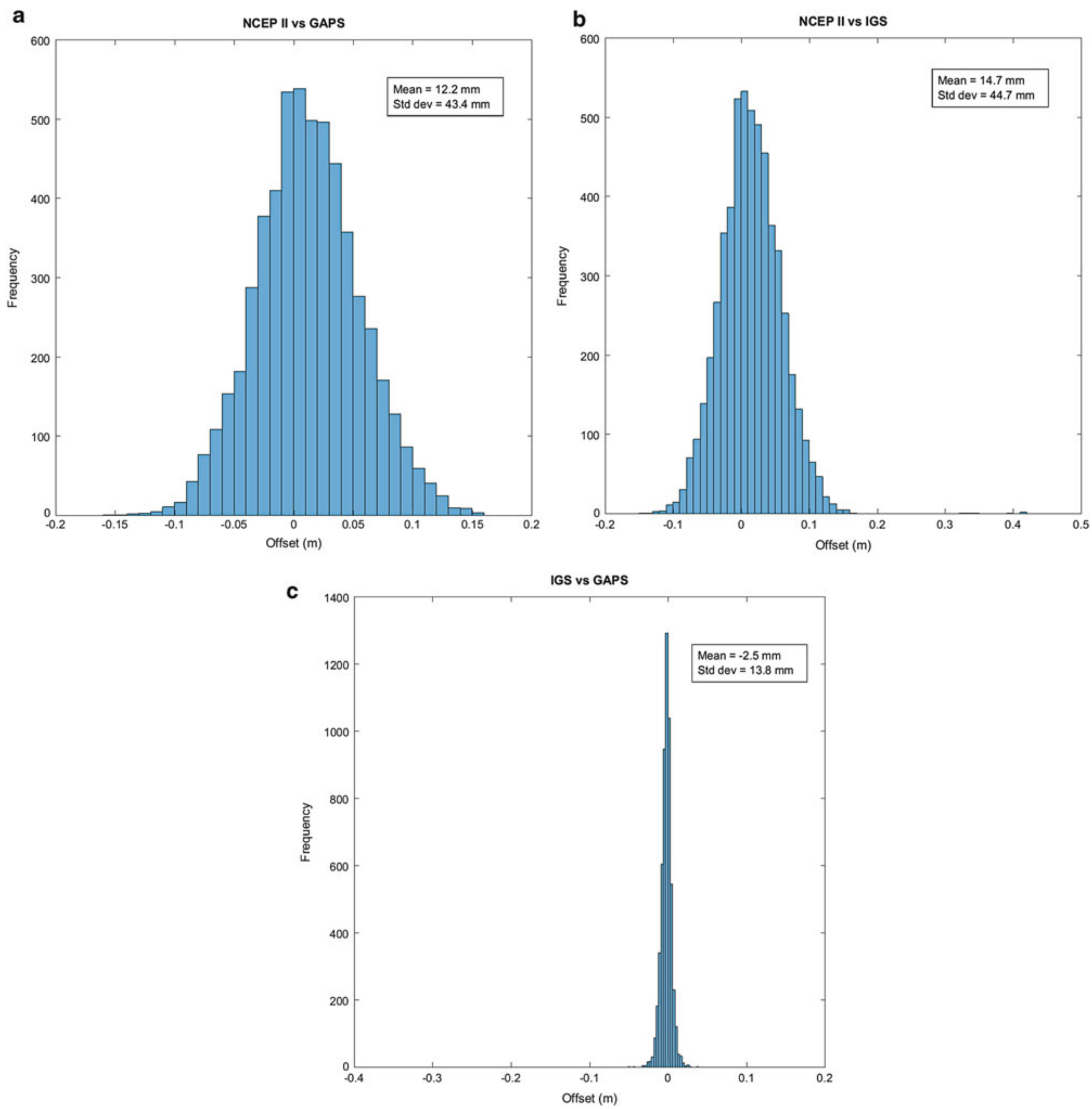

Fig. 4 (**a**) NCEP II and GAPS offset histogram for the IGS stations. (**b**) NCEP II and IGS offset histogram for the IGS stations. (**c**) IGS and GAPS offset histogram for the IGS stations

4 Conclusion

The adaptability of the NIGNET for meteorological studies in Nigeria was assessed using the ZTD estimates from the PPP processing of GPS observations. The precision of these estimates was assessed with comparisons to ray-traced ZTDs from NCEP Reanalysis II NWM and IGS ZPD products. The estimated ZTD for the NIGNET stations depict known latitudinal and seasonal variations. In comparing the ZTD estimates from the different sources, the results show that the mean offsets between the GAPS PPP and the NCEP II estimates for all the NIGNET and IGS stations, for the 6-year duration, vary between −6.4 and 23.9 mm, with their standard deviations between 33.1 and 44.9 mm. The difference between the GAPS PPP and the IGS estimates gives mean offsets of −2.4 and −0.1 mm, with standard deviations of 9.9 and 13.8 mm. The comparisons of the GAPS and the IGS estimates between the NCEP II estimates for the IGS stations have similar results, with standard deviations just under 45 mm, perhaps indicating deficiencies with NCEP II around the country.

With proper management and maintenance of the NIGNET infrastructure, near real-time ZTD estimates can be produced using PPP with the IGS ultra-rapid orbit and real-time clock products. The near real-time ZTD estimates, if made publicly available, could then be assimilated into regional and global NWM to enhance the quality of their forecasts for Nigeria and the surroundings countries.

The continuation of this project includes an assessment of the inherent uncertainty of the PPP derived neutral atmospheric parameters in the computation of integrated water vapor. Also, a least-squares spectral analysis of the ZTD and its components (hydrostatic and wet delays, and horizontal gradients) is prepared to study other spatial and temporal (seasonal) trends that may be intrinsic in the data, in comparison to precipitation trends studies in the country.

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