Analysis of Precipitable Water Vapour in Nigeria using GNSS Observations

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Dedication

This dissertation is cheerfully dedicated to my children, Sotonte Destiny Bala, Somiete Dominion Bala and Sonate Desiree Bala as a source of inspiration for their academic aspirations.

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Top on the list is my core supervisor Prof. Rui da Silva Fernandes who despite the disrupting global pandemic, ensured that this research work became a success. Your tutelage and patience are greatly appreciated and am very grateful to you Sir.

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Resumo

A estimativa de vapor de água usando observações do Sistema Global de Navegação por Satélite (GNSS) é uma tecnologia bem estabelecida que tem dado um contributo importante para a realização de previsões meteorológicas, investigação e monitorização climática. O vapor de água na atmosfera está diretamente relacionado com a precipitação que pode levar a eventos extremos (por exemplo, inundações). A área de estudo do uso de dados GNSS para detetar a quantidade total de vapor de água integrado ao longo do caminho do sinal na troposfera é designado de meteorologia GNSS. O GNSS tem como vantagem de poder ser utilizado em todas as condições climáticas, apresentar baixo custo e alta resolução temporal e espacial quando comparado a outros métodos clássicos de medição de vapor de água, normalmente mais caros e/ou com baixa cobertura espacial e temporal. Quando os sinais GNSS são transmitidos dose satélites para recetores terrestres, existe um atraso troposférico (uma fonte de erro no posicionamento GNSS) frequentemente representado na meteorologia GNSS como o *Atraso Zenital Total* (ZTD em Inglês). O ZTD é a soma do *Atraso Zenital* e do *Atraso Zenital* Húmido e é um dos produtos do processamento de dados GNSS. O ZTD pode ser convertido em PWV quando os valores de temperatura e pressão da superfície são conhecidos no local através de um fator de conversão (∏) que depende da temperatura média ponderada (Tm) e da pressão.

Esta dissertação tem como objetivo a estimativa e análise de vapor de água na Nigéria usando observações GNSS. As observações e produtos das estações da Rede Permanente GNSS da Nigéria (NIGNET) foram obtidos através da infraestrutura implementada pelo OSGoF. O processamento dos dados foi realizado por meio de software online (GipsyX) para a estimativa do ZTD. Dados de quinze estações GNSS foram utilizadas na análise correspondendo ao período entre 2009 a 2021, para avaliar as características da ZTD sobre o território da Nigéria. A faixa de variação de ZTD na Nigéria para o período considerado foi de aproximadamente 1900mm a 2700mm nas estações NIGNET. As duas principais estações climáticas na Nigéria destacaram-se, com picos baixos que ocorreram durante a estação seca (inverno), e picos altos observados durante a estação chuvosa (verão). A amplitude da variação sazonal no período sob investigação é entre um mínimo de 36mm e um máximo de 124mm com a região norte tendo valores mais elevados que a região sul. Pelos resultados obtidos das análises foi ainda possível verificar que a variação da ZTD nas regiões Norte e Sul são influenciadas pelos 4 climas distintos e outras condições climáticas locais, incluindo temperatura e ventos alísios do deserto do Saara e do Oceano Atlântico.

Palavras-Chave

Vapor de água Precipitável , GNSS, Meteorologia GNSS, Atraso Zenital Total, NIGNET – Rede de Estações Permanentes da Nigéria

Abstract

Water Vapour estimation using ground-based Global Navigation Satellite System (GNSS) observations is a well-established technology that contributes to weather forecast, research, and climate monitoring. Water vapour in the atmosphere is directly related with precipitation that may lead to extreme event (e.g., floods). The application of GNSS to sense the total amount of water vapour integrated along the signal path in the troposphere is what is referred to as GNSS meteorology. GNSS has the advantage of all-weather condition, low cost with high temporal and spatial resolution when compared to other classical methods of water vapour measuring that are expensive and/or with low spatial and temporal coverage. When GNSS signals are transmitted from GNSS satellites in space to ground-based GNSS receivers, they experience a tropospheric delay (an error source in GNSS positioning) often represented in GNSS meteorology as the Zenith Total Delay (ZTD). The ZTD is the sum of the Zenith Hydrostatic Delay and the Zenith Wet Delay and it is one of the products of GNSS data processing. The ZTD can be converted to Precipitable Water Vapour (PWV) when surface temperature and pressure values are known at the GNSS site using a conversion factor ($\prod$) that is dependent on the weighted mean temperature (T_m) and pressure.

This dissertation focuses on the estimation and analysis of water vapour in Nigeria using GNSS observations. The Nigerian Permanent GNSS Network (NIGNET) stations observations and products were retrieved from the infrastructure implemented by Office of the Surveyor General of the Federation (OSGoF). Processing of the data was carried out using online software (GipsyX) for the estimation of ZTD. Fifteen GNSS stations were used in this research and the period 2009 to 2021 was considered. The characteristics of the ZTD over the territory of Nigeria was investigated. The range of ZTD variation in Nigeria for the period used in this research was found to be approximately between 1900mm to 2700mm in the NIGNET stations. The two main seasons in Nigeria were significantly noticed as low peaks were found to be occurring during the dry (winter) season while high peaks were remarkably seen during the rainy (summer) season. The amplitude of the seasonal variation within the period under investigation is between a minimum of 36mm to a maximum of 124mm with the Northern region having higher values than the Southern part. It was discovered ultimately by the results obtained from the analyses, that ZTD variation in both the Northern and Southern regions are influenced by the 4 distinct climates and other local weather conditions including temperature and the trade wind from Sahara Desert and the Atlantic Ocean.

Keywords

Precipitable Water Vapour, GNSS, GNSS Meteorology, Zenith Total Delay, Nigerian Permanent GNSS Network.

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List of Acronyms

AC	Analysis Centre
AFREF	African Geodetic Reference Frame
APPS	Automatic Precise Positioning Service
BEIDOU	China Global Navigation Satellite System
BSW	Bernese Software
CDMA	Code Division Multiple Access
CGIS	Canadian Geographic Information System
CODE	Centre for Orbit Determination in Europe
CORS	Continuously Operating Reference Station
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
COST	Cooperation in Science and Technology
DOY	Day of Year
DD	Double Difference
DORIS	Doppler Orbit Determination and Radiopositioning Integrated by Satellite
E-GWAP	European Meteorological Network (EIG-EUMETNET) GPS Water Vapour Program
EIG-EUMETNET	Economic Interest Group - European Meteorological Network
EPN	EUREF Permanent Network
ERP	Earth Rotation Parameters
ESRI	Environmental System Research Institute
EUREF	European Reference Frame
FCT-PT	Portuguese Science Foundation Portugal
FCT	Federal Capital Territory
FDMA	Frequency Division Multiple Access
GALLILEO	European Global Navigation Satellite System
GGOS	Global Geodetic Observing System
GIPSY-OASIS	GNSS Infrared Positioning System-Orbit Analysis Simulation Software
GIS	Geographic Information System
GLONASS	Globalnaya Navigasionnaya Sputnikovaya Sistema
GMF	Global Mapping Function
GNSS	Global Navigation Satellite System
GNSS4SWEC	GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate
GPS	Global Positioning System
GPT	Global Pressure and Temperature
GRIB	General Regularly Distributed Information in Binary
IAG	International Association of Geodesists
IDW	Inverse distant Weight
IGS	International GNSS Service
ITRF	International Terrestrial Reference Frame
IWV	Integrated water vapour

JPL	Jet Propulsion Laboratory
MAGIC	Meteorological Applications of GPS Integrated Column Water Vapour Measurement
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
NetCDF	Network Common Data Form
NIGNET	Nigerian GNSS Permanent Network
NIMET	Nigerian Meteorological Agency
NMF	Niell Mapping Function
NRT	Near Real Time
NS	Network Solution
NWP	Numeric Weather Prediction
OSGOF	Office of the Surveyor General of the Federation
OTL	Ocean Tide Loading
PBO	Plate Boundary Observation
PCO	Phase Centre Offset
PPP	Precise Point Positioning
PRN	Pseudo Range Noise
PWV	Precipitable Water Vapour
QZSS	Quasi-Zenith Satellite System
RINEX	Receiver Independent Exchange Format
RS	Radiosonde
RT	Real Time
SEGAL	Space & Earth Geodetic Analysis Laboratory
SLR	Satellite Laser Ranging
SRIF	Square Root Information Filter
TOUGH	Targeting Optimal Use of GPS Humidity Measurement in Meteorology
UCAR	University Corporation for Atmospheric Research
WAVEPOINT	Water Vapour Experiment for Regional Operational Network Trials
WG	Working Group
WVR	Water Vapour Radiometer
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Total Delay
ZWD	Zenith Wet Delay

Chapter 1

Introduction

The study of water vapour in the Earth's atmosphere is important to understand its formation, variability, estimation and analysis in weather and climate related activities. It is one of the elements in the Earth's atmosphere (water vapour) that greatly influence Global Navigation Satellite System (GNSS) signals travelling from a GNSS satellite in space to ground-base GNSS receiver. Therefore, its accurate estimation for analysis is vital. In this chapter, we explore atmospheric water vapour, traditional atmospheric water vapour measuring instruments before the use of GNSS, GNSS as an atmospheric water vapour sensing system and the framework of this dissertation in the background. Other sections include the motivation of the study, problem statement, aims and objectives of the study, the research procedure, the contribution of the study to knowledge and the structure of the dissertation.

1.1 Background

Water vapour is a fundamental greenhouse gas with ample greenhouse effect on planet Earth. It is also one of the key components of the Earth's atmosphere and hydrological cycle. It varies highly in space and time and has a large impact on weather formation (Liu et al., 2019; Lou et al., 2021). The total water vapour content in a vertical column of air which is the Precipitable Water Vapour (PWV) also known as the Integrated Water Vapour (IWV), can assist operational meteorologist retrieve possible precipitation in that column of air in an ideal situation making it an important signal for weather and climate investigations. Atmospheric water vapour is the main means by which heat energy is transported into the troposphere and obviously the source of rainfall (Jones et al., 2019). The detection and the distribution of the water vapour can provide the required information for forecasting of weather and research in meteorology. In addition, water vapour is a source of error in GNSS meteorology fields of study therefore its accurate observation and estimation is of the utmost importance (Alshawaf et al., 2015).

According to Li et al., (2018) different methods have been used to measure atmospheric water vapour. They can be divided into satellite based (space to Earth) and ground-based (Earth to space). The most widely used traditional techniques for the measurement of atmospheric water vapour or PWV includes, but are not limited to: Water Vapor Radiometer (WVR) (Bleisch et al., 2011; Fionda et al., 2019) and Radiosonde (RS) (Li et al., 2003; Zhang et al., 2018). However, these conventional techniques have low spatial and temporal resolution (in case of RS) with high measuring cost (Abbasy et al., 2017). It is in the effort to find solution to these limitations by exploring other techniques that accurately retrieve Zenith Total Delay (ZTD) /PWV, that the use of GNSS was first proposed by Bevis et al., (1992) and is known as GNSS meteorology.

Global Navigation Satellites Systems is a general word for several positioning and navigations satellite systems developed and owned by some countries of the world. It is comprised of the Global Positioning System (GPS) of the United States of America (USA), GLObalnaya NAvigatsionna Sputnikovaya Sistema (GLONASS) of Russia, GALILEO of Europe, BEIDOU of China. Many years ago, GNSS was basically known for its application in position determination, navigation, and timing. The constellation design of GNSS results in a global coverage. The use of GNSS to sense atmospheric water vapour for the evaluation and estimation ZTD/PWV is what is referred to as GNSS meteorology. It has the advantages of being used in all-weather condition with high temporal resolution and with the improvement of its spatial resolution when more continuously operating stations are installed. The aforesaid has therefore made the use of ground-based continuously operating GNSS measurement to derive and analyse ZTD/PWV a research topic (Adams et al., 2011; Alshawaf et al., 2015) and (Isioye et al., 2017).

When GNSS signal propagates through the lower part of the Earth's atmosphere (troposphere), it experiences a delay known as the tropospheric delay which is caused by water vapour content amongst others. This tropospheric delay according to Bosy et al., (2011) is one of the results of GNSS data processing in GNSS meteorology and it is represented by the ZTD which is usually expressed in units of length using the speed of light in vacuum. The ZTD is divided into two components called the Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). The ZHD is caused by atmospheric gases such as Carbon dioxide, Nitrogen and Oxygen and can be obtained from surface pressure measurements. The ZWD is basically caused by the atmospheric water vapour and can be obtained by subtracting ZHD from ZTD. The wet delay unlike the hydrostatic delay is estimated as part of data processing. The ZWD can otherwise be converted to PWV using a conversion factor as demonstrated in Liu et al. (2019).

There are two main methods of GNSS data processing to obtain ZTD. They are the Precise Point Positioning (PPP) or zero-difference (Zumberge et al., 1997) and the Network solution or Double Difference (Pacione et al., 2017) strategies which will be discussed in subsequent chapters with different state-of-the-art processing software.

Though, the emphasis in this dissertation is on GNSS, it is pertinent to inform that Geographic Information System (GIS) tools are applied, and GIS explored especially as it relates to weather. GIS according to e.g., Feidas et al., (2007) has become an indispensable tool (technology) in the efficient utilization and management of bulk dataset arising from meteorology and climatology for a host of applications and has enabled instant plotting, visualisation and interpolation of these data.

This dissertation, Analysis of Precipitable Water Vapour in Nigeria using Global Navigation Satellite System Observations, is within the framework of the Portuguese research project SUGGEST-AFRICA funded by Portuguese Science Foundation (FCT) and Aga Khan Develop Network (AKDN). One major aim is for knowledge transfer and capacity building in Africa by equipping the beneficiary with sound knowledge of the estimation and analysis of water vapor in the atmosphere using Global Navigation Satellite System (GNSS) observations (together with meteorological data) over the territory of Nigeria (and Mozambique and Angola). Some of the continuously operating permanent GNSS stations in

Nigeria will be processed for the estimation of ZTD. The Nigerian Reference GNSS Network (NIGNET) basically installed for positioning, navigation and timing services are now collocated with meteorological sensors in five of the stations supported by SUGGEST-AFRICA project to obtain temperature and atmospheric pressure data necessary for the conversion of ZTD to PWV. Temperature and pressure information can also be obtained from global meteorological model to enable the conversion of ZTD into PWV.

1.2 Motivation

Weather and climate conditions has become a daily, seasonal and long-term threat globally, especially in Nigeria. Therefore, the need to explore new technique besides the traditional methods to solve problems associated with it has endeared me to this research. Flooding, because of constant heavy rain, leading to loss of lives and destruction of infrastructures is a source of concern. This concern has led scientist around the world to encourage interdisciplinary measures by bringing geodesy and meteorology on a common scale to investigate further and proffer solutions with GNSS Network stations in Real Time (RT) or Near-Real-Time (NRT), hence GNSS meteorology. The floods (c.f. Figure 1.1) in 2019 in Lokogoma area of the Federal Capital Territory (FCT) of Nigeria shows the importance of these stations.

Figure 1. 1: Flooding on 6th June 2019 in the Federal Capital Territory. Source: Verbatim (2019).

The massive flooding due to torrential rainfall affected most parts of the FCT especially the Lokogoma district and rendered many homeless. Similar incident had been reported to have occurred in July 2017 which claimed the life of a man and his two children. It is therefore imperative to use this technique of GNSS meteorology that is low cost, fast and characterised by all-weather conditions with high temporal and spatial resolution to sense the atmospheric water vapour which is a major source of precipitation. This will complement traditional techniques and Numeric Weather Prediction (NWP) models in providing accurate information that will assist in accurate weather prediction and other climate processes.

1.3 Statement of Problem

Atmospheric water vapour is a major source of extreme weather event and climate related issues. It has attracted the attention of researchers all over the world for the investigation and analysis of its variability and sudden occurrence mostly in the form of precipitation. The aforesaid is sometimes very severe and usually leads to loss of lives and destruction of properties as illustrated in Figure 1.1. In the light of the above, GNSS technology has proven to be reliable in the estimation of ZTD/PWV a source of heavy rainfall that leads to flooding. It will assist the operation of relevant agencies like the Nigerian Meteorological Agency (NIMET) by assimilating these tropospheric and meteorological products into their weather prediction models for improved weather forecast and giving of timely advise and warning to her citizen to avert or reduce the menace usually caused by weather and climate conditions.

1.4 Aims and Objectives.

The main aim of this dissertation is to investigate the short-term and long-term variations of Precipitable Water Vapour over the territory of Nigeria.

Also, to estimate and analyse water vapour in the atmosphere using Nigerian permanent Global Navigation Satellite System network (NIGNET) observations.

The above can be achieved by the following objectives:

- Acquisition of NIGNET Observations data.
- Processing of the GNSS observations.
- Extraction of Zenith Tropospheric Delay (ZTD).
- Extraction of meteorological parameters (temperature and pressure) from collocated GNSS stations.
- Computation of PWV from ZWD with the meteorological parameters.
- Production of the time-series and spatial ZTD/PWV estimates.
- Analysis of the time-series and spatial variation of ZTD/PWV estimates over Nigeria.

1.5 Research Procedure

The Permanent GNSS stations used in this dissertation were retrieved from the Space & Earth Geodetic Analysis Laboratory (SEGAL)/OSGoF infrastructure (TeroNet Software). SEGAL has been the core installer and maintainer of the Nigerian Permanent GNSS Network stations. The GNSS stations were selected bearing in mind some criteria for selection of the stations for processing. NIGNET stations without or with limited data to serve the purpose of the project were removed. The Receiver Independent Exchange (RINEX) format file for CBCR was downloaded from TeroNet and processed with the online GNSS Processing software using PPP approach to obtain the ZTD for analysis. Data for long-term ZTD of the GNSS stations were retrieved from the archive of SEGAL/OSGOF infrastructure for analysis. Precipitation data was also retrieved from Abuja weather history to compare and understand ZTD characteristics as a potential product for precipitation investigation.

1.6 Contributions to Knowledge

The following are contributions to knowledge of this dissertation:

a. Laying of foundation for GNSS meteorology, a relatively new field in Nigeria which will propel further investigations of ZTD/PWV as a key component of atmospheric processes.
b. Computation of PWV that will assist relevant authorities in Nigeria for weather prediction and other climatic conditions.
c. Understanding the variation and analysis of ZTD/PWV over the territory of Nigeria.
d. It will serve as reference material for researchers and others that requires foundational knowledge in GNSS meteorology field of endeavour.

1.7 Dissertation Structure

This Dissertation is organised as follows:

Chapter 1: **Introduction**: Which gives a background knowledge of GNSS meteorology, motivation of the research, statement of problem, aims and objectives, research procedure and contributions of the research to knowledge.

Chapter 2: **GNSS Overview and GNSS Network in Nigeria**: Gives an overview of GNSS (GNSS measurements principles, errors sources in GNSS), water vapour estimation from GNSS and the evolution and usefulness of GNSS Network and meteorological stations in Nigeria.

Chapter 3: **State-of-the-Art**: Presents the status of ground-based GNSS meteorology, the methods of processing GNSS observations and different processing software. Sources of Satellite Orbits and Clocks (the International GNSS Service and the Jet Propulsion Laboratory), troposphere mapping functions, meteorological parameters and Geographic Information System especially as it relates to weather.

Chapter 4: GNSS Processing and PWV Computation. This Chapter focuses on the practical aspect of the research and methods used. The study area, processing of GNSS observations for the estimation of ZTD using the Nigerian Permanent GNSS stations and the process of calculating PWV with meteorological parameters especially surface temperature and pressure.

Chapter 5: Tests and Discussion of Results: will focus on the results obtained by analysing the time-series and spatial ZTD/PWV variation in Nigeria. It will explore analysis such as daily, monthly and seasonal variations**.**

Chapter 6: Conclusions and Recommendations: This chapter summarizes the dissertation by highlighting on the main findings with the submission of recommendations and future work.

Chapter 2

GNSS Overview and GNSS Network in Nigeria

GNSS is an acronym for Global Navigation Satellite System. It means the constellation of satellites which send signals from space to ground-based GNSS receiver and the receiver in turn uses these data for fixing location. GNSS was mostly known for position determination, navigation, and timing services. But today, its application as an atmospheric sensing system is evident and remarkable especially in Europe. The relevance of GNSS has made researchers worldwide to engage in its several applications including weather and climate related investigations. In this chapter, we discuss GNSS overview (GNSS measurement principles, GNSS error sources), estimation of water vapour from GNSS, GNSS network and collocated meteorological stations in Nigeria.

2.1 GNSS Overview

Before the advent of GNSS or Satellite-based Navigation as an atmospheric sensing system for meteorology, its application was primarily for positioning, navigation, and timing services. The GPS, GLONASS, GALILEO, BEIDOU and QZSS are all forms of GNSS. Some vital features of GNSS are presented in table 2.1.

Table 2. 1: Features of the GNSS constellation (Ahmed, 2010).

	GPS	GLONASS	GALILEO	BEIDOU	QZSS
Country	USA	Russia	Europe	China	Japan
No. of satellites	32	24	30	35	24
No. of orbital planes	6	3	3	10	6
Orbital height (km)	20,200	19,140	23,222	21,150	32,000
Orbital Period	11h 58m	11h 15m	14h 06m	12h 48m	23h 56m
Orbital Inclination	55°	64.8°	56°	55.5°	43°
Coding	CDMA	FDMA	CDMA	FDMA	FDMA
Carrier Frequencies (MHz)	1575 1228 1176	1559-1592 1243-2063	1579 1279 1207 1192 1176	1590 1561 1269 1207 1192	1575.42

From the above systems, GPS was the first to become fully operational in 1993 having three dimensional positioning with timing information and positioning accuracy down to sub-decimetre levels (Jones et al., 2019). While GPS, GLONASS, GALILEO and BEIDOU have global constellation, QZSS has regional constellation. GNSS uses Code Division Multiple Access (CDMA) or Frequency Division Multiple Access (FDMA) as their signal source (Manandhar, 2018). These signals are either carrier signal, code, or navigation data. All GNSS has three main segments as demonstrated in Figure 2.1 for GPS which are the space segment (constellation of satellite in Medium Earth Orbit (MEO) that sends coded signals to user), the ground segment (monitoring or master control stations on the ground that sends corrected data about the clocks and orbits of the satellite) and the user segment (the GNSS receivers).

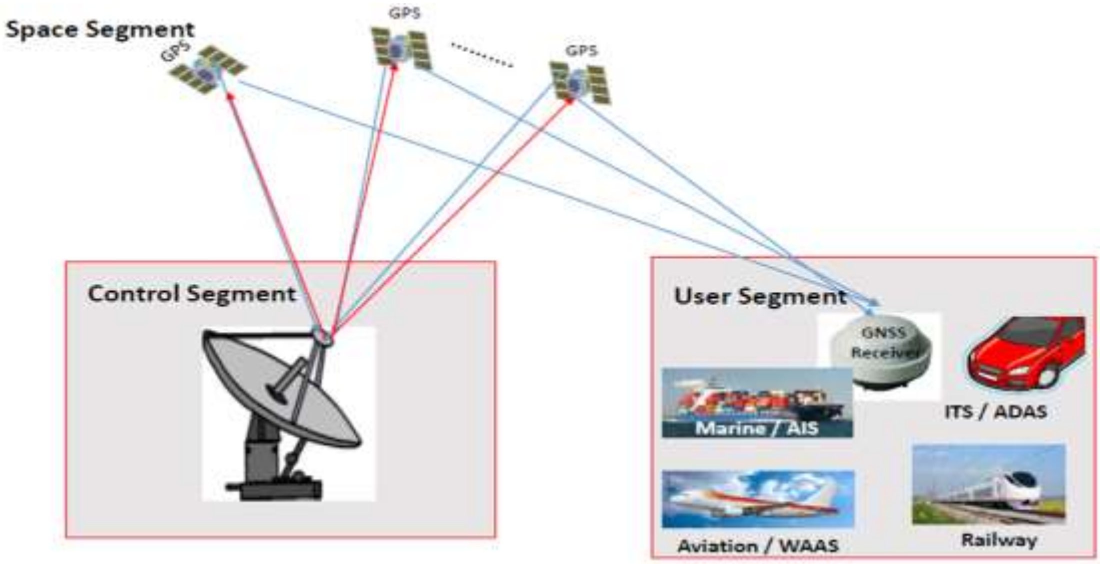


Figure 2. 1: GPS Segments source: Manandhar (2018).

2.1.1 GNSS Measurements Principle

Global Navigation satellite systems are satellite-based positioning system that provides three dimensional (3D) geodetic coordinates of a measurement point. GNSS satellites sends coded signal and the antenna at the user segment receives the coded signal and estimate the time of travel from the satellite to the ground receiver. Similarly, the satellites also send messages which helps the ground receiver determine the position of the satellites in space as depicted in Figure 2.2.

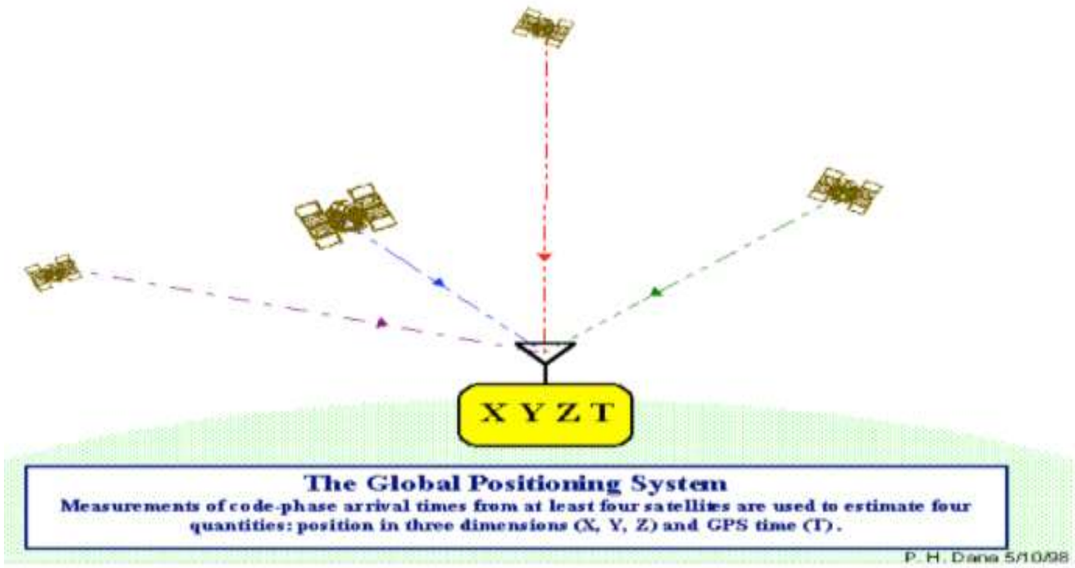


Figure 2. 2: GPS Positioning technique: Source: Jones et al., (2019).

For the ground receivers' position to be measured, there must be at least four satellites in view at any point in time on the surface of the Earth, which will give rise to the determination of the 3D coordinates (XYZ) and the time (T) as shown in Figure 2.2.

The two types of measurements or observables provided by the GNSS receivers are the Pseudo or code range and carrier phase measurements. Both measurements are used to derive a measure of the visible distance with respect to time or phase difference between the satellite and the receiver. This is demonstrated in Figure 2.2 by GPS, one of the key systems of GNSS. Furthermore, the GPS sends out the signal with code and phase information at two frequencies, called L1 and L2. It was reported that if the phase modulated L1 and L2 codes of a GPS can be decoded by the ground-based receiver which is the user segment, it is possible to give the user position and velocities (Jones et al., 2019). In the code measurement technique, the satellites send out Pseudorandom Noise (PRN) codes to the ground-based receivers. The ground-based receivers then agree with and uses the PRN codes transmitted by the satellites in space to determine its position and time. The code measurements are noisy but are not ambiguous because of the PRN codes while the carrier phase measurements are precise but ambiguous because of the total unknown number of cycles slips (loss of signal tracking) between the satellites and the receivers. Though, the code and phase measurement techniques are intended for high precision positioning. However, the code measurement has less precision when compared to the carrier phase measurement (Langley et al., 2015).

2.1.2 GNSS Error Sources

When signals are propagated through the Earth's atmosphere from GNSS satellites in space to the ground-based GNSS receiver / antenna, they are usually affected by interferences that generates errors and noise which causes delay in time of the signal transmission (Karaim et al., 2018). These error sources are a contribution from the three segments of GNSS.
The error sources include but not limited to:

- Satellite and receiver clock errors: GNSS satellites are equipped with very precise atomic clocks with nanosecond accuracy. However, most receiver clocks have low accuracy which causes shift in time despite their synchronisation. This shift introduces error in positioning which can be corrected by the ground control station.

- Satellite orbit error: Even though satellites move in orbits that can be accurately predicted, like the satellite clock they also experience a small orbital shift due mainly to gravitational forces which introduces positioning error. To correct this error in the predicted orbits that are broadcasted by the GNSS satellites, the IGS calculated orbits are used.

- Multipath error: Multipart error occurs when signal from the satellite arriving at the GNSS receiver encounters reflections from the objects (example: buildings, roads, trees etc) around the receiver. The effect of this error cannot be predetermined as such will negatively impact on the arrival time of the signal thereby introducing positioning error. This error can be greatly minimised by avoidance of sites with reflections or by the choice of a suitable antenna design.

- Ionospheric Delay: The electrically charged ions resident in the upper layer of the atmosphere ranging from approximately 50-1000 km above the Earth surface due to solar radiation and other factors are potential sources of error in determining positioning accuracy. These high concentration of ions in this atmospheric layer affect the satellite signals propagating through it to the GNSS receiver by causing refraction or bending of the signal. The Ionosphere is dispersive in nature and its errors are compensated for by using Differential GNSS and RTK. If the reference station and the GNSS station at the point of interest are not more than 20 – 30km apart, then they experience the same ionospheric delay which then cancels out during the analysis of the data. Also, signal delay in the ionospheric region is inversely proportional to frequency and this error can be removed by transmitting GNSS signal in dual frequency (i.e., L1 and L2 signals).

- Tropospheric Delay: The troposphere is the lowest layer of the Earth's atmosphere. Unlike the ionosphere that is dispersive the troposphere is non-dispersive and it is the neutral region of the atmosphere that causes delay of signals propagating from the GNSS satellites to the GNSS ground receivers' antenna causing signal refraction (that is to slow and bend the signal). The tropospheric region is electrically neutral and primarily influenced by pressure, temperature, and water vapour. Since tropospheric delay does not depend on frequency, it cannot be easily eliminated by the combination of the measurements of L1 and L2 GNSS signals (dual frequency method). This delay is the component among the error sources in GNSS that is of importance to meteorology used for the estimation of ZTD from GNSS data processing and subsequent conversion to PWV with meteorological parameters like temperature and pressure for weather prediction and climate investigation.

The error budget for the error sources is shown in Table 2.2.

Table 2. 2: GNSS Error Sources and Range. Source: (Langley et al., 2015).

Error Sources	Error Range (m)
Satellite Clocks	±2
Satellite Orbit	±2.5
Multipart	±1
Ionospheric Delay	±5
Tropospheric Delay	±0.5
Receiver Noise	±0.3

2.2 Water Vapour Estimation from GNSS

In the opening Chapter, it was already established that the use of GNSS satellites in space and ground-based GNSS receivers to sense atmospheric water vapour was first put forward by Bevis et al., (1992) as depicted in Figure 2.3.

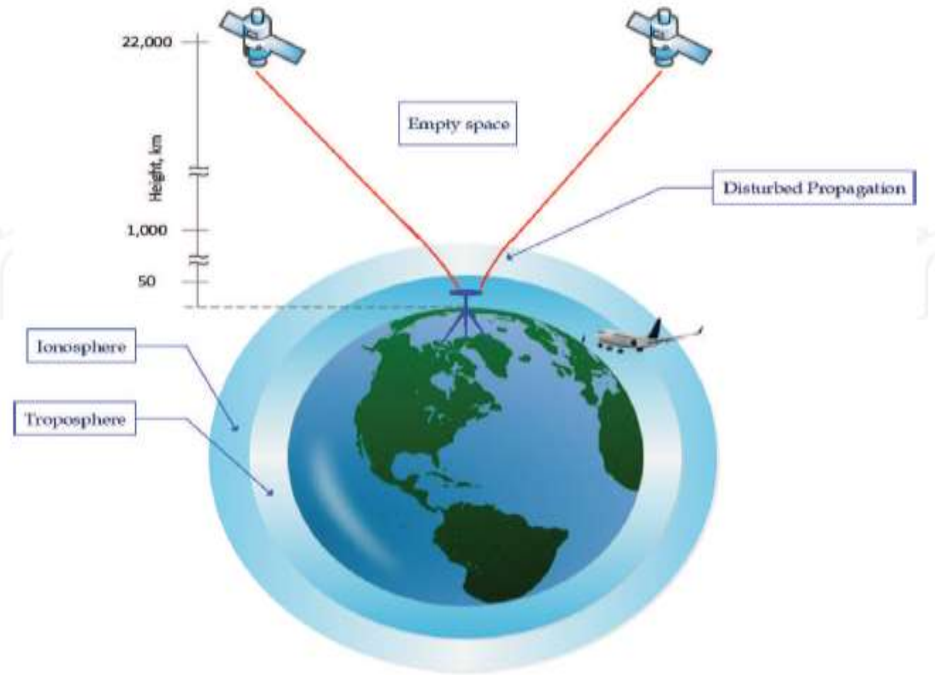


Figure 2. 3: Structure of the Atmosphere and influence on Propagation Path.
Source: Karaim et al., (2018).

In Figure 2.3, it can be observed that the troposphere (about 50km high) is the closest atmospheric layer to the Earth surface. This layer is made up of dry gas contents like carbon dioxide, oxygen, nitrogen and varying quantity of water vapour influencing it (Chayanin & Constantin-Octavian, 2018). The effects, GNSS signals suffer in the troposphere because of these atmospheric contents before it arrives at the ground-based GNSS receiver is called the tropospheric delay and in GNSS meteorology this delay along the line of sight of each satellite and the receiver is mapped to the zenith and represented as the Zenith Total Delay (ZTD) (Zhang et al., 2018). When processing for the ZTD, the application of mapping function is necessary which is an indication of the ratio between the tropospheric delay from the zenith direction and any other elevation angle.

The ZTD consist of two components: the Zenith Hydrostatic Delay (ZHD) which depends on dry air gases in the atmosphere and accounts for about 90% of the delay. The ZHD can easily be modeled if the surface pressure at the GNSS station is known. The second component is the Zenith Wet Delay (ZWD) that is mainly influenced by moisture content in the atmosphere with significant level of water vapour that accounts for the remaining 10% of the delay. The ZWD is related to the water vapour and unlike the ZHD cannot be modeled easily because of its high temporal and spatial change. ZWD is therefore estimated during GNSS data processing.

The ZTD (with unit m or mm) is related to the two components using equation 2.1 (Zhang et al., 2018).

$$ZTD = ZHD + ZWD \tag{2.1}$$

Applying the surface pressure measurement P in Hectopascal (hpa) at the observation station, ZHD can be calculated accurately from Saastamoinen empirical model (Liu et al., 2019) as:

$$ZHD = \frac{0.002277 \times P}{1 - 0.00266\cos(2\emptyset) - 0.00028 \times H} \tag{2.2}$$

In Equation 2.2, Ø is the latitude of the station in radian, H is the station height from geoid in km.

The Precipitable Water Vapour is the integrated amount of water vapour in the zenith direction. Therefore, the PWV can be obtained from the ZWD.

From equation 2.1, ZWD can be obtained as expressed in equation 2.3 (Liu et al., 2019).

$$ZWD = ZTD - ZHD \tag{2.3}$$

The ZWD is a measure of the water vapour and temperature. It means that PWV can be estimated when the weighted mean atmospheric temperature (T_m) is computed. The PWV is related to ZWD by a conversion factor $\prod$ (Zhang et al., 2018) as in equation 2.4.

$$PWV = \prod \times ZWD \tag{2.4}$$

In Equation 2.4

$$\prod = \frac{10^6}{\rho . R_V \left(\frac{K_3}{T_m} + K_2^{'}\right)} \tag{2.5}$$

Where $\rho = 1000\, kg/m^3$ is the density of liquid water, $R_V = 461.495\, J/K_g . K = 4.61495\, m^3\, mbar/(kg\, K)$ specific gas constant of water vapour.
$K_2^{'} = 22.1\, K/mb,\ K_3 = 3.739 \times 10^5\, K^2/mb$ and are the physical constants of atmospheric refractivity. T_m is the weighted mean temperature of the troposphere.

An empirical formula was derived for the weighted mean temperature (T_m) by Bevis et al., (1992) that depends on the surface temperature(T_s) in Kelvin (K) as follows;

$$T_m = 70.2 + 0.72T_s \tag{2.6}$$

The T_m like the T_s is an important meteorological parameter in the conversion of ZWD to PWV in ground-based GNSS meteorology. Accurate data for T_m can be provided by reanalysis models but are not suitable for real-time applications due to the delay in time of release. However global models based on the principles of spatiotemporal variation of T_m have made the calculation of T_m values in real time possible. When determining T_m from global model, meteorological data are not needed as inputs, only parameters such geographic coordinates of the GNSS station and Universal Coordinated Time (UTC). (Liu et al., 2019).

2.3 GNSS Network and Collocated Meteorological Stations in Nigeria

2.3.1 GNSS Network

Previously, Nigeria used the geodetic reference ellipsoid based on Clark 1880 as its geocentric datum which was established on traditional survey techniques. The station is located at the centre of the primary triangulation referred to as MINA DATUM (L40). As technology advances, the inefficiency and obsolete form of this local datum to correlate with global geocentric coordinate frames became obvious (Dodo et al., 2011). It makes the use of regional and global geodetic information difficult (Onyeka, 2006). These deficiencies also cause distortions in the network, hence the need for a reference system (Global Navigation Satellite System) that is globally compatible and applicable.

GNSS based Continuously Operating Reference Station (CORS) has revolutionized the world. Its numerous applications and benefits are obvious in science and technology to mention a few. This revolution brought about the idea of its implementation by the Nigerian government through the Office of the Surveyor General of the Federation (OSGoF), the apex Survey and Mapping agency, in the year 2008. In addition, the Nigerian Permanent GNSS Network was conceived with the aim of implementing a new reference frame for Nigeria in line with the recommendation of the United Nation Economic Commission for Africa (UNECA) through its committee on Development, Information, Science and Technology (CODIST) (Fernandes et al., 2010). NIGNET is comprised of state-of-art geodetic equipment such as Trimble NetR8, NetR9 and Septentrio with choke-ring antennas as depicted in Figure 2.4.

Figure 2. 4: GNSS Stations Located on OSGoF and UNILAG Buildings
Source: Fernandes et al., (2010)

Other components of the NIGNET include USB modem, GSM cellular network, router, and solar power systems. NIGNET is connected to the existing reference frame. The idea was also for the NIGNET to serve as a contribution to achieving the objective of the African Geodetic Reference Frame (AFREF) project in line with the International GNSS Service (IGS) standards (Ayodele et al., 2020).

By the end of 2010, eleven NIGNET stations has been installed and homogeneously distributed across the country for further densification. As of 2020, Nigerian government through OSGoF has built fifteen NIGNET stations and two (CGGT and RECT) belonging to other government institutions out of which some of the stations will be used in this dissertation for processing and analysis as shown in Table 2.3 and Figure 2.5.

Table 2. 3: GNSS Stations and their Location Information.

GNSS ID	Agency	Longitude	Latitude	Altitude (m)
ABFC	OSGOF	7.486342	9.027666	532.645
AKON	OSGOF	5.136436	7.298648	415.996
BIKE	OSGOF	4.229242	12.468577	250.012
CBCR	OSGOF	8.351571	4.950306	60.586
ENEN	OSGOF	7.504991	6.424806	254.405
GBTA	OSGOF	11.183940	6.917199	1795.643
KNKN	OSGOF	8.543769	11.984241	542.689
LGLA	OSGOF	3.397623	6.517327	44.575
MDGR	OSGOF	13.130851	11.838059	351.800
OWIM	OSGOF	7.033336	5.434578	92.661
YLAD	OSGOF	12.497798	9.349743	247.406
ZRKD	OSGOF	7.648687	11.151740	705.066
EKAK	OSGOF	7.916623	4.638411	41.870
CGGT	CGGT	9.118312	10.123095	916.432
RECT	RECT	4.524476	7.505488	281.943
HUKP	OSGOF	7.559092	12.921146	565.010
RUST	OSGOF	6.978521	4.801836	45.5766

This state-of-the-art geodetic infrastructure (NIGNET) has contributed greatly to survey and mapping and navigation in Nigeria but has not been utilised to its full potential in the field of meteorology which will be of immense benefits.

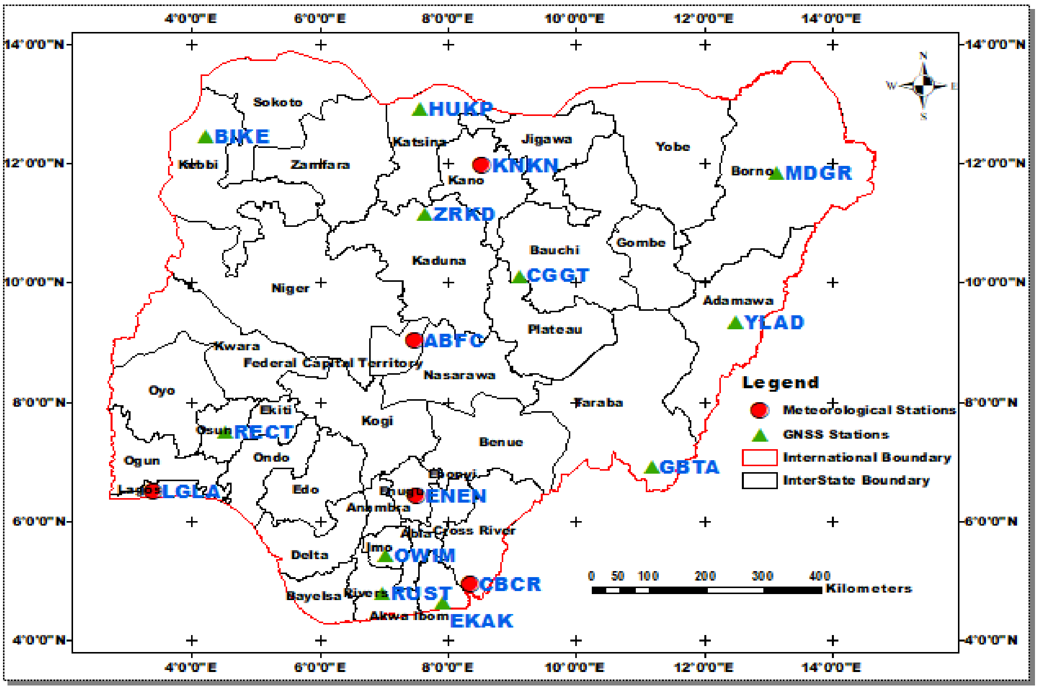


Figure 2. 5: Map of Nigeria showing the distribution of 16 GNSS Stations (in green triangle) Collocated with 5 Meteorological Stations (in red circle).

2.3.2 Meteorological Stations

Prior to the year 2021, there were no collocated meteorological stations as depicted in five of the NIGNET stations (KNKN, ABFC, ENEN, LGLA and CBCR) in Figure 2.5 and Figure 2.6 for CBCR. These stations were magnanimously installed by the Portuguese government funded by FCT and AKDN in collaboration with OSGoF through SUGGEST-AFRICA project to support Nigeria in tackling meteorological and climatological phenomena that is a global concern. The stations are comprised of wind sensor, precipitation sensor, temperature, pressure and humidity sensor and accessories.

Figure 2. 6: Meteorological Station (left) Collocated with GNSS Station (right) for CBCR Station.

In GNSS meteorology these stations are important for the retrieval of meteorological parameters (data) such as temperature, pressure, precipitation, humidity wind direction and speed etc. in other to solve problems related to weather and climate conditions.

2.4 Summary

This chapter presents first what GNSS is all about, its measurement techniques, error sources and the estimation of water vapour from GNSS. It was affirmed that the Tropospheric Delay among the error sources is the error that is used mostly in GNSS meteorology for the estimation of atmospheric water vapour for weather and climate related investigations. This error often represented as the ZTD is achieved during GNSS data processing and subsequently converted to PWV with meteorological parameters such as surface pressure and temperature. Finally, the chapter highlighted on the idea that brought about GNSS infrastructure and Meteorological stations to Nigeria and their relevance.

Chapter 3

State-of-the-Art

In this chapter, the practice of ground-based GNSS meteorology is presented. The application of tropospheric and meteorological products in Europe and other continents are highlighted. The methods of processing GNSS observations, processing software, sources of satellite orbits and clocks (IGS, JPL), troposphere mapping functions required for the processing of GNSS observations to obtain Zenith Total Delay and meteorological parameters needed for conversion from ZTD to PWV as well as Geographic Information System especially as it relates to meteorology are explored.

3.1 Ground-Based GNSS Meteorology

The Global Navigation Satellite System meteorology is dependent on GNSS observations (Bosy et al., 2010). GNSS meteorology, is an interdisciplinary operational and research field for weather and climate related processes which was first put forward by Bevis et al., (1992) with the assumption that the time varying wet component of the tropospheric delay is proportional to the Precipitable Water Vapour. According to Bosy et al., (2011), GNSS meteorology is the application of GNSS to remotely sense the troposphere to derive information about its condition. Ma et al., (2019) in their research, explain GNSS meteorology as the newest implementation of GNSS technology for the remote sensing of the Earth's atmosphere to determine temperature and water vapour content in keeping track of weather and climate change processes.

Network of continuously operating ground-based GNSS receivers can therefore be used to retrieve ZTD/Integrated Water Vapour also known as PWV at each GNSS receivers' station. These reference network of Continuously Operating Reference Stations (CORS) in some countries were initially established for surveying, mapping, navigation, engineering, and research purposes.

Today, meteorological application using GNSS technology is widely used around the world. The European Reference Frame (EUREF) Permanent Network is the key geodetic infrastructure over Europe that is comprised of more than 280 GNSS CORS with several Analysis Centres (AC) for the estimation of the Zenith Total Delay in Near Real Time (NRT) and station coordinates (Pacione et al., 2017).

Guerova et al., (2016) state that GNSS meteorology in Europe has lasted about two decades and has gained ground both operationally and for research purposes. According to the authors, these projects are collaborative projects aimed at the exploitation of GPS/GNSS observations for the monitoring of atmospheric water vapour.

These major European projects aiming to enhance and advance GPS/GNSS meteorology began in 1996. Just to mention few of the projects. The Economic Interest Group - European Meteorological Network (EIG-EUMETNET) GPS Water Vapour Program (E-GVAP) was established in 2005 with the aim of fully operationalising GPS meteorology within Europe as opposed to the usual research and development field (Guerova et al., 2016). Subsequently, E-GVAP was charged with the responsibility of providing EIG- EUMETNET members with GNSS-derived ZTD estimates and PWV in NRT for operational purposes. COST Action ES1206, Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate (GNSS4SWEC) was first established at Brussels in May 2013 with the objective to:

- Enhance existing and develop new ground-based multi-GNSS tropospheric products.
- Assess how such tropospheric products can be used in severe weather forecast and climate monitoring.
- Improve GNSS accuracy through enhanced atmospheric modeling.

and GNSS4SWEC project has today form the basis for the present day state-of-the-art in GNSS meteorology with its Final Action Dissemination Report of May 2019 (Jones et al., 2019).

There are other GNSS Network around the world for the estimation of ZTD/PWV for weather and climate related operations. In North America, University Corporation for Atmospheric Research (UCAR), managers of the SuomiNet a network of GPS with real-time atmospheric sensing capability provides Near-Real-Time PWV estimates (Isioye et al., 2015).

Similarly, in Asia, the Japanese GPS Earth Observing Network (GEONET) with over 1200 GPS network contributes to the assimilation of GPS PWV data into Japanese Meteorological Agency (JMA) Mesoscale Numeric Prediction Model. In addition, the United Kingdom (UK) Met Office uses NRT ZTD in their NWP operations (Isioye et al., 2015).

It is pertinent to mention that the state-of-the-art of GNSS meteorology today is as a result of the invaluable contributions from Global Geodetic Observing System (GGOS) products through the services of the International Association of Geodesist (IAG) and the International GNSS Service (IGS) that makes available satellite (clock and orbits) and tropospheric products that is of great importance to GNSS meteorology (Guerova et al., 2016).

More significantly, is the provision of precise products by IGS for multi-GNSS (GPS and GLONASS) offering new satellites and signals with the aim of strengthening estimated parameters especially ZTD, as the accuracy of PWV is also dependent on the accurate estimation of the ZTD.

As already stated earlier in section 2.1.2, ground-based GNSS meteorology is dependent on the tropospheric delay which is one of the GNSS error sources and one of the results of GNSS data processing. GNSS observations can therefore be processed for the estimation of this delay with high level of accuracy.

3.2 GNSS Observations Processing Methods

There are two main state-of-the-art methods accepted globally for the processing of GNSS observations in other to estimate ZTD in ground-based GNSS meteorology. They are the Precise Point Positioning (PPP) and the Double Difference (DD) techniques which are going to be explored briefly in the subsections.

3.2.1 Precise Point Positioning

Precise Point Positioning (PPP) is one of the techniques used in GNSS data processing to obtain coordinates and tropospheric information using a single receiver (Zumberge et al., 1997). PPP adopts zero-difference observation from a single station. It is considered as an absolute technique in the sense that errors, generated by a GNSS receiver/antenna at a station, are not propagated between or among stations. This processing method mostly depends on the availability and use of precise satellite products such as orbits and clocks corrections (Afifi & El-Rabbany, 2016).

Prior to 2013, due to delay of satellite product, there were no very accurate satellite orbits and clocks products in real time for now-casting weather applications (Jones et al., 2019). This limitation necessitated most E-GVAP AC prefer DD technique over PPP, where there is not much dependence on satellite clock products. However, following the development of International GNSS Service Real-Time Pilot Project (RTPP) in April 2013, real time satellite orbits and clock products can now be obtained for nowcasting weather applications (Zhao et al., 2018). One advantage of PPP data processing mode is that it is faster since only the station for case study is utilised.

3.2.2 Double Difference

Double Difference (DD) (Stepniak et al., 2018) is another method used in GNSS data processing for the derivation of station coordinates and tropospheric information among others. Unlike PPP where the processing strategy is dependent on a single station, DD uses a network of stations for processing as such there is likelihood of propagation of errors among stations. An advantage of this processing strategy is that it yields results where most of the errors like satellite and receiver clocks are being eliminated. Baseline formation is an essential integral part of the network of stations in DD approach. Stepniak et al., (2018) posited that baseline design strategy in DD network processing has great influence with regards to the standard and progress of ZTD time series. The Authors further maintained that there is a need to improve on DD processing strategy as most EUREF Permanent GNSS Network (EPN) and E-GVAP AC rely on network approach.

By the evaluation of the two processing methods, the PPP processing strategies is considered due to the sparse nature of the GNSS network in Nigeria.

3.3 GNSS Observations Processing Software

There are different state-of-the-art Software for the processing of GNSS observations. They include but not limited to; Bernese, GAMIT/GLOBK, GipsyX, which will be briefly explored in the following subsections. According to Pacione et al., (2017) these three software are the main GNSS processing software.

3.3.1 Bernese GNSS Software

Bernese Software (BSW) (Dach et al., 2015) is a high performance and accuracy GNSS and Satellite Laser Raging (SLR) post-processing software designed for the space geodetic community (Bertone, 2015). BSW was developed at the Astronomical Institute, University of Berne, Switzerland. It is used by the Centre for Orbit determination in Europe (CODE) as an AC of the International GNSS Services and European Permanent Network (Bertone, 2015) . BSW can be used in Microsoft Windows, MAC and Unix/Linux platforms and is based on Least Square Fit techniques. BSW has the capability of both handling the Precise Point Positioning and Double-Difference processing strategies. The Bernese Processing Engine (BPE) can be used to carry out automated processing that is mostly suited for large network processing and reprocessing. BSW is widely used all over the world due partly to its flexibility, reliability, user friendly interface and online help service system.

3.3.2 GAMIT Software

GAMIT/GLOBK (Herring et al., 2008) is one of the state-of-the-art high precision GPS/GNSS processing software. It was developed by the Department of the Earth Atmospheric and Planetary Sciences at Massachusetts Institute of Technology (MIT), USA. GAMIT ("GNSS at MIT") is a collection of Programs to process phase data to estimate three dimensional relative positions of ground stations and satellite orbits, atmospheric zenith delays and Earths orientation parameters (EOP). The software can run under any UNIX operating system and it is based on Kalman Filter technique (UNAVCO, 2021).

3.3.3 GipsyX Software

GipsyX (Bertiger et al., 2020) owned by JPL replaces GIPSY-OASIS. It is the 4th major GNSS data analysis software that is redesigned by JPL and is one of the latest software packages for carrying out position determination, navigation, timing and Earth science by various geodetic measurement methods like GNSS, SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). It is one of the precise space geodetic data analysis packages that has the capability to at the same time process geodetic and geophysical data using Kalman filter technique in real time or postprocessing modes. The output information of this processing software includes among others, the coordinates of the station, satellite orbits and clocks and the tropospheric delays etc. GipsyX has high precision and accuracy, flexible in operation, and has good interface support system. Some of its areas of applications are determination of precise orbit position in real-time, PPP in resolving ambiguity, ephemeris prediction etc. With regards to Earth model, GipsyX executes the International Earth Rotation and Reference System Service (IERS) standards (Bertiger et al., 2020).

In this dissertation online GipsyX software was used for the processing of the GNSS observations (data) for the estimation of ZTD.

3.4 Sources of Satellite Orbits and Clocks

Satellite orbits and clocks are vital requirements in the processing of GNSS observations especially when using the PPP strategy as in the case of this dissertation. Two main sources will be explored in the following subsections. They are the International GNSS Service and Jet Propulsion Laboratory.

3.4.1 International GNSS Service

The International GNSS Service (IGS) is one of the main providers of precise satellite orbits and clocks products for the processing of GNSS observation. IGS (Ansari et al., 2017) was established in June 1994 by the IAG. It is a non-commercial and collaborative efforts of about 200 contributing research organisations from over 80 countries that owns and maintain permanent GNSS stations and providing quality products that will enhance the accuracy of GNSS observations and processing. IGS provides raw GNSS data, highly precise satellite orbit and clock data, ensure the improvement and extension of the International Terrestrial Reference frame (ITRS), amongst others. According to Ansari et al., (2017) as at May 2017, IGS has a total of 506 stations in the IGS Network used to generate various products as shown in Figure 3.1.

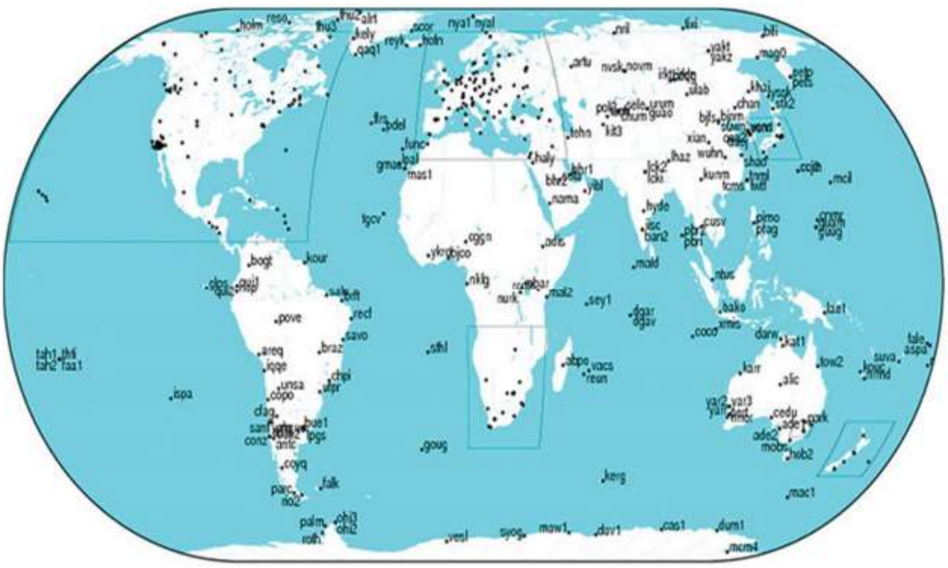


Figure 3. 1: IGS Station Network. Source: Ansari et al., (2017).

IGS has several Analysis Centres that process GNSS observations to compute satellite orbits and clock products. It has various operational products such as precise GNSS satellite ephemerides, position, and velocities of station in global GNSS network, station, and satellite clock solution. Other products archived by the Crustal Dynamics Data Information System (CDDIS) in support of IGS include troposphere Zenith Path Delay (ZPD) estimates (both dry and wet components) and global troposphere map in support of Working Groups (WG) or Pilot Projects (IGS, 2020).

Presently, there are about 9 IGS Analysis Centres that contributes daily ultra-rapid, rapid and final GPS/GNSS orbit and clock solution to the IGS combination. The ultra-rapid product was conceived and designed originally to cater for meteorological activities and Low Earth Orbiter and has also become a very useful product for real-time and near real-time applications.

In 2009 the IGS initiated reprocessing campaign and a similar reprocessing campaign also in 2013 called repro-1 and repro-2, respectively. The GNSS data for these campaigns were reprocessed by the IGS AC using the global network of the IGS stations. The campaigns were carried out from 1994 to 2007 for repro-1 and from 1994 to 2013 for repro-2 with the aim of providing adequately consistent product using most recent models and processing strategies (Griffiths, 2018). The IGS products are:

- IGS Final Products (IGS): The IGS Final products are fundamental to the IGS reference frame with the highest quality and internal consistency when compared to other IGS products. These products are available daily on weekly basis with a delay of about 13 days with the exception of the IGS final troposphere estimates produced between 1 to 7 days after the IGS final orbits, clocks and Earth Rotation Parameters (ERP) have been computed (IGS, 2020).

- IGS Rapid Products (IGR): IGS Rapid products are of close quality when compared to the IGS final. In fact, these products are considered as the next in standard to the IGS final products. IGR is a daily solution available with a delay of approximately 17 hours after the end the preceding Coordinated Universal Time (UTC) day. Published daily at 17:00 UTC (IGS, 2020).

- IGS Ultra-rapid Products (IGU): The IGU products was established by IGS in November 2000 for Near Real-Time and Real-Time applications. These products are GPS orbits, satellite orbits and ERP for a sliding 48-hour period from which 24 hours is for the observed orbits estimates and the other 24hours for the predicted. IGU products are available 4 times per day (3:00, 9:00. 15:00 and 21:00) UTC. The latency of these products is 3 hours indicating that the prediction will have an average age of 9 hours suitable for NRT. (IGS, 2020).

3.4.2 Jet Propulsion Laboratory

The Jet Propulsion Laboratory of the National Aeronautics and Space laboratory Administration (NASA) is a research and development laboratory managed by the California Institute of Technology. The JPL orbits are described here because they are used by GipsyX for data processing using PPP strategy.

Like the IGS, they also provide their satellite orbits and clocks products in three different formats. They include the final, rapid and ultra-rapid products (JPL, n.d.-a).

- Final – The final products of JPL are the most precise with a latency of 14 days and an accuracy of 2.5cm.
- Rapid – The rapid products are next to the final product with respect to precision. They are available the next day with an accuracy of 3.5cm.
- Ultra - Rapid – These products have a duration of 30-hour moving window with a delay of 2 hours and an accuracy of 5cm. The products are updated every hour.

3.5 Troposphere Mapping Functions

A Mapping function is key element in the processing of GNSS observations in other to obtain the tropospheric delay. It can be explained as a relationship between the amount of the propagation delay at different elevation angles when compared to that in the zenith direction as shown in Figure 3.2. The import of mapping function is to make up for the variation in the delay as a function of the elevation angle. Mapping function can be used to project the average Precipitable Water Vapour content from GNSS signals delay in the slant directions with different elevation angles and azimuth unto the zenith direction.

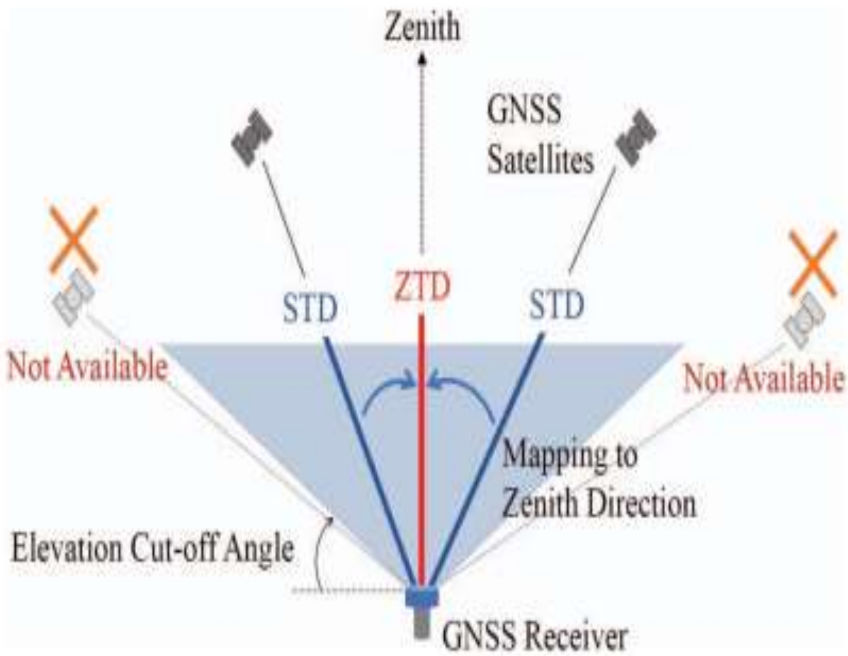


Figure 3. 2: Mapping Slant Total Delay (STD) to Zenith Direction: Source: Imaoka et al., (2019).

During GNSS observations, the satellites being tracked by GNSS receivers are not in the zenith direction but in the slant directions as illustrated in Figure 3.2. Hence the delay value between pair of satellites and the receivers is calculated in the slant direction not in the zenith direction. It is in this manner that mapping function is used to relate the slant at different elevation angles to the zenith.

Qiu et al., (2020) in their research informed of the difficulty that processing of GNSS data would have encountered for the estimation of tropospheric delay directly because of the uncertainties that would have been initiated into the equations of the processing software. The authors said, for the uncertainties to be reduced for the estimation of the tropospheric delay, the Slant Total Delay (STD) is used as a function of the ZTD (a piece-wise linear value), mapping functions and gradient models. Mapping functions are of two components: the hydrostatic called the dry component and the non-hydrostatic known as the wet component.

Application of Mapping functions to geodetic and meteorological activities can be dated back to the 1970s with that of Marini (1972). Herring mapping function Herring (1992) and Niell mapping function Niell (1996) was an improvement of Marini`s. Niell mapping function then was the most preferred and widely used which was built on radiosonde profiles from the northern hemisphere only, which makes latitude dependent biases to be largest in high southern latitudes. As time went by, other mapping functions were developed using NWP models provided by the European Centre for Medium - range Weather Forecasts (ECMW) to cover for the deficiency of the Niell mapping function (Won et al., 2010).

These numerical model dependent mapping functions are Vienna Mapping Factions (VMF, VMF1) and Global Mapping Function (GMF) (Won et al., 2010).

Table 3.1 gives an overview of Niell, Vienna and Global Mapping Functions widely used in the processing of GNSS observations.

Table 3. 1: Troposphere Mapping Functions.

Mapping Functions	Developer	Year	Input Parameters
Niell Mapping Function (NMF)	AE Niell	1996	Station Latitude, Height and Day of Year
Vienna Mapping Function 1 (VMF1)	Boehm et al.	2006	Numerical weather models
Global Mapping Function (GMF)	Boehm et. al	2006	Direct Raytracing

Fundamental to most mapping functions is a mathematical expression that is in a continued fraction form put forward by Marini (1972) and normalised by Herring (1992) as shown in equation 3.1.

$$m_i(e) = \frac{1 + \frac{a_i}{1 + \frac{b_i}{1 + c_i}}}{\sin e + \frac{a_i}{\sin e + \frac{b_i}{\sin e + c_i}}} \tag{3.1}$$

Where e is the elevation angle and a, b and c are coefficients that indicates the atmospheric condition with each mapping functions determining its own coefficients differently. From equation 3.1, i can be marked as h for Hydrostatic Mapping function and as w for the Wet Mapping function (Won et al., 2010).

3.6 Meteorological Parameters

Meteorological parameters especially temperature and pressure are indispensable parameters that play key role in the conversion of the ZTD to PWV in GNSS meteorology. Bevis et al (1992) in their research informed that the conversion of ZWD one of the components of ZTD to PWV needs temperature profiles that are gotten from surface values.

In the best practice of ground-based GNSS meteorology, meteorological sensors are ideally collocated at GNSS sites for the accurate retrieval of surface temperature and pressure for the conversion of ZTD to PWV. However, in the case of the Nigerian Permanent GNSS Network, none of the stations were equipped or collocated with meteorological sensors before this dissertation. In the light of transferring knowledge to develop Africa within the framework of the SUGGEST-AFRICA project, five of the GNSS stations (ABFC, KNKN, ENEN, LGLA and CBCR, see Figure 2.5) are now collocated with meteorological sensors as a pilot scheme to support meteorological and climatological activities in Nigeria.

3.7 Geographic Information System

3.7.1 Origin and Definition

GIS (using geographic method) may be said to have originated in 1854 by John Snow in his effort to investigate the source and cause of a cholera outbreak in London by using points to represent the locations of some specific cases on his cartographic map. He discovered at the end of his investigation that the disease was not an airborne but through water in one of the pipes (Steenson, 2019). Within this period there were no computer and mapping were normally carried out using paper due to poor development in GIS then.

However, operational GIS started in the 1960`s with the advent of computer technology. The then new technology was taken advantage of by Roger Tomlinson widely referred to as the father of GIS to develop modern GIS in Canada called the Canadian Geographic Information System (CGIS) (Steenson, 2019). CGIS was said to be unique by using a layer method to produce maps.

The improvements of computer memories graphic, and processing capabilities brought about the design of GIS software and the Environmental System Research Institute (ESRI), recognised as the world leading experts in GIS is one of the biggest GIS software company in the world. The continuous advancement in computers led to increase GIS software choices (Steenson, 2019).

Geographic Information System is a computer-based information system that has rapidly evolved into an indispensable tool or technology in various fields of application over time. There are several definitions of GIS from different perspective and field of study. The definition of GIS in most cases is either tailored towards its capability with regards to function or the components it is made up of.

Zhang & Drake (2014) define GIS as a wide encompassing computer-based tool for capturing, storing, generating, analysing, and displaying geographic data for purposes of consolidated decision support system. A GIS has the capacity to adequately store, retrieve, update, change manipulate, combine integrate, exchange, interpolate, visualize, analyse, and give geospatial and non-geospatial information. The input data in a GIS can be but not limited to maps, spreadsheets, charts or pictures (Al-Mahdi & Maina, 2013) and (Sanderson, 2014). GIS helps us to give answer to questions like what, when and where.

3.7.2 Major Components of GIS

There are six basic components which all functioning or operational GIS must possess as shown in Figure 3.3. All six components play vital role to make a GIS function optimally. It includes People, Hardware, Software, Data. Procedure and Network.

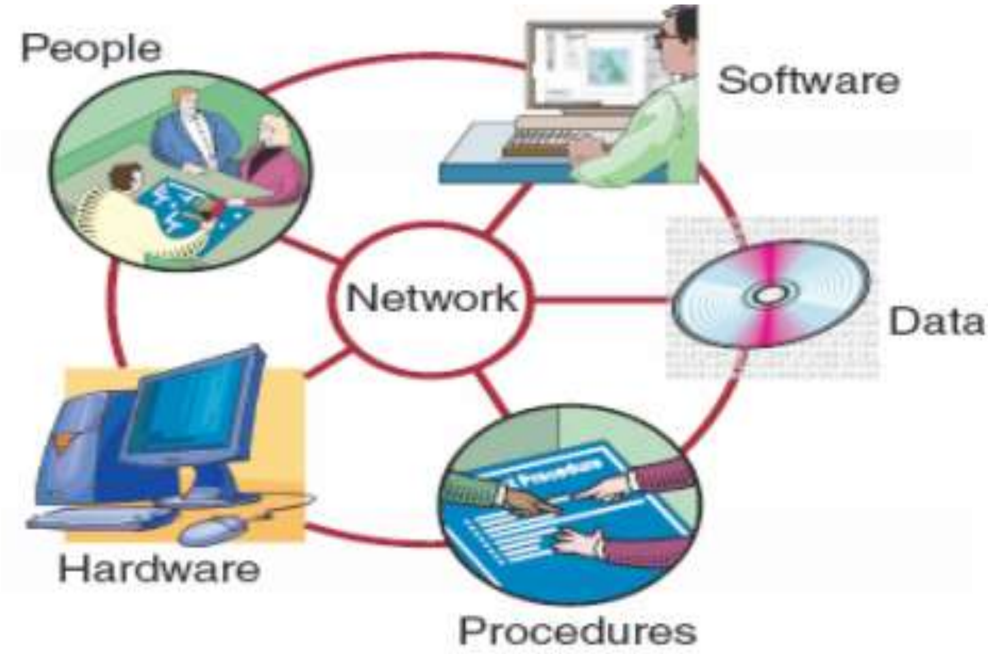


Figure 3. 3: Basic Components of GIS. Source Eldrandaly (2007).

- People: people are vital and usually recognised as the live wire of any functioning GIS to drive the process for the performance of the GIS. This is with regards to an individual or group of people knowing what to do and setting out the strategy for accomplishment.
- Hardware: Hardware is what people implementing GIS task directly interacts with. Hardware components include computer, plotter, digitizer, palmtop, workstation etc.
- Software: The software aspect of GIS goes beyond just GIS software. It also includes Database, program, drawing, statistics, imaging etc.
- Data: Data is what makes GIS what it is. Though all components are unique, data is a very crucial component of GIS. Everything GIS does requires data. It is both geographic and attribute. The reliability of the data influences the overall outcome of the results.
- Procedure: Working with GIS demands adequate knowledge, following basic principles and reliable approach to achieve quality results.

- Network: Network is a means by which high-speed communications and information sharing in digital format is carried out. The Internet is one of the best things that happened to GIS. It rapidly facilitates transmission of data from one point to another.

3.7.3 GIS Application in Weather Related-Activities

In the year 2001, 18 European countries saw the need to bridge the gap by linking GIS and meteorological data through an European Cooperation Action, European Cooperation for Science and Technology (COST) often referred to as COST Action 719. The objective was to demonstrate the competence of GIS technology in meteorological applications there by adding more values to it (Dyras et al., 2005). This led to the formation of three WG to investigate and ensure the possibilities.

The integration of satellite imagery together with remote sensing technology with GIS, has given GIS an advantage of its numerous applications in different fields of human endeavour including meteorology (Feidas et al., 2007). The authors maintained that GIS is now an essential tool in weather-processing system permitting immediate interpolation and plotting of weather data at various pressure level of the atmosphere. In addition, GIS is used to combine various layers of weather information for classification and other purposes.

GIS has made possible the unification of the output of numerical weather models into weather processing systems, whereby satellite imagery and topography are overlayed, a method that enhances the potential for weather predictions (Feidas et al., 2007). The aforesaid is very important because numeric weather models have over the years proven to be reliable and essential for our day-to-day weather-related activities.

Shivers et al., (2019) in their study to analyse the variation of atmospheric water vapour over a complex agricultural region in California central valley deployed the combination of hyperspectral reflectance Imagery and GIS layer of Field data. The authors used the Inverse Distance Weight (IDW), a GIS tool for the interpolation of meteorological parameter. IDW is a well-known interpolation tool in weather and climate study for the interpolation of temperature, pressure, wind, precipitation (Shivers et al., 2019).

GIS approach in meteorological application has become progressively recognised and applied beginning with the acceptance of open GIS data format by the Advance weather Interactive Processing System (AWIPS) as well as the agreement for the standard of exchange and interoperability of GIS data especially in the area of web applications (Shipley, 2005). The author used GIS functions to analyse Rawinsonde (raster background) tracks as seen in Figure 3.4 at high altitude revealing GIS as a tool beyond just map making which was believed in the past to be the only purpose of GIS.

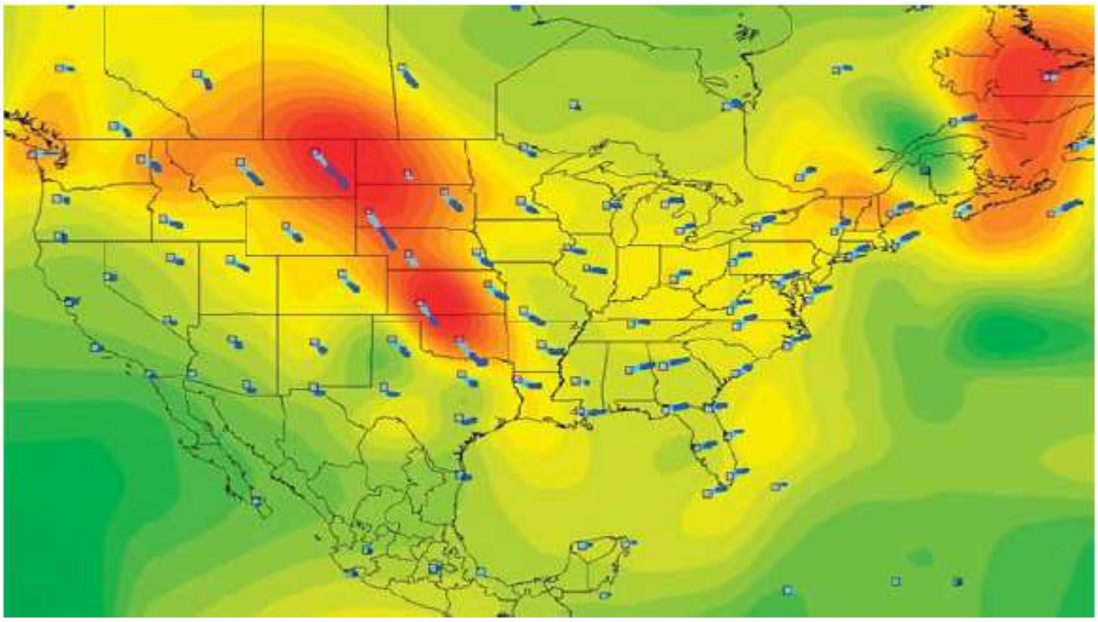


Figure 3. 4: Rawinsonde tracks showing extent of spatial offset at high altitude of 100-hpa reanalysis using GIS. Source: Shipley (2005).

GIS is one the single most robust integrating technology. For example, Dyras & Serafin-Rek., (2005) in their study demonstrated the potential of GIS technology in precipitation mapping by developing GIS with different atmospheric layers such as precipitation and other parameters derived from satellite, NWP models and hydro-meteorological data which aided the combination of different thematic layers for analysis as well as the visualisation of meteorological parameters.

The National Oceanic and Atmospheric Administration (NOAA) make use of GIS to monitor the behaviour of storms globally, the United States Geological Survey (USGS) utilizes GIS to gather and examine data concerning earthquake, tsunami and volcanoes and the US Department of Agriculture (USDA) tracks the danger caused by drought on the nations crop using GIS (Dangermond & Artz, 2010).

Shukla et al., (2017) used geospatial technology such as GIS and Remote Sensing (RS) in their research to evaluate rainfall event in an arid area as well as investigating the form of atmospheric total column precipitable water vapour in that region. They concluded that geospatial dataset which is in good agreement with the in-situ measured dataset can be used as substitute.

It is important to state that in the past different file formats hindered data interoperability and broad range application of GIS in some field of endeavour. However, today GIS is now compatible with various bulk data file sharing formats like Network Common Data Form (NetCDF) and General Regularly Distributed Information in Binary form (GRIB) for visualising meteorological and climatological data.

3.8 Summary

In this chapter, ground based GNSS meteorology in some parts of the world were examined. Some projects and programs aimed at the exploitation of GPS/GNSS observations for the monitoring water vapour for atmospheric studies were presented. Tropospheric products used by different continents and country for operational and research purposes in weather and climate related investigation were also explored. Types of GNSS observations processing methods to estimate the Zenith Tropospheric Delay and processing software as well as different products and parameters required in ground-based GNSS meteorology to obtain PWV were discussed. Finally, Geographic Information Systems origin and definition and as it relates to weather was briefly investigated.

Chapter 4

GNSS Processing and PWV Computation

Vital to any GNSS observations for effective utilisation in any investigation, analysis, and related applications, is the processing of such observations (data). The processing of the observations in this dissertation was carried out with the online GipsyX-Automatic Precise Positioning Service (APPS) software to obtain amongst others, the tropospheric products necessary for analysis. It is pertinent to inform that some of the tropospheric products were retrieved from SEGAL Infrastructure for analysis. In this chapter, we explore the study area, GNSS data acquisition, GNSS observation processing and PWV computation process. This chapter was carried out with the aim of obtaining results necessary for analysis in the next chapter.

4.1 Study Area

4.1.1 Location and Weather

Nigeria is a sovereign country in West Africa with 36 states plus the FCT. It is divided into six regions with mainly north and south divide. Nigeria is sharing border with four other countries as shown in Figure 4.1. It has a total area of about 923, 768 Sq. km with river Benue and Niger as two main rivers.

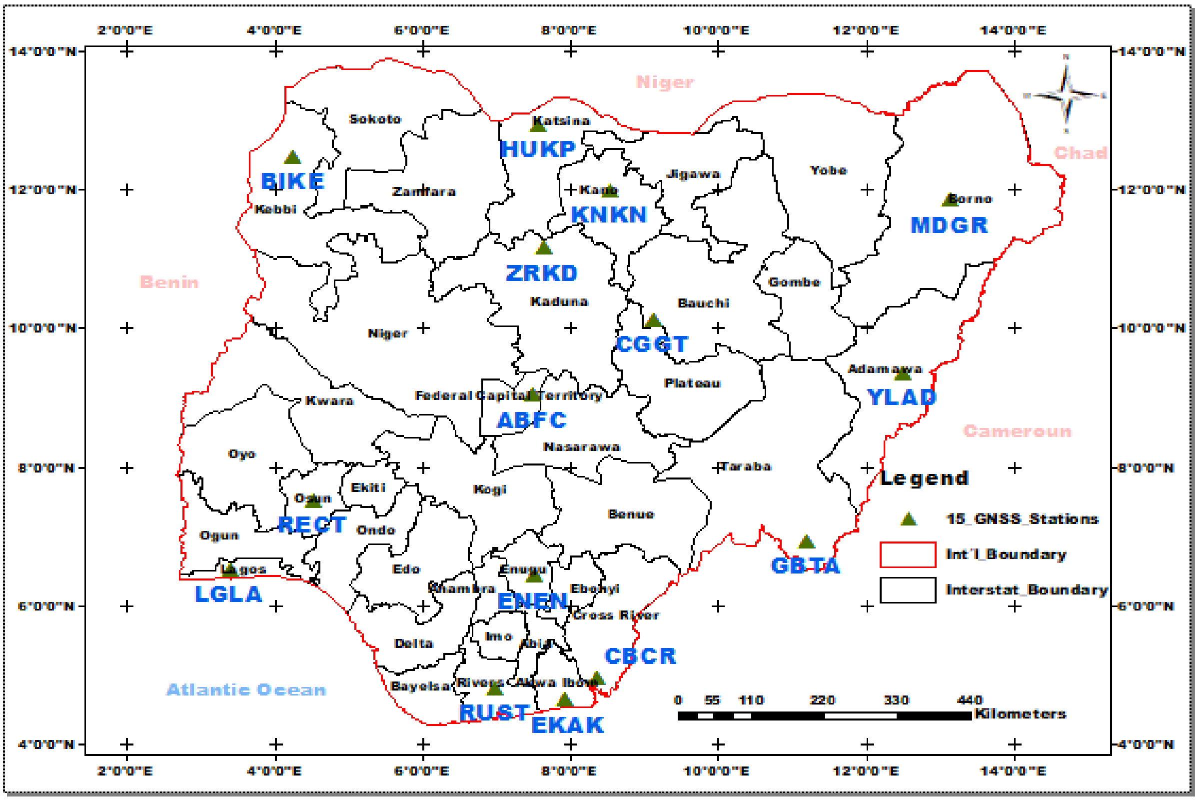


Figure 4. 1: Geographic Location of Nigeria with Fifteen GNSS Stations (green triangles) and Station ID in blue colour Adopted for the Study.

Nigeria has Niger in the north, Chad in the northeast, Cameroon in the east and Benin in the west. It also has a coast border with Gulf of Guinea and the Atlantic Ocean in the south and the Sahara Desert in the north. Nigeria lies between latitude 4° and 14° N and longitude 2° and 15°E. It has a tropical climate with variable dry (winter) and rainy (summer) seasons influenced by what is referred to as the trade wind (north-east and south-west winds). In the south the rainy season lasts from March to October while in the north it lasts from May to October. The rainy season comes with lower monthly temperature and the lowest temperature is observed during the harmattan (dry) season that last from December to February.

According to (Akande et al., 2017) Nigerian weather is primarily influenced by the Intertropical Discontinuity which is referred to as the area of lowest pressure in the region of West Africa that divides the moist Southwest Monsoon from the Atlantic Ocean and the northeast wind from the Sahara Desert. Nigeria is made up of 4 distinct climatic zones that are dependent on seasonal rainfall and the behaviour of temperature. In the north-east we have warm desert climate, other parts of north has the warm semi-arid climate, the south-south has the monsoon climate (i.e. short dry season) while the north-central and some parts of south-west has the tropical savanna climate (Akande et al., 2017) as shown in Figure 4.2.

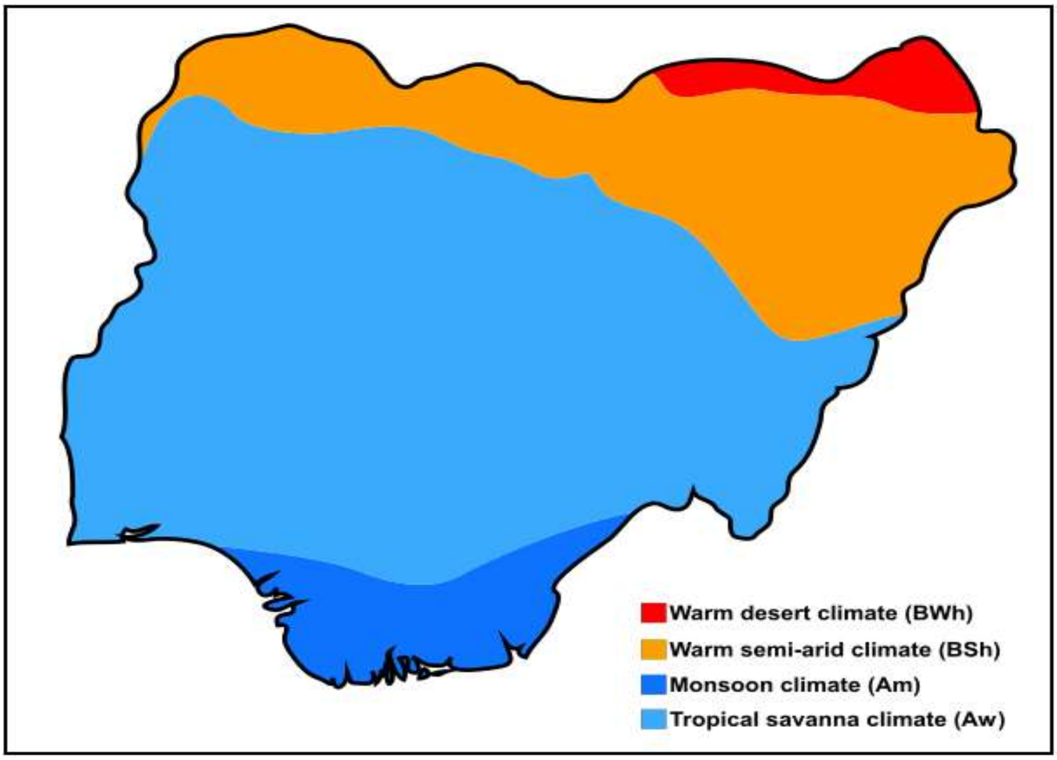


Figure 4. 2: Nigerian Map of Koppen Climate Classification. Source: Mobolade & Pourvahidi (2020).

4.2 GNSS Data Acquisition

4.2.1 TeroNet Software

TeroNet is a GNSS network data management platform that was initially developed by Space and Earth Geodetic Laboratory Analysis (SEGAL). As earlier said in Chapter 1, SEGAL is the installer and maintainer of the Nigerian Permanent GNSS Network. The TeroNet platform is being administered by OSGOF with the support of SEGAL. TeroNet user interface in Figure 4.3 consists of but not limited to: Station name, Localisation, Agency, and Action to include (details of each station, daily data, hourly data, and ephemeris data).

Figure 4. 3: TeroNet Platform with NIGNET Observations. Source: TeroNet (2021).

It also includes "custom data download" having calendar with data range and data rate. In addition, the platform shows the locations on Nigerian map where some of the GNSS stations (in blue colour) are located. Figure 4.3 shows some of the key features of the public interface of TeroNet.

4.2.2 TeroNet GNSS Data Flow

When raw GNSS observations are received into the TeroNet server, the data are by default arranged in a row in the order of reception to be converted into RINEX and Ephemeris files (Teromovigo, 2019). The quality of the data processed is also ensured by the software before been assessed by a registered user as in the case of this dissertation through a web platform as depicted in Figure 4.4. The quality component of the software allows user to know the amount of data per file per day even before the downloading is carried out. This helps the user to know if a particular data or station is good enough for the work. For instance, there are daily files that has no data in it while some have 100% daily data and others have less than 100% data.

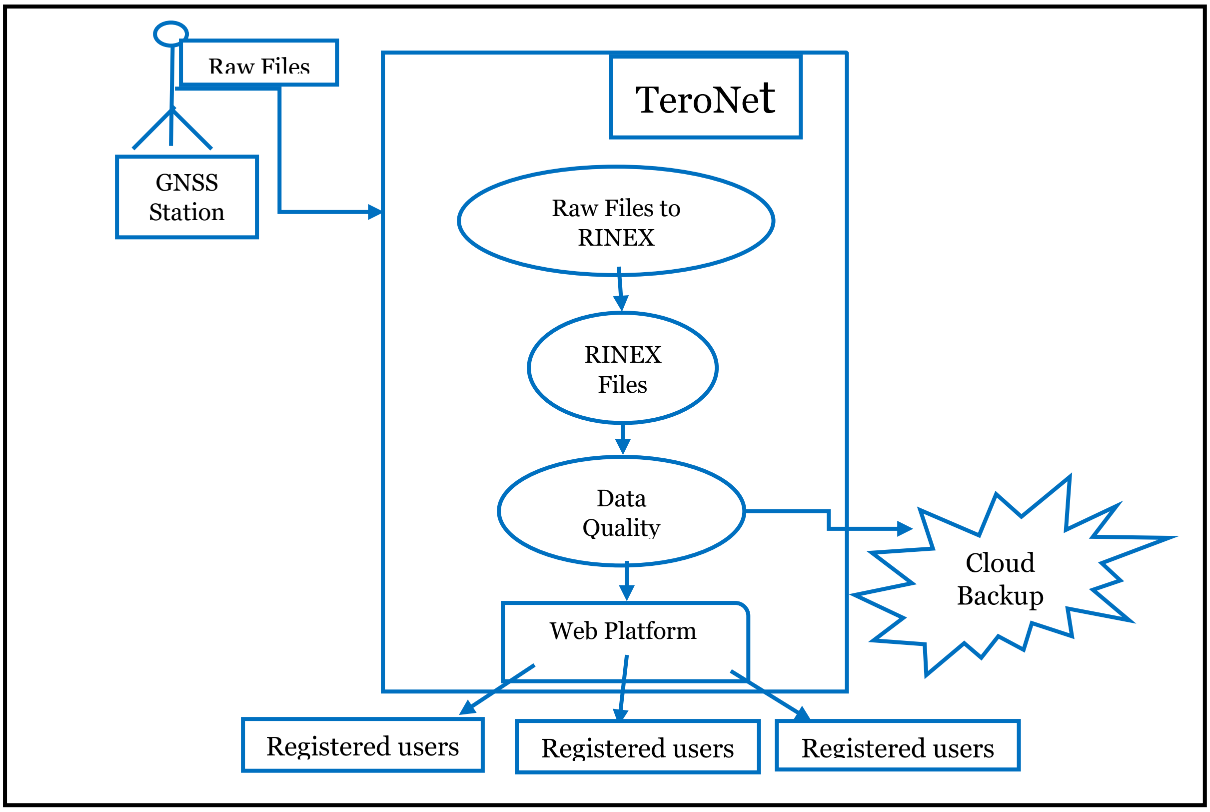


Figure 4. 4: TeroNet Software Data Flow

4.2.3 NIGNET Observations

The GNSS stations (observations) used in this dissertation as shown in Figure 4.1 and Table 4.1 were in Receiver Independent Exchange (RINEX) format from the TeroNet platform.

Table 4. 1: GNSS Stations with Location Information Adopted for the study.

Station ID	Longitude	Latitude	Altitude (m)	Region	Location/State
ABFC	7.486342	9.027666	532.645	North-Central	FCT
CBCR	8.351571	4.950306	60.586	South	Calabar
CGGT	9.118312	10.123095	916.432	North-East	Bauchi
KNKN	8.543769	11.984241	542.689	North-West	Kano
RUST	6.978352	4.801684	46.600	South	Rivers
ZRKD	7.648687	11.151740	705.066	North-Central	Kaduna
EKAK	7.916623	4.638411	41.870	South	Akwa-Ibom
YLAD	12.497798	9.349743	247.406	North-East	Adamawa
BIKE	4.229242	12.468577	250.012	North-West	Kebbi
LGLA	3.397623	6.517327	44.575	South-West	Lagos
RECT	4.524476	7.505488	281.943	South-West	Akure
MDGR	13.130851	11.838059	351.800	North-East	Borno
GBTA	11.183941	6.917199	1795.615	South-East	Taraba
HUKP	7.559092	12.921146	565.010	North-West	Katsina
ENEN	7.504991	6.424806	254.405	South-East	Enugu

The selection of these GNSS stations as depicted in Figure 4.1 and Table 4.1 were influenced by the following criteria:

- Data availability during the period considered in this dissertation.
- GNSS stations operated by OSGOF and other Agencies.
- The quality of the data.
- Representation of regional distribution.

4.3 GNSS Observations Processing

One of the main reasons of processing GNSS observations in GNSS meteorology is to obtain the tropospheric delay parameter (Zenith Total Delay) and stations coordinate, among others. The processing of the GNSS observations and subsequent analysis helps to characterise the ZTD/PWV variations in time and space over the territory of Nigeria. This was done with the motive of achieving the aims and objectives of this dissertation.

4.3.1 Analysis Software

The GipsyX Automatic Precise Positioning System of the Global Differential GPS (GDGPS) System software in PPP was used for the processing of the GNSS Observations to obtain the ZTD. Among other things, the software solves for the transmitter and receiver position, model the orbital parameters and tropospheric delay parameters. The software is an online (open source) GNSS data processing software developed and owned by the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory of the California Institute of Technology (Caltech) as shown in Figure 4.5. The choice of the software is due to the long-time usage by SEGAL, availability, flexibility, fast processing capability and user-friendly interface.

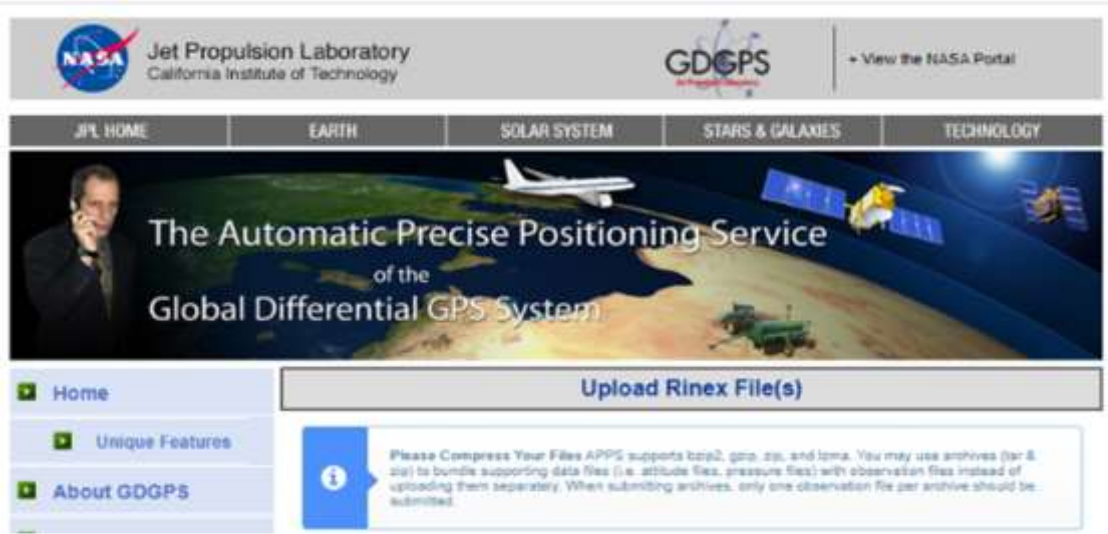


Figure 4. 5: GNSS Observations Processing Software. Source: (JPL, n.d.-b).

The software uses JPL's final, rapid and ultra-rapid orbits and clocks products for its position determination and estimation of tropospheric and other parameters. However, in this dissertation the JPL's ultra-rapid orbits were used. The software supports inputs in RINEX 2, 2.11 and 3 input files. It uses the ITRF 2014 as its reference frame. In addition, it uses the python Application Programming Interface (API) to upload and retrieve files.

4.3.2 Processing Parameters

The GNSS observations for processing was in RINEX format. The ZTD estimation based on PPP solution (output) for the station was carried out every 300 sec (5min) interval with 24-hour daily observation files using an elevation cut-off angle of 7.5° (degrees). The Global Mapping Function was applied as the tropospheric model to map the slants to the zenith direction. Ocean tide loading (OTL) and model tides corrections were also applied by the software during the processing in static mode. OTL effect is a fundamental error which affect the accuracy of ZTD derived from GNSS. The parameters used for the processing of the GNSS observations to obtain ZTD are listed in Table 4.2.

Table 4. 2: Summary of the Parameters for processing GNSS Observations.

Parameter	Description
Observations	Precise Point Positioning (PPP)
Satellite Orbits	JPL Ultra- Rapid
Mapping Function	Global Mapping Function (GMF)
Elevation Cut-off Angle	7.5 degrees
Station Coordinates	Tightly constrained to IGS14 reference frame
Satellite and Receiver PCO	IGS Standard (igs14_2131 atx)
ZTD Output	300 Second Interval (5 minutes)
Station Displacement	Model Tides and Ocean Tide Loading corrections

The aforesaid implies that the choice of OTL model in processing GNSS observation is crucial to achieving ZTD that is of high accuracy. An example of OTL model is the Finite Element Solution (FES2004) recommended by the International Earth Rotation Service (IERS).

The GipsyX APPS GNSS observations processing platform is shown in Figure 4.6.

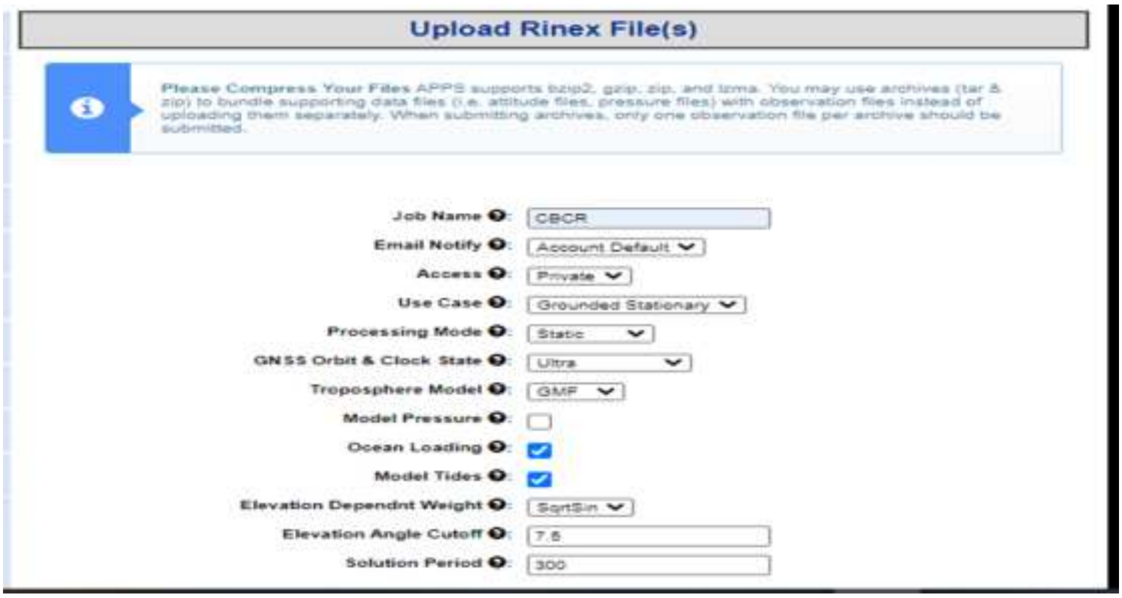


Figure 4. 6: APPS GNSS Observations Processing Platform.

The processing Summary file for the APPS online software for CBCR station is shown in Figure 4.7.

```
##################################################################################
#########              BETA BETA BETA BETA BETA BETA BETA BETA BETA BETA          #########
##################################################################################
# APPS Summary file produced from RINEX file CBCR20210409523.21D on 2021-04-08 23:57:53.671902
# The reference frame is IGS14 (with semi-major axis = 6378137m; flattening factor = 1/298.257222101)
# Output data rate is 300 seconds.
# Elevation Dependent Weight: SQRTSIN
# Elevation Cutoff Angle: 7.5
# Satellite antenna phase center offset and maps taken from IGS Standards igs14_2131.atx
#
# Receiver antenna phase center offset and maps taken from IGS Standards igs14_2131.atx
# The antenna reference point offset from the monument reference, based on the RINEX file header is 0.171 m
#
#
# Product used to process CBCR20210409523.21D: JPL Ultra
#
#
# Total number of Phase measurements:    476.  RMS post-fit Phase residuals:    0.009 m. Number of excluded Phase measurements:     77
# Total number of Range measurements:    553.  RMS post-fit PRange residuals:    0.432 m. Number of excluded PRange measurements:     0
#
# Estimated Cartesian coordinates:    X =  6287174.1596 m Y =   922979.6737 m Z =   546713.9517 m
# Estimated Geodetic coordinates(WGS84/GRS80): Lat =   4.950302882 deg East_Lon =   8.351570789 deg Height =   57.5749 m
#
# Time variable estimated parameters:
#Secs_from_start  GPS_Time(yyyy:mm:dd:hh:mm:ss.ssss)  HZTrop(m) WZTrop(m)  Sig(m)   TropGrad_N(m)  Sig(m)   TropGrad_E(m)   Sig(m)   Clock(m)   Sig(m)
       0.0000        2021:04:05:12:00:00.0000      2.2842    0.3251    0.004   -0.0003        0.0005   0.0030        0.0005   -10.599   0.063
     300.0000        2021:04:05:12:05:00.0000      2.2842    0.3251    0.004   -0.0003        0.0005   0.0030        0.0005   -10.806   0.063
     600.0000        2021:04:05:12:10:00.0000      2.2842    0.3250    0.004   -0.0003        0.0005   0.0030        0.0005   -10.823   0.063
     900.0000        2021:04:05:12:15:00.0000      2.2842    0.3249    0.004   -0.0003        0.0005   0.0030        0.0005   -10.996   0.063
    1200.0000        2021:04:05:12:20:00.0000      2.2842    0.3248    0.004   -0.0003        0.0005   0.0030        0.0005   -11.005   0.063
    1500.0000        2021:04:05:12:25:00.0000      2.2842    0.3246    0.004   -0.0003        0.0005   0.0030        0.0005   -10.803   0.063
    1800.0000        2021:04:05:12:30:00.0000      2.2842    0.3245    0.004   -0.0003        0.0005   0.0030        0.0005   -10.362   0.063
    2100.0000        2021:04:05:12:35:00.0000      2.2842    0.3244    0.004   -0.0003        0.0005   0.0030        0.0005   -10.511   0.063
    2400.0000        2021:04:05:12:40:00.0000      2.2842    0.3243    0.004   -0.0004        0.0005   0.0030        0.0005   -10.551   0.063
    2700.0000        2021:04:05:12:45:00.0000      2.2842    0.3243    0.004   -0.0004        0.0005   0.0030        0.0005   -10.343   0.063
    3000.0000        2021:04:05:12:50:00.0000      2.2842    0.3242    0.004   -0.0004        0.0005   0.0029        0.0005   -10.279   0.063
```

Figure 4. 7: APPS Summary File.

4.3.4 Processing Scheme

The processing scheme for the GNSS observations to estimate the ZTD and the conversion to PWV includes but not limited to the following data collection and processing procedures:

- Downloading and uploading of GNSS observations in RINEX formats into the processing software.
- Application of JPL`s satellite orbit and clock products and other parameters for the estimation of the unknowns by the processing software.
- Estimation of station coordinates, tropospheric ZTD and other parameters by the GNSS processing software.
- Downloading of surface meteorological parameters (Temperature and Pressure) from collocated GNSS station or global meteorological model.
- Conversion of ZWD to PWV with the meteorological parameter (T_m)) related to a conversion factor ∏.

The Processing scheme for the GNSS observations is presented in Figure 4.8.

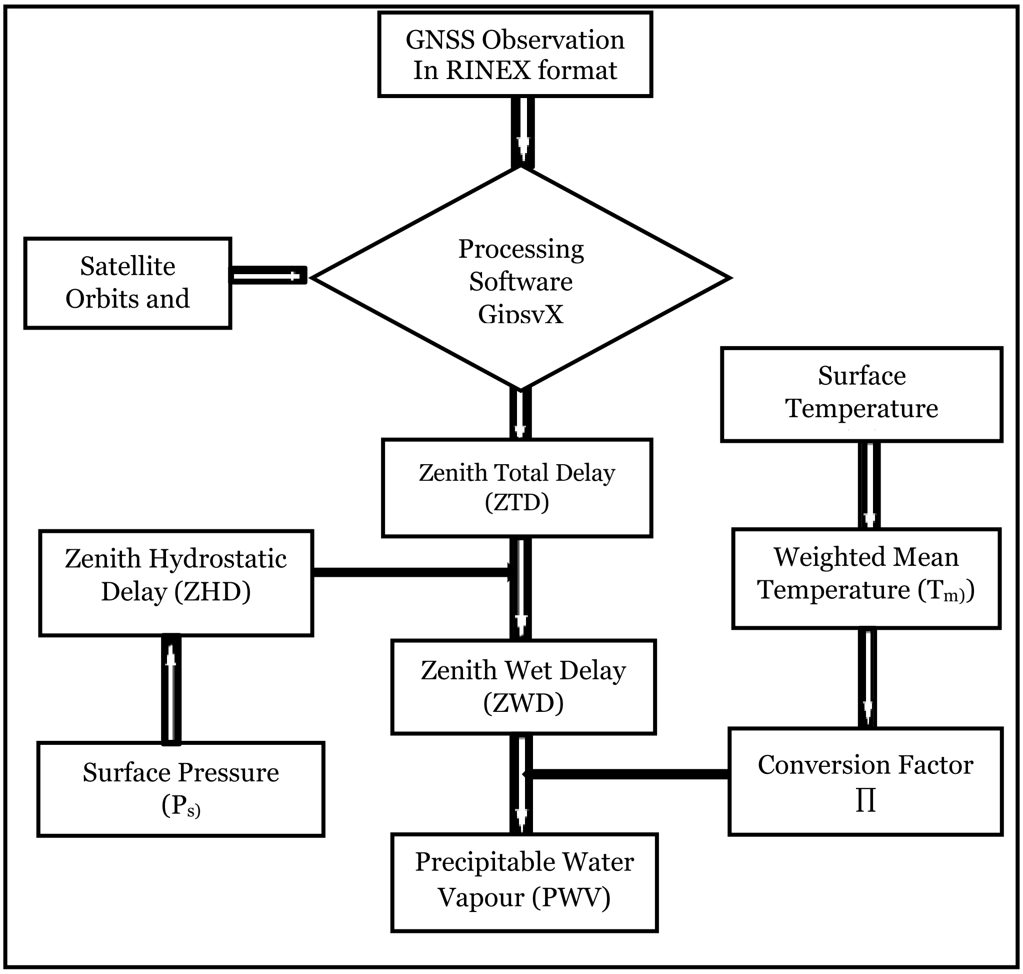


Figure 4. 8: GNSS Observations Processing Scheme to obtain ZTD and Conversion to PWV

4.4 PWV Computation Process

4.4.1 Temperature and Pressure

In the calculation of PWV, information about the surface temperature and surface pressure values at the GNSS station is vital (Alshawaf et al., 2015). The GNSS-derived ZTD is separated from ZHD to obtain ZWD component. The ZHD can be calculated with some degree of accuracy by using surface meteorological parameters such as surface pressure. The ZWD on the other hand, is often obtained as an estimated parameters during GNSS data processing for purposes of achieving high accuracy. Then the obtained ZWD which is considered as a measure or fraction of the entire PWV in the atmosphere along the signal path, is multiplied by a conversion factor that is dependent on weighted mean temperature (T_m) as described in Equation. 2.5 and depicted in Figure 4.8 to calculate the PWV.

The European Centre for Medium Range Weather Forecast (ECMWF) global reanalysis model ERA5 hourly data on single level (Copernicus, 2018) can be interpolated at 5-minutes sampled data to the NIGNET stations data. This idea will be to correlate the GNSS derived ZTD estimates interval which is 5 minutes with the meteorological data for NRT application. The ERA5 is the fifth generation and most recent reanalysis model of the ECMWF with horizontal resolution of 0.25 x 0.25 for global weather and climate and has replaced ERA-Interim reanalysis. To be able to obtain the variables or meteorological parameters (surface temperature and pressure) values from the model; year, month, day, time of observation and the longitude and latitude of the grid nodes are required. Also, to automatically convert ZTD to PWV the following steps are required:

i. Input RINEX meteorological file with temperature and pressure
ii. Input ZTD SINEX file
iii. The latitude of the stations
iv. Orthometric height of the stations
v. Offset between antenna and sensors
vi. PWV output SINEX file

The ERA5 Climate Data Store (CDS) Application Programming Interface (API) can be used to carry out the initial download of the ERA5 data.

It is important to state however that meteorological parameters derived from collocated GNSS stations are far accurate and reliable compared to that from global meteorological models. Hence ERA5 meteorological data were not considered in this research.

It is pertinent to inform that, the ZHD can be computed using Saastamoinen empirical model as described in Equation. 2.2 and the ZWD can be computed using Equation 2.3. The T_m which is the weighted mean temperature at the GNSS site in Kelvin can be computed using Equation 2.6 and finally the PWV can be computed using Equation 2.4 and 2.5.

All computations and graphs used in this dissertation for analysis were carried out in Microsoft Excel work sheet, Office 365 while the maps were prepared using ArcGIS 10.7.1.

4.5 Summary

Processing of GNSS observation is a necessity in GNSS meteorology to enable the estimation of the tropospheric delay parameter (ZTD) and its subsequent conversion to PWV for analysis. In this chapter, the study area (Nigeria) with regards to the fifteen GNSS stations used for the study including the weather and climate conditions were explored. The criteria for selecting the GNSS stations, software used in the processing, processing parameters, processing workflow or scheme and finally the PWV computation process were discussed.

Chapter 5

Tests and Discussion of Results

This chapter aims to analyse the results obtained at the different GNSS stations used in this study. It was initially intended to analyse the PWV estimates. However, due to lack of meteorological data only the ZTD estimates are used for the presentation of the results. First, some tests are described to ensure that the selected stations have enough data and that the presented results are accurate. Different time spans of the observation files were tested and analysed to see the influence of the time span on ZTD estimates. The time series and spatial ZTD patterns were also analysed to understand the nature of the variations and perhaps the possible causes over the territory of Nigeria. In this chapter we present the results of GNSS stations reliability test, time influence test on ZTD estimates, ZTD characteristics over Nigeria, and ZTD variation for precipitation investigation.

5.1 NIGNET Stations Reliability

The Nigerian Permanent GNSS Network stations were analysed for reliability to ensure the availability of some relatively good number of processed daily files to avoid too many data gaps. The investigation was also carried out to detect and exclude GNSS stations without a minimum percentage of processed daily files that are below the threshold of 15 percent as shown in Table 5.1.

Table 5. 1: Percentage of Processed file per NIGNET station.

S/n	Site	Initial Process	Final Process	No. of Years	Total No. of Files	Processed Files	Percentage of Available Data
1	EKAK	17/10/2018	14/08/2021	2.8	692	689	66.8
2	ZRKD	24/01/2010	11/11/2021	11.8	2775	2767	64.2
3	CBCR	20/03/2011	20/11/2021	10.7	2467	2456	63.0
4	YLAD	07/02/2010	02/07/2021	11.4	2570	2559	61.5
5	BIKE	25/01/2010	14/06/2019	9.4	2024	2021	59.0
6	CGGT	06/02/2010	06/09/2013	3.6	751	745	57.0
7	ABFC	12/10/2009	20/11/2021	12.1	2409	2395	54.2
8	HUKP	03/04/2012	14/12/2015	3.7	733	722	53.5
9	ENEN	04/02/2010	17/10/2021	11.7	2306	2247	52.6
10	KNKN	01/04/2016	16/06/2021	5.2	966	964	50.7
11	RUST	12/02/2010	06/07/2013	3.4	544	543	43.8
12	RECT	21/07/2007	27/06/2012	4.9	693	692	38.4
13	MDGR	16/03/2011	04/06/2014	3.2	367	367	31.2
14	LGLA	05/10/2009	21/07/2021	11.8	1290	1289	29.9
15	GBTA	09/02/2010	01/02/2017	7.0	460	398	15.6
	Average						49.4

For example, EKAK (S/n 1) has an observation span of 2.8 years which should correspond to 1023 daily files if there were no missing data. However, only 692 files were available of which three could not be processed. As a result, only 66.8% is processed as indicated in the last column of Table 5.1. Also in Table 5.1, the fifteen NIGNET stations used in this study are presented. The minimum percentage of processed files is 15.6% for GBTA while the maximum is 66.8% for EKAK. It can be observed that the average percentage of processed files for all GNSS stations is 49.4% which is not reliable. There are several causes for the high number of missing files in each station: system failures, vandalization, internet problems, power outage, etc.

5.2 Time Influence Test On ZTD

Here, the 30-hour timespan or window of the JPL ultra-rapid orbits as was explained in section 4.3.3, were used as a reference to estimate solutions for different time spans (1H, 6H,12H and 24H) at different times of the day to see the influence of the length of observations on the ZTD estimates. CBCR station on the 5th of April 2021 illustrates the test carried out.

The difference in ZTD calculation of the various observation files (1H, 6H,12H, 24H) ZTD with reference to the 30H timespan ZTD are depicted in Figure 5.1 to Figure 5.4 for 24H, 12H, 6H and 1H comparison respectively, with the major statistics showing for each period in Table 5.2 to 5.5 respectively.

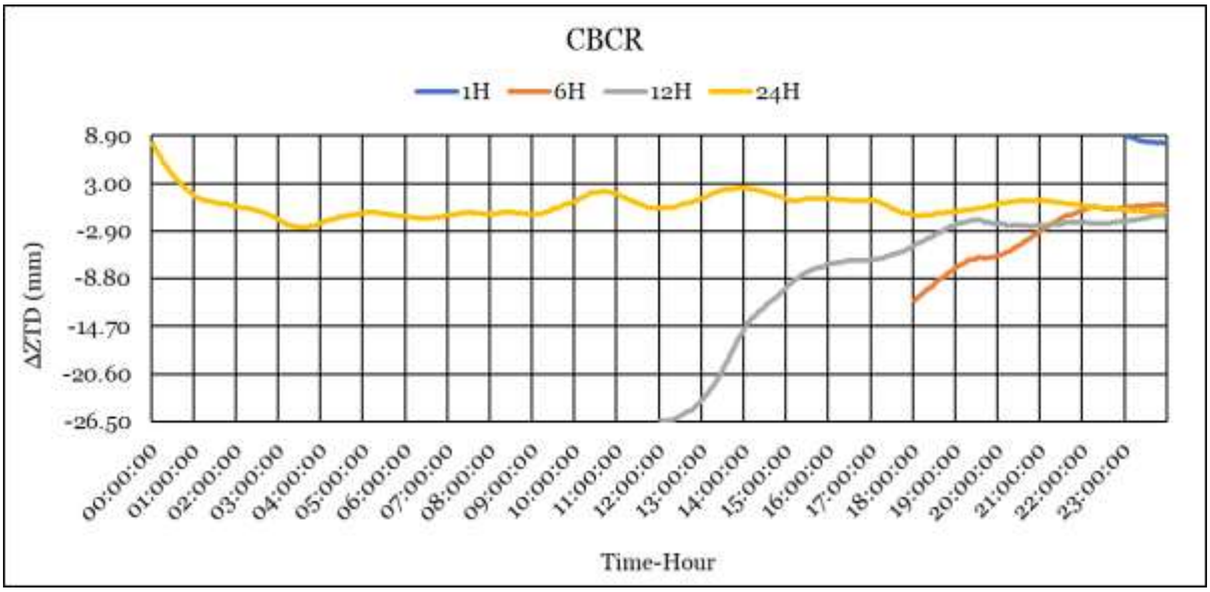


Figure 5. 1: Comparative Graph of 0H to 24H.

Table 5. 2: Statistics of the Difference of 24H ZTD and 30H ZTD

Reference = 30H, Solution = 0H to 24H				
Difference	1H	6H	12H	24H
Min				-2.50
Max				7.90
Stdev (mm)				1.42

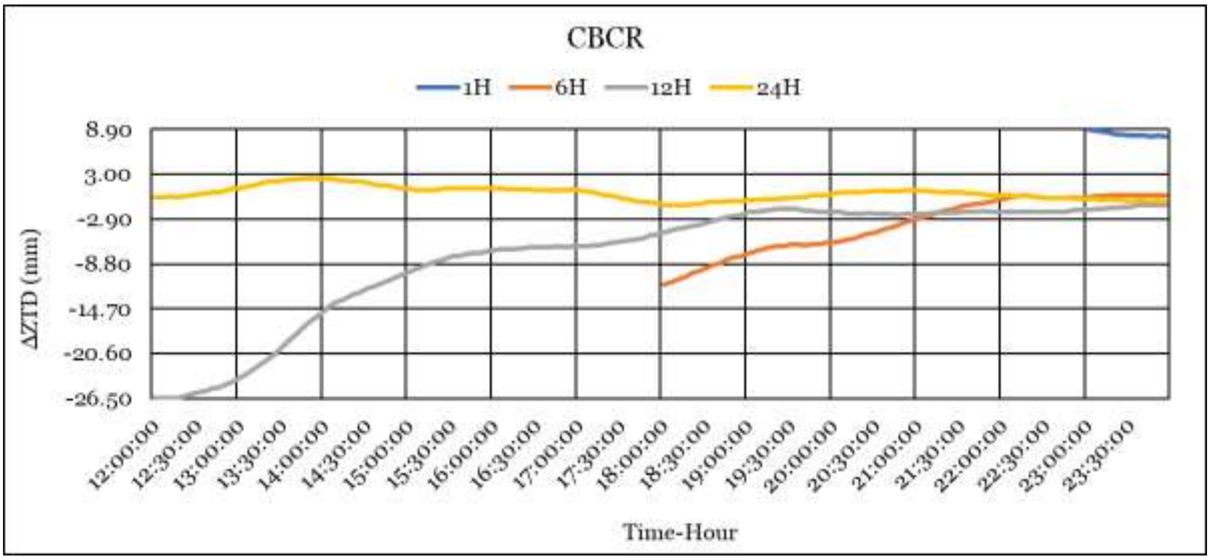


Figure 5. 2: Comparative Graph of 12H to 24H

Table 5. 3: Statistics of the Difference of 12H ZTD and 30H ZTD

Reference = 30H, Solution = 12H to 24H				
Difference	1H	6H	12H	24H
Min (m)			-26.50	-1.10
Max (m)			-1.00	2.50
Stdev (mm)			7.66	0.88

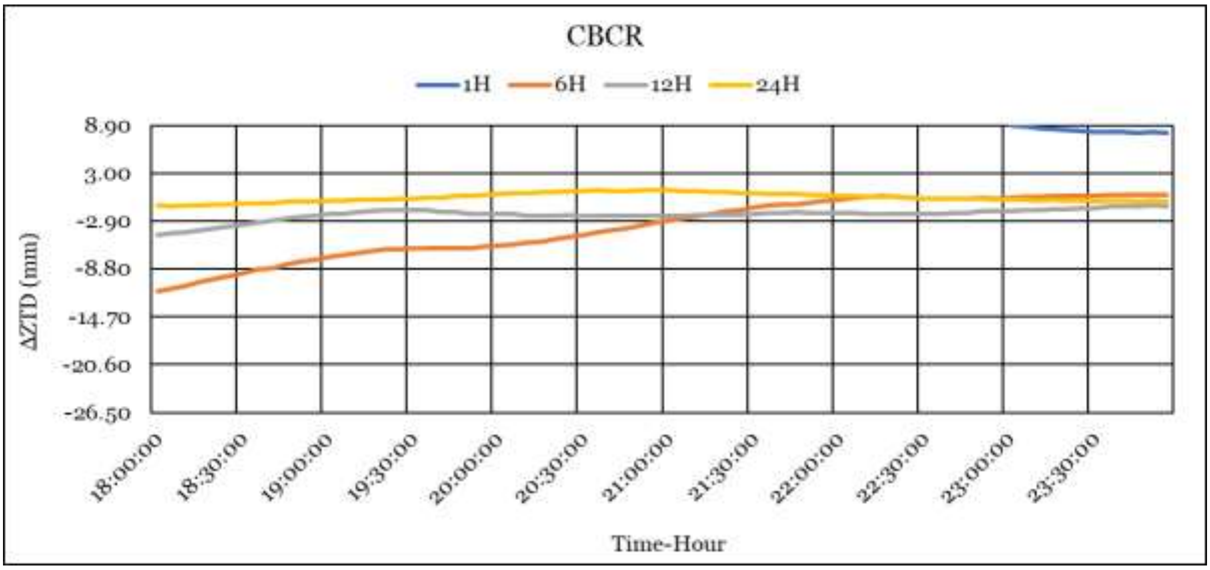


Figure 5. 3: Comparative Graph of 18H to 24H

Table 5. 4: Statistics of the Difference of 6H ZTD and 30H ZTD

Reference = 30H Solution 18H – 24H				
Difference	1H	6H	12H	24H
Min (mm)		-11.50	-4.60	-1.10
Max (mm)		0.30	-1.00	0.90
Stdev (mm)		3.66	0.74	0.57

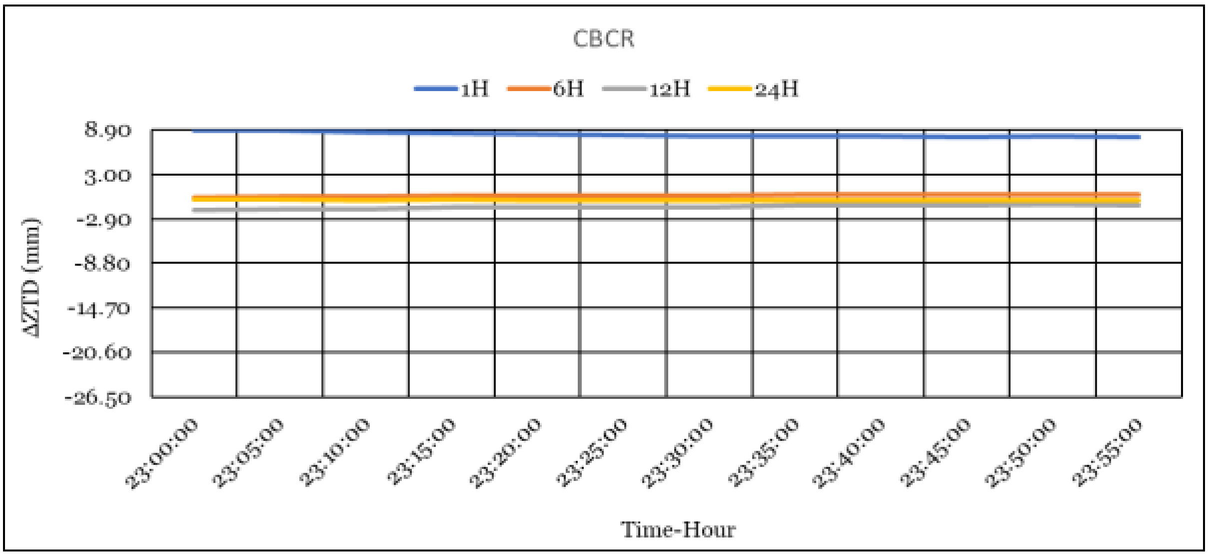


Figure 5. 4: Comparative Graph of 23H to 24H.

Table 5. 5: Statistics of the Difference of 23H ZTD and 30H ZTD

Reference = 30H, Solution = 23H to 24H				
Difference	1H	6H	12H	24H
Min (m)	8.00	0.00	-1.70	-0.50
Max (m)	8.90	0.30	-1.00	-0.30
Stdev (mm)	0.31	0.10	0.24	0.07

It is observed from the different Figures, in Figure 5.1 and 5.2, that the convergence for a similar value is clear for the 12- and 6-hour solutions. The 1-hour solution is too short to converge to the correct value.

It is also observed that the 24H observation file has the best results with the smallest standard deviation in all the solutions. The test furthers reveals that the 24H has less variation when compared to others. This support the conclusion that longer observation file usually culminates into better result since less time of observation will translate into estimates that are less reliable. This was expected.

5.3 Characteristics of ZTD in Nigeria

The ZTD is a very important component of the Earth's atmosphere for weather and climate investigation and variation study. In fact, it is used in United Kingdom (UK) meteorological office, France meteorological office and most Analysis Centres in Europe instead of PWV for assimilation into NWP models. According to Fernandes R.M.S et al., (2014) even though ZTD and PWV are different variables, the two are comparable and have high positive correlation. This may be due partly to the dependence of PWV estimation on ZTD and the time varying wet component (ZWD) that is constituted in both quantities influenced by highly variable amount of water vapour of about 10% of the total delay and temperature. The results of the temporal and spatial characteristics of ZTD with the fifteen NIGNET stations for the period of 2009 to 2021 are presented in the subsections.

5.3.1 ZTD Temporal Variation Over Nigeria

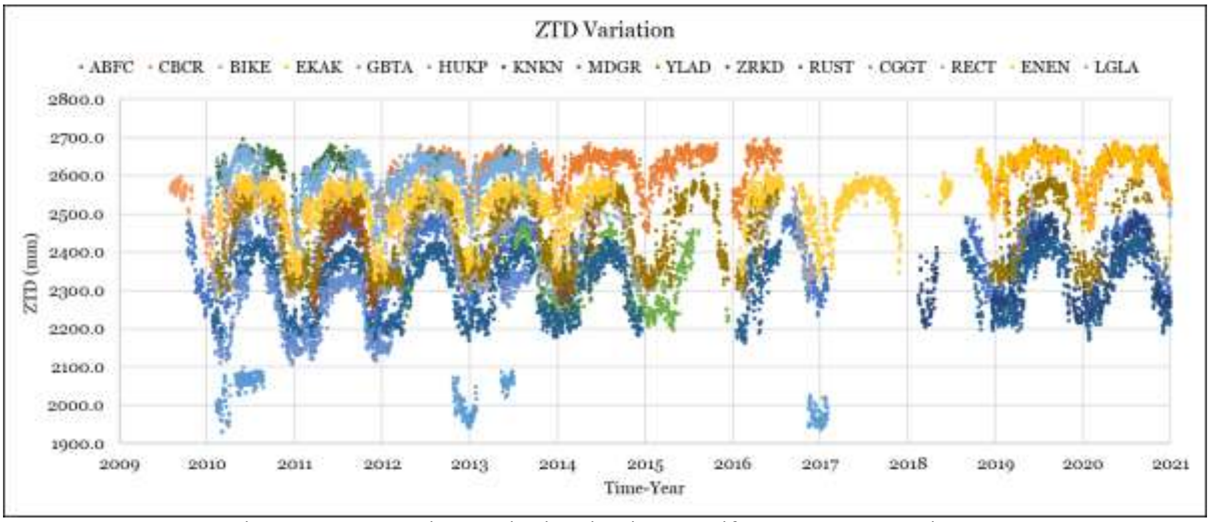


Figure 5. 5: ZTD Time Series in Nigeria over Fifteen NIGNET Stations.

It can be seen in Figure 5.5 that the variation range of ZTD over Nigeria with the fifteen NIGNET stations used in the research is approximately between 1900mm to 2700mm. These values are consistent with the research work of another scholar in the region, please see Appendix A1 for each station. GNSS stations in the Southern region (CBCR, EKAK, GBTA, RUST, RECT, ENEN and LGLA) have high ZTD values than those in the Northern part. Particularly CBCR, EKAK, RUST, LGLA that are in coastal states.

The aforesaid is an indication of the fact that these areas are in actual sense wetter or moist in the atmosphere due mainly to their proximity to the Atlantic Ocean and the wet Monsoon climate in the region compared to the stations in the Northern region (ABFC, BIKE, HUKP, KNKN, MDGR, YLAD, ZRKD and CGGT) with warm desert and warm semi-arid climate influenced by dry Northeast wind from Sahara Desert.

Figure 5.5 also depicts significant seasonal variations at all GNSS over Nigeria. The low peaks occurring around January and February while the high peaks in June and July correlating with the two main seasons, the dry (winter) and rainy (summer) seasons respectively.

The difference in ZTD variations between stations in the Northern region and Southern part over the territory of Nigeria may also be attributed to the differences in atmospheric dynamics and local weather conditions like temperature at the different regions at different times. Though, there is need for caution here as higher ZTD values and higher variability are two completely different properties. A station can have small value and high variability and vice vasa, as this depends largely on the climate and other factors. There is latitudinal dependence for the high and low ZTD values in both regions. For example, in the Northern part the latitude is high while in the South latitude is low. This is with an exception to GBTA with the highest altitude in Nigeria. Table 5.6 shows the statistics of the GNSS stations.

Table 5. 6: Statistics of Annual Averaged ZTD Estimates.

Site	Region	Altitude (m)	Long.	Lat.	Min ZTD (mm)	Max ZTD (mm)	Annual Average ZTD (mm)	Amplitude (mm)
YLAD	North	247.406	12.500	9.350	2286.1	2604.8	2460.0	124
BIKE	North	250.012	4.229	12.469	2277.9	2604.0	2433.0	119
MDGR	North	351.800	13.131	11.838	2244.8	2549.7	2393.6	114
KNKN	North	542.689	8.544	11.984	2204.4	2509.2	2335.8	112
HUKP	North	565.010	7.559	12.921	2197.1	2500.1	2320.0	112
ZRKD	North	705.066	7.649	11.152	2160.4	2447.4	2311.1	104
CGGT	North	916.432	9.118	10.123	2108.2	2363.7	2245.3	100
ABFC	North	532.645	7.486	9.028	2222.9	2509.1	2392.4	92
ENEN	South	7.505	6.425	254.405	2322.5	2679.9	2523.8	68
RECT	South	281.943	4.524	7.506	2337.4	2604.2	2525.5	61
GBTA	South	1795.65	11.184	6.917	1929.5	2098.3	2019.5	51
LGLA	South	3.398	6.517	44.575	2397.9	2684.8	2599.6	49
EKAK	South	41.870	7.917	4.638	2457.5	2684.6	2616.1	48
CBCR	South	60.586	8.352	4.950	2453.1	2696.5	2618.5	48
RUST	South	46.600	6.978	4.801	2434.2	2694.9	2629.3	36

In Table 5.6 the minimum, maximum, annual averaged and amplitude of ZTD are presented for the period 2010 to 2021 at all GNSS stations in the Southern region compared to those in the Northern region. The amplitude was calculated as shown in Appendix A2. In contrast to the minimum, maximum and annual average ZTD with high values in the Southern region and low values in the Northern part, it can be observed that GNSS stations in the Northern region indicates high amplitude while GNSS stations in the Southern region have low amplitude. These high amplitude of variation values in the Northern region compared to the Southern part within the period under investigation is attributed to among other things, the seasonal variation. It means that there are large variation between seasons in the North than in the South.

In general, it can therefore be said that the variation of ZTD over the territory of Nigeria is dependent on the temperature and the 4 distinct climates as illustrated in chapter 4 influenced by the trade wind effects (northeast wind from Sahara Desert and southwest wind from the Atlantic Ocean) giving rise to the two distinct seasons, dry (winter) and rainy (summer) seasons. There was also discovered a weak temporal correlation average of 0.03 which may be attributed to among other things the inhomogeneity or inconsistency of the data and variation in temporal scale.

5.3.2 ZTD Variation in CBCR and KNKN Stations

To understand the pattern of ZTD variation, the daily ZTD data was grouped into monthly averages for CBCR in the Southern region and KNKN in the Northern region for the year 2020 and the result is presented in Figure 5.6.

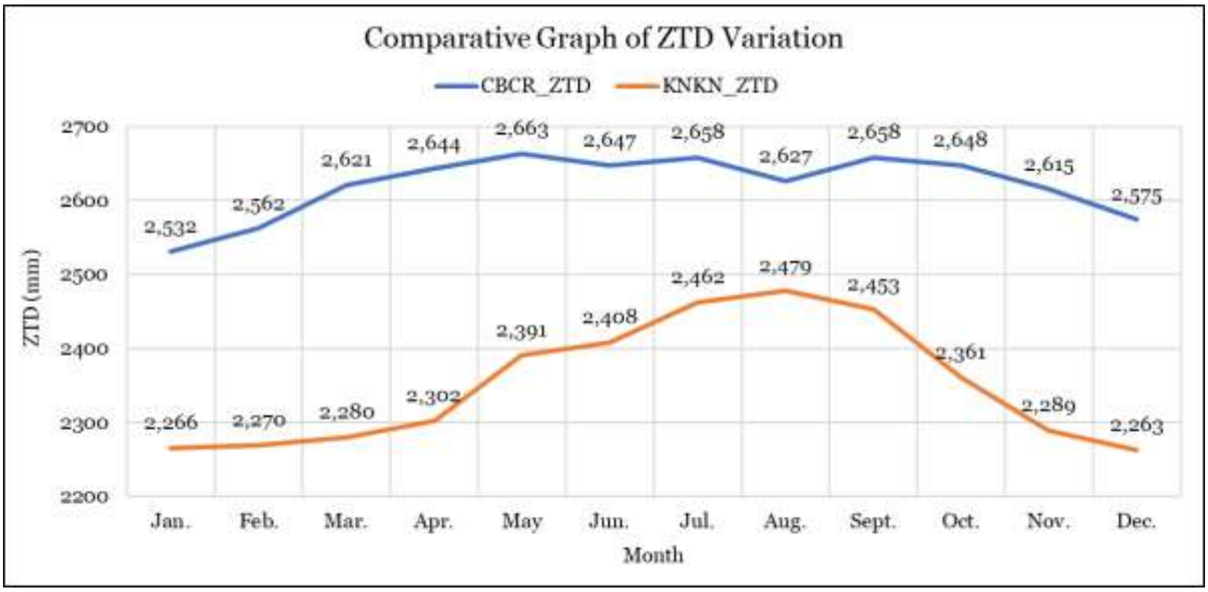


Figure 5. 6: Comparison of daily Averaged ZTD Time Series for CBCR and KNKN in 2020.

Figure 5.6 also demonstrate a seasonal interplay and a relatively typical scenario of ZTD variation in both the Southern and Northern regions of Nigeria using CBCR and KNKN as a case study. ZTD variation in CBCR has its minimum and maximum in January and May respectively while the minimum and maximum for KNKN was observed in December and August. This may be attributed to the fact among other things that water vapour forms at different times influenced by local weather conditions and the climates in both regions seasonally and the rain in both regions does not start in the same month.

Usually, the rain comes earlier in the Southern region around March and may fall to even November due to the proximity of the Atlantic Ocean and other atmospheric changes while in the Northern region, the rain starts around May and gradually fizzle out by October. The trade wind in both regions is also a factor that brings about the different seasons. It can be observed a steady or continuous increase of ZTD in KNKN from January to August which was the peak before it starts reducing and gave way to the dry season while in CBCR there was a continuous increase from January and peaked in May. Then fluctuation began till October where it starts giving way for the dry season. Again, the situation in CBCR (Southern region) can be attributed to the peculiarity of the region where water vapour variation is prevalent owing to the proximity of CBCR to the Atlantic Ocean.

5.3.3 ZTD Spatial Variation in Dry Season

To characterise the spatial ZTD variation in Nigeria during the dry (winter) season, 15^{th} January was chosen across the different GNSS stations in each year. The result of the annual mean ZTD at the fifteen GNSS stations used in this research and for the period (2010 to 2021) are presented in Figure 5.7. The Inverse Distance Weight (IDW) Interpolation of the Spatial Analyst Tool in ArcGIS was used for the characterisation of the ZTD spatial variation during the dry season.

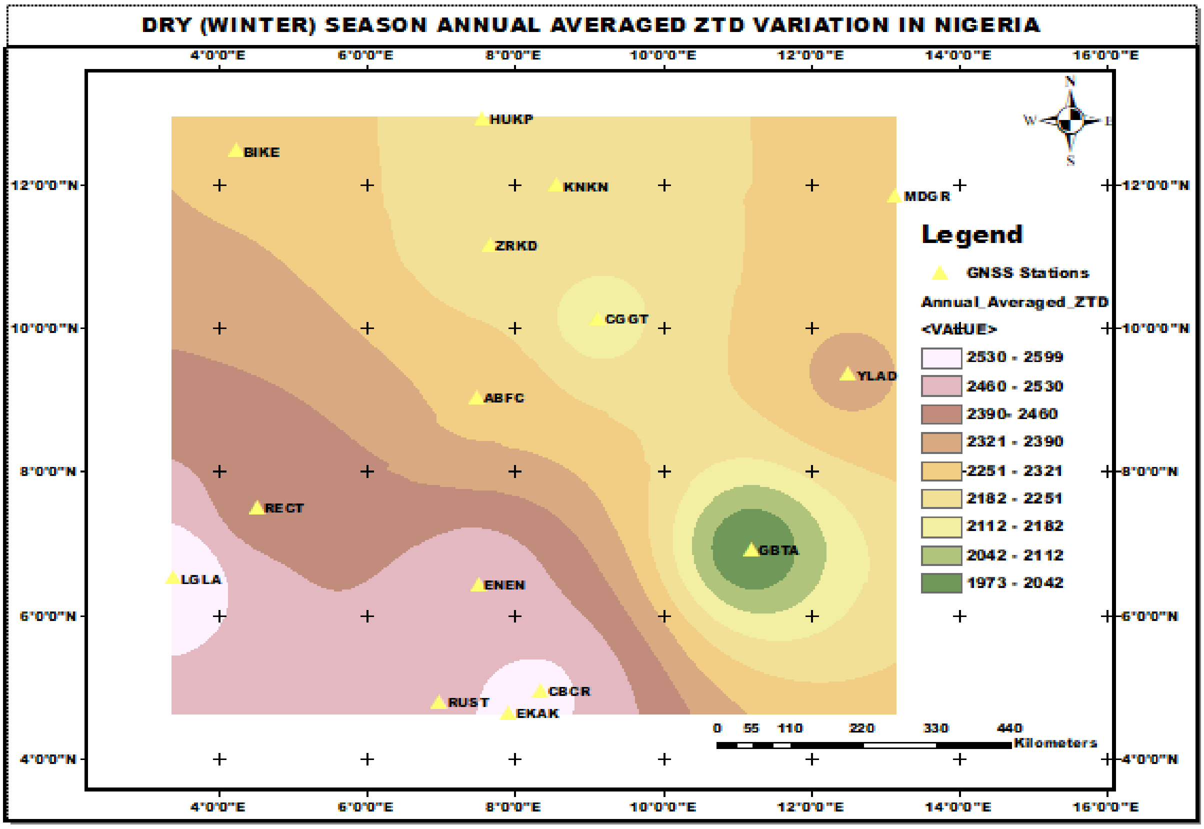


Figure 5. 7: Spatial Variation of Annual Averaged ZTD during Dry (Winter) Season

Figure 5.7 depicts the annual averaged spatial variation of ZTD from 2010 to 2021 for the dry (winter) season. The variation range of ZTD values is approximately between 2000mm to 2600mm. From the Figure, it can be noticed that ZTD increased from the far Northern region to the Southern area apart from GBTA which has the highest altitude of about 1796m among the GNSS stations in Nigeria. The Increase in ZTD from North to South may be due to climate differences and other atmospheric dynamics during the season. During the dry season, the Northern region usually experience very high temperature, semi-arid in nature and exhibit very low humidity that may have also contributed to the low ZTD values in the region. The extremely hot northeast wind originating from Sahara Desert during the dry season may perhaps be another reason for the low varying pattern of the ZTD over the GNSS stations.

5.3.4 ZTD Spatial Variation in Rainy Season

To further understand the spatial behaviour of ZTD in Nigeria during the rainy (summer) season, 196 "day of Year" corresponding to July was chosen across the different GNSS stations per year. The result of the annual average ZTD at the fifteen GNSS stations used in this research and for the period (2010 to 2021) during the wet season is presented in Figure 5.8. The IDW interpolation was also used to characterise the ZTD during the rainy season.

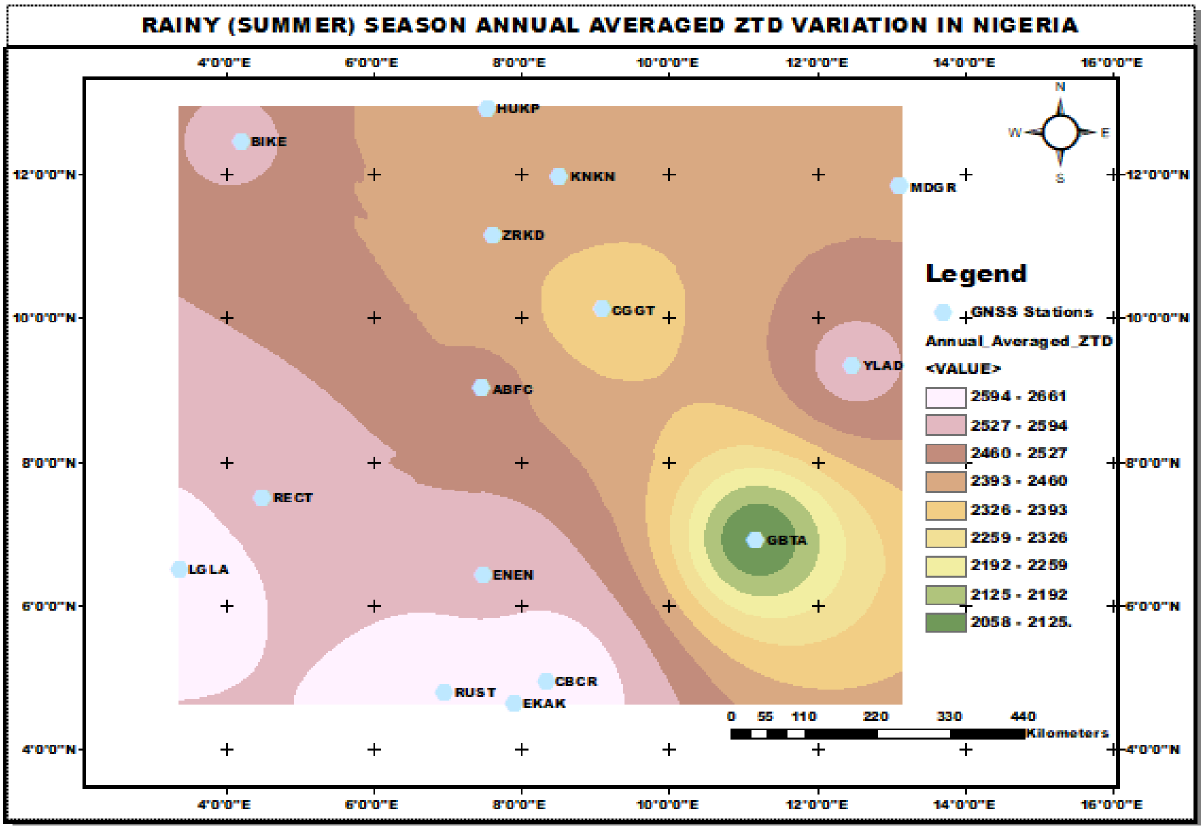


Figure 5. 8: Spatial Variation of Annual Averaged ZTD during Rainy (Summer) Season.

In Figure 5.8, the variation range of ZTD values is approximately between 2100mm to 2700mm for the rainy (summer) season, indicating an increase in ZTD of about 100mm. Though ZTD increased from the Northern region to the Southern part, the minimum ZTD is noticed on GBTA that has the highest altitude amongst the GNSS stations in Nigeria. On all GNSS stations in both seasons and regions, the spatial variation of ZTD in the rainy (summer) season is higher than in the dry (winter) season. This may be attributed to the increase in water vapour content and high humidity that usually culminates to heavy rainfall during this season. Furthermore, it is observed that the ZTD values in the Southern region (CBCR, ENEN, EKAK, RUST LGLA GBTA and RECT) are higher, especially RUST, CBCR, EKAK and LGLA that are in the coast near the Atlantic Ocean where heavy and prolong rain is prevalent because of the southwest wind transporting water vapour from the Atlantic Ocean to the region during this season.

The results of the spatial distribution pattern of the annual average ZTD values for the period (2010 to 2021) over the GNSS stations in Nigeria is also presented in a colour map using symbology in ArcGIS as illustrated in Figure 5.9. Latitudinal dependence on the ZTD estimates is obvious which can be attributed to the ZHD component of the ZTD due to surface pressure (Zhao et al., 2018). It can be seen in the Figure that low ZTD values are in the Northern region comprised of (North-East, North-Central and North-West) characterised by high latitude while high ZTD values are found in the Southern region comprised of (South-West, South-South and South-East) mostly characterised by lowland or low latitude. It was discovered a weak spatial correlation, the maximum which was found to be 0.04 by paring the GNSS stations which may be attributed to among other things, a very wide distance between one GNSS station to another, as the NIGNET is not dense but highly sparse.

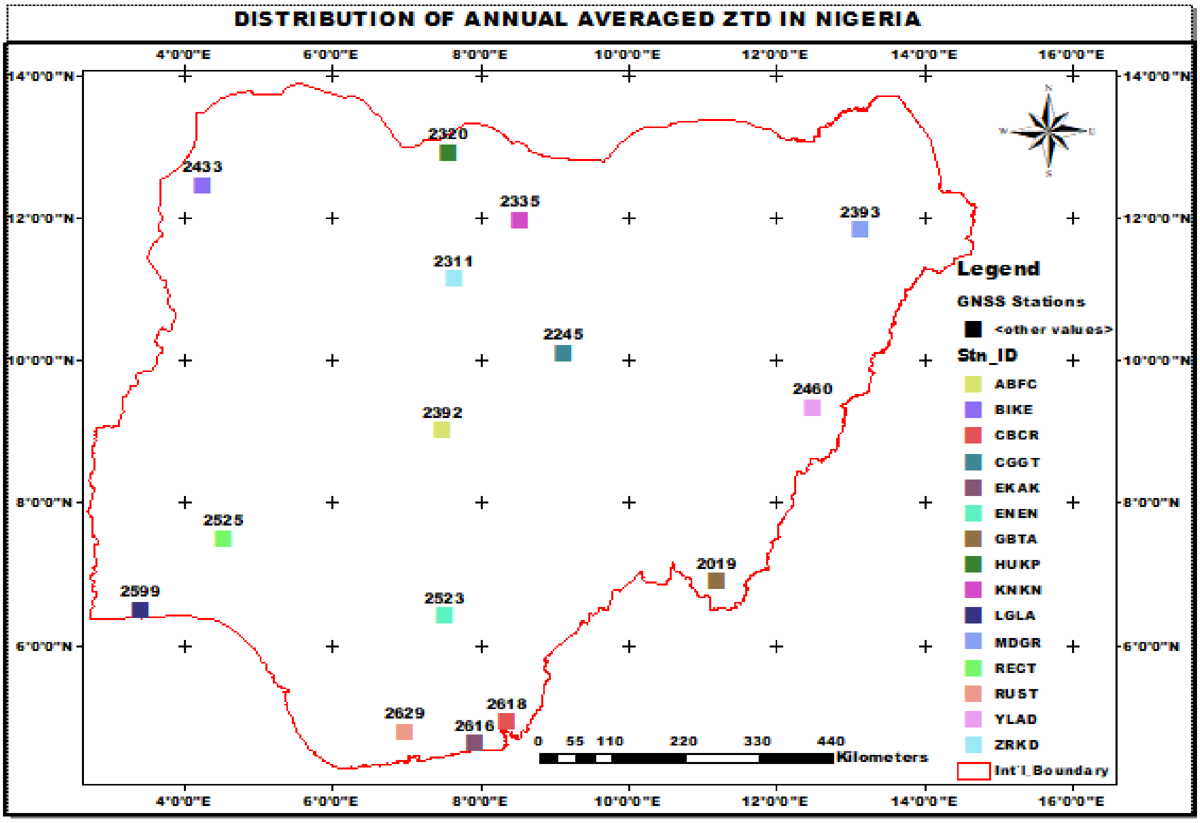


Figure 5. 9: Distribution of Annual Average ZTD Variation over the GNSS Stations from 2010 to 2021.

5.4 ZTD Variation for Precipitation Investigation

The result of the motivation of this research is shown in Figure 5.10. There was a torrential rainfall in Nigeria, around the Lokogoma district of the FCT on the 6th of June 2019 as was illustrated in Figure 1.1. The GNSS derived ZTD at ABFC station for 5 days was used for this investigation.

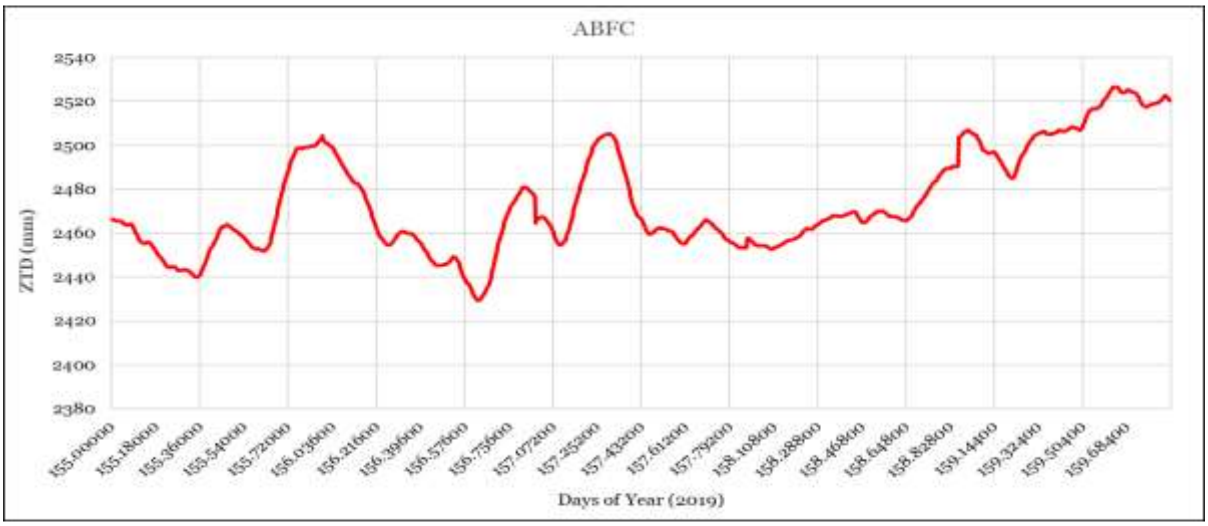


Figure 5. 10: ZTD Variation for Precipitation Investigation on 6th (DOY 157) of June 2019.

The ZTD time series indicates the “days of year” (DOY) for the five days from 155 to 159 corresponding with 4th to 8th of June 2019 respectively. That is, 2 days before and 2 days after the event. The study is to ascertain the applicability or potential of ZTD estimates for precipitation study. To put in another way, the correlation of ZTD and precipitation. It is intended to see the behaviour of the ZTD on the 6th (DOY 157) of June 2019.

In most cases, it is believed that in GNSS meteorology before precipitation occurs resulting in heavy down pour, that may lead to flood, ZTD (water vapour content) swiftly goes up and gets to a certain peak and suddenly starts coming down sharply (Li et al., 2021). This is clearly seen in the variation of ZTD as depicted in Figure 5.10, the case under investigation on the 6th (day 157) of June 2019.

In Figure 5.10, before the precipitation being investigated occurred on the 6th of June, the ZTD remarkably rises about 50mm within less than half of the day and starts reducing sharply to about 40mm within the same day. Then it starts fluctuating in an increasing order with maximum variation of 2524mm in the following days for likelihood of other precipitation events. For the precipitation to occur ZTD significantly increased to its peak value of 2504mm. The heavy precipitation that led to the flooding may also be as result of the previous day 5th (DOY 156) of June rainfall that is also suspected in the behaviour of the ZTD variation where it was observed two significant peaks. This was also clearly seen in the precipitation data of Abuja weather history within the period (4th to 8th) of June 2019 in Meteostat (2019) and the precipitation chart corresponding to DOY 155 to 159 that is in Appendix B1.

Though not every sharp increase and sudden decreases in ZTD variation that always culminate into heavy precipitation. In most cases, ZTD increases rapidly before precipitation and decrease sharply after the precipitation. Considering the case under investigation, the pattern of the ZTD variation when compared to the precipitation chart, has proven to be a potential tropospheric product that can be used to investigate the onset of extreme weather events including torrential rainfall.

5.5 Summary

Results are the end goals of any investigation or research work. The results of the various analysis performed with the tropospheric product (ZTD) are presented. Discussions are also carried out with regards to the various analysis and results obtained. In this chapter, we present GNSS station reliability test, time influence test on ZTD estimates, Characteristics ZTD temporal variation over Nigeria, ZTD variation in CBCR and KNKN stations, ZTD spatial variation in dry (winter) season, ZTD spatial variation in rainy (summer) season and ZTD variation for precipitation investigation.

Chapter 6

Conclusions and Recommendations

The estimation of water vapour and analysis is key for understanding the variability of extreme weather events including very high precipitation. This was achieved by processing GNSS observation to estimate ZTD. This research was aiming to investigate the short-term and long-term variations of PWV over the territory of Nigeria using the GNSS observations provided by NIGNET. In this chapter, we present the main findings that are summarised from the tests and results as well as the shortfall and contributions of the research in the conclusions and submit recommendations based on the experience of the research that will enhance future work.

6.1 Conclusions

In this section we present the summary of the tests and results of the main research findings of analysing GNSS data for 15 stations in Nigeria for the period 2009 to 2021, including the limitation and contributions of the research work as follows.

- The availability and reliability of data is very crucial to any scientific investigations. In the light of the foregoing, the data of the 15 GNSS stations used for this study were verified to ascertain their viability with regards to the above. It was discovered that there were missing data considering the span of years of each GNSS stations which led to the reduction in quantity of the available daily files. The effect of the available data which is below 50% percent was seen in the result as it was discovered weak temporal correlation within the period used in this research.

- The sensitivity study of the data span used to estimate the ZTD values revealed the convergence of values when 6-hour and 12-hour observations or longer are used. The 1-hour observation dataspan was seen to be too short to converge to the correct value. 24-hour observation indicates the best result with the smallest standard deviation in all solutions. The experiment also show that less time of observation will give result that is less reliable. Our explanation is that the filter used in GipsyX software needs sufficient amount of data (i.e., longer timespan) to converge away from nominal/modelled values to the actual/true values. This implies and encourage longer time of observation for good analysis and results.

- The range of daily averaged ZTD variation (values) on the GNSS stations used in this research over the territory of Nigeria for the period of 2009 to 2021 is approximately between 1900mm to 2700mm. The result indicates significant seasonal variations depicting clearly winter and summer periods in Nigeria. The low peaks were seen to be occurring around January and February while the high peaks are occurring around June and July correlating with the dry (winter) and rainy (summer) seasons respectively. It was also seen that GNSS stations in the Southern region have high ZTD values while GNSS station in the Northern region have low ZTD values in all related investigations in this research. Part of this difference can be explained by the difference in height of the stations in these two regions. The climate conditions prevalent at the different regions per time and seasonally is a major factor to these varying ZTD. For instance, the transporting of water vapour from the Atlantic Ocean by the wet Southwest monsoon can result in the high-water vapour content in the Southern region than in the Northern part where the climate is warm desert and semi-arid influenced by the Northeast wind emanating from the Sahara Desert.

- The amplitude of variation ranges between a minimum of 36mm to a maximum of 124mm over the territory of Nigeria using the 15 GNSS stations under investigation. The results show higher amplitudes in the Northern region and low amplitude in the Southern part. The amplitude is due to seasonal variation. There is large variation between seasons in the North than in the South. The seasonal variation is caused by high temperature, latitude, altitude and the Northeast wind from Sahara Desert that characterise the Northern region. The high and low amplitude in the North and South respectively does not mean more or less water vapour in the atmosphere. It indicates that there are less variation between dry (winter) and rainy (summer) seasons in the South than in the North.

- The two seasons in Nigeria were investigated to characterise the spatial variation of the ZTD using GIS tool, the Inverse Distance Weight interpolation. This is to corroborate Section 3.7 that GIS is not just a tool for map making. The results indicates that ZTD increased from Northern part to the Southern region except for GBTA that has the highest altitude among the GNSS stations in Nigeria. High ZTD values were noticed in the rainy (summer) season than in the dry (winter) season which was not strange. Two of the NIGNET stations (KNKN and CBCR) used as case studies from the far North and South respectively, also indicates seasonal interplay from January to December in both regions owing to the climate and local weather conditions influenced by the temperature, water vapour and the trade wind.

- The spatial distribution pattern of the annual average ZTD values within the period 2010 to 2021 over the GNSS stations in Nigeria was presented using symbology, a GIS tool. The results indicate low ZTD values in the Northern region comprised of (North-East, North-Central and North-West) having high latitudes while high ZTD values are seen in the Southern region comprised of (South-West, South-South and South-East) mostly in lowland with low latitude. It was discovered a weak spatial correlation, the maximum which was found to be 0.04 by paring the GNSS stations which may be attributed to among other things, a very wide distance between one GNSS station to another, as the NIGNET is not dense but sparsely located and may not truly reflect complete water vapour content over the country. This calls for the installation of more GNSS stations.

- ZTD variation for precipitation investigation was also carried out with regards to the motivation of this research. The characteristic of the ZTD reveals its usefulness in weather and climate related applications. The investigated date indicates sudden increase in ZTD before the precipitation and sharply decreases after the rain. Precipitation data that match the date under investigation correlates positively with the behaviour of the ZTD on the investigated date. It was also observed and commented that though not all sharp increases and sudden decreases of ZTD usually culminates into heavy precipitation. For the case under investigation ZTD shows its correlation with precipitation.

The main shortfall of this research is the lack of meteorological data to compute the PWV which was originally intended to be used for the analysis instead of the ZTD. This was due mainly to the global pandemic. Though this limitation is acknowledged and much regretted, the methodologies explained in this research can be used to calculate the PWV when meteorological and more GNSS data are derived in the future. The research is worthwhile and has sparked interest in this interdisciplinary field of GNSS and meteorology. The study also attempted to answer the problem stated in the research. The research work among other contributions will assist relevant authorities in Nigeria and will also be a foundation for those that are new in this field.

6.2 Recommendations

These submissions are borne out of the experience gathered in this research and are made with regards to the Nigerian government through OSGoF as follows:

- For better estimation of accurate water vapour field that guarantees dependable weather monitoring, predictions and climate related investigations and operations, there is the need to install more Nigerian Permanent GNSS Network stations ensuring wider and dense coverage over the territory.

- The beneficiary of this opportunity recommend training on Python programming language to staff of OSGoF as it is very relevant in data science such as retrieval of meteorological data from collocated stations and models for easy manipulation and use of the meteorological parameters like temperature and pressure required for the conversion of ZTD into PWV.

- If the GNSS collocated meteorological stations installed by the Portuguese government in Nigeria through her collaboration with OSGOF is densified, it will help in complementing the classical weather stations in Nigeria in tackling weather and climate related investigations and operations by assisting the relevant authorities as data retrieved from such station are more dependable than those from regional or global meteorological models.

6.3 Future Work

Every or most research work provides opportunity for improvement by exploring areas of limitation and finding ways to solve them. As such, I would like to improve upon this research in the future based on the shortfall and willingness to break new grounds. These areas are as follows:

- Setting up an operational computation of Precipitable Water Vapour by integrating the processing of GNSS observations.

- GIS-Based spatial analysis of Precipitable Water Vapour for detailed studies of weather events based on GNSS observations.

Bibliography

Abbasy, S., Abbasi, M., Asgari, J., & Ghods, A. (2017). Precipitable water vapour estimation using the permanent single GPS station in Zanjan, Iran. *Meteorological Applications*, *24*(3), 415–422. https://doi.org/10.1002/met.1639

Adams, D. K., Fernandes, R. M. S., & Maia, J. M. F. (2011). GNSS precipitable water vapor from an Amazonian rain forest flux tower. *Journal of Atmospheric and Oceanic Technology*, *28*(10), 1192–1198. https://doi.org/10.1175/JTECH-D-11-00082.1

Afifi, A., & El-Rabbany, A. (2016). Precise point positioning using triple GNSS constellations in various modes. *Sensors (Switzerland)*, *16*(6), 1–14. https://doi.org/10.3390/s16060779

Ahmed, F. (2010). *Evaluation of GNSS as a Tool for Monitoring Tropospheric Water Vapour*. 55. http://studentarbeten.chalmers.se/publication/129976-evaluation-of-gnss-as-a-tool-for-monitoring-tropospheric-water-vapour

Akande, A., Costa, A. C., Mateu, J., & Henriques, R. (2017). Geospatial Analysis of Extreme Weather Events in Nigeria (1985-2015) Using Self-Organizing Maps. *Advances in Meteorology*, *2017*. https://doi.org/10.1155/2017/8576150

Al-Mahdi, A. M., & Maina, M. L. (2013). The Role of GIS and Remote Sensing in Mapping the Distribution of Greenhouse Gases. *European Scientific Journal*, *9*(36), 404–410. https://core.ac.uk/download/pdf/236411262.pdf

Alshawaf, F., Fuhrmann, T., Knöpfler, A., Luo, X., Mayer, M., Hinz, S., & Heck, B. (2015). Accurate Estimation of Atmospheric Water Vapor Using GNSS Observations and Surface Meteorological Data. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(7), 3764–3771. https://doi.org/10.1109/TGRS.2014.2382713

Ansari, K., Corumluoglu, O., Verma, P., & Pavelyev, V. S. (2017). *An Overview of the International GNSS Service (IGS)*. *December*. https://doi.org/10.13140/RG.2.2.18533.91367

Ayodele, E. G., Okolie, C. J., Ezeigbo, C. U., & Fajemirokun, F. A. (2020). Evaluating the Stability and Adequacy of NIGNET for the Definition of Nigerian Geodetic Reference Frame. *Nigerian Journal of Technological Development*, *17*(1), 1–12. https://doi.org/10.4314/njtd.v17i1.1

Bertiger, W., Bar-Sever, Y., Dorsey, A., Haines, B., Harvey, N., Hemberger, D., Heflin, M., Lu, W., Miller, M., Moore, A. W., Murphy, D., Ries, P., Romans, L., Sibois, A., Sibthorpe, A., Szilagyi, B., Vallisneri, M., & Willis, P. (2020). GipsyX/RTGx, a new tool set for space geodetic operations and research. *Advances in Space Research*, *66*(3), 469–489. https://doi.org/10.1016/j.asr.2020.04.015

Bertone, S. (2015). *Switzerland Swiss Geodetic Commission Suisse Swiss National Report on the ACTIVITÉS GÉODÉSIQUES* (Issue June). https://www.researchgate.net/publication/279403724_Bernese_GNSS_Software

Bevis M, Businger S, Herring T, Rocken C, Anthes R, W. R. (1992). GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system. *Journal of Geophysical Research*, *97*(D14). https://doi.org/10.1029/92jd01517

Bleisch, R., Kämpfer, N., & Haefele, A. (2011). Retrieval of tropospheric water vapour by using spectra of a 22 GHz radiometer. *Atmospheric Measurement Techniques*, *4*(9), 1891–1903. https://doi.org/10.5194/amt-4-1891-2011

Bosy, J., Rohm, W., Sierny, J., & Kaplon, J. (2011). GNSS Meteorology. *Navigational Systems and Simulators*, *5*(1), 19–23. https://doi.org/10.1201/b11343-5

Bosy, J., Rohm, W., & Sierny, J. (2010). The near real time atmosphere model based on the gnss and the meteorological data from the ground based augmentation system Asg-eupos. *Acta Geodynamica et Geomaterialia*, *8*(3), 366–371. https://www.isprs.org/proceedings/xxxviii/part8/pdf/W03A04_20100301214019.pdf

Chayanin and Constantin-Octavian (2018). Atmospheric water estimation using GNSS precise point positioning method. *Engineering Journal*, *22*(6), 37–45. https://doi.org/10.4186/ej.2018.22.6.37

Copernicus (2018). *ERA5 hourly data on single levels from 1979 to present. Retrieved September 21, 2021, from:* https://doi.org/DOI: 10.24381/cds.adbb2d4

Dach, R., Lutz, S., Walser, P., & Fridez, P. (2015). *Bernese GNSS Software Version 5.2* (Issue November). https://doi.org/10.7892/boris.72297

Dangermond, B. J., & Artz, M. (2010). Climate Change is a Geographic Problem The Geographic Approach to Climate Change. *Esri*, 32. ttps://www.esri.com/library/ebooks/climate-change.pdfTable

Dodo, J. D.; Yakubu, T. A.; Usifoh, E. S., and Bojude, A. C. (2011). *ITRF 2008 Realization of the Nigerian Geocentric Datum (GDN2012): Preliminary Results Corresponding Author : Dodo , J . D. 2*(6), 978–986.

Dyras, I., Dobesch, H., Grueter, E., Perdigao, A., Tveito, O. E., Thornes, J. E., van der Wel, F., & Bottai, L. (2005). The use of Geographic Information Systems in climatology and meteorology: COST 719. *Meteorological Applications*, *12*(1), 1–5. https://doi.org/10.1017/S1350482705001544

Dyras, I., & Serafin-Rek, D. (2005). The application of GIS technology for precipitation mapping. *Meteorological Applications*, *12*(1), 69–75. https://doi.org/10.1017/S135048270400146X

Eldrandaly, K. (2007). Expert systems, GIS, and spatial decision making: Current practices and new trends. *Psychology of Decision Making*, *May*, 115–136. https://www.researchgate.net/publication/235644401_Expert_systems_GIS_and_spatial_decision_making_Current_practices_and_new_trends#:~:text=Clarke (2001) defined GIS as,display of spatial data".

Feidas, H., Kontos, T., Soulakellis, N., & Lagouvardos, K. (2007). A GIS tool for the evaluation of the precipitation forecasts of a numerical weather prediction model using satellite data. *Computers and Geosciences*, *33*(8), 989–1007. https://doi.org/10.1016/j.cageo.2006.12.001

Fernandes, R.M.S., Viterbo, P., Bos, M.S., Martins, J., Andre sa., Valentim, H., Jones, J. (2014). *NUVEM - New methods to Use gnss water Vapor Estimates for Meteorology of Portugal*. *December*, 3151. https://www.researchgate.net/publication/281859516_NUVEM_-_New_methods_to_Use_gnss_water_Vapor_Estimates_for_Meteorology_of_Portugal

Fernandes R.M.S, Barde J., Adeyemi A., Nuno G. (2010). *NIGNET – The new permanent GNSS network of Nigeria NIGNET – The new permanent GNSS network of Nigeria*. *April 2010*, 11–16. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=4BFE5019C4ECA018E2C44EEE51E630F0?doi=10.1.1.631.7961&rep=rep1&type=pdf

Fionda, E., Cadeddu, M., Mattioli, V., & Pacione, R. (2019). Intercomparison of integrated water vapor measurements at high latitudes from co-located and near-located instruments. *Remote Sensing*, *11*(18). https://doi.org/10.3390/rs11182130

Griffiths, J. (2018). Combined orbits and clocks from IGS second reprocessing. *Journal of Geodesy*, *93*(2), 177–195. https://doi.org/10.1007/s00190-018-1149-8

Guerova, G., Jones, J., Douša, J., Dick, G., De Haan, S., Pottiaux, E., Bock, O., Pacione, R., Elgered, G., Vedel, H., & Bender, M. (2016). Review of the state of the art and future prospects of the ground-based GNSS meteorology in Europe. *Atmospheric Measurement Techniques*, *9*(11), 5385–5406. https://doi.org/10.5194/amt-9-5385-2016

Herring, T. A. (1992). Modeling of Atmospheric Delay in the Analysis Space Geodetic Data. *Symposium on Refraction of Transatmospheric Signals in Geodesy: PROCEEDINGS OF THE SYMPOSIUM THE HAGUE, THE NETHERLANDS, MAY 19 - 22,1992*, *36*, 208. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.367.9583&rep=rep1&type=pdf#page=167

Herring, T. A., King, R. W., & McClusky, S. C. (2008). *Introduction to GAMIT / GLOBK Basic framework : GAMIT Basic framework : GLOBK GAMIT Structure*. *July 2008*, 1–16. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.534.6776&rep=rep1&type=pdf

IGS (2020). *Products – International GNSS Service. Rtrieved March 3, 2021 from:* https://www.igs.org/products/

Imaoka, K., Higashino, T., & Okada, M. (2019). Investigation of rainfall forecasting using the difference of GNSS zenith total delay with elevation cut-off angles. *Asia-Pacific Microwave Conference Proceedings, APMC*, *2019-Decem*(2), 1056–1058. https://doi.org/10.1109/APMC46564.2019.9038361

Isioye, O. A., Combrinck, L., & Botai, J. O. (2017). Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria. *International Journal of Remote*

Sensing, *38*(20), 5710–5735. https://doi.org/10.1080/01431161.2017.1346401

Isioye, O. A., Combrinck, L., Botai, J. O., & Munghemezulu, C. (2015). The potential for observing African weather with GNSS remote sensing. *Advances in Meteorology*, *2015*. https://doi.org/10.1155/2015/723071

Jones, J., Guerova, G., Dousa, J., Dick, G., Siebren de H., Pottiaux, E., Bock, O., Pacione, R., R. van M. (2019). Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate. In *Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate*. https://doi.org/10.1007/978-3-030-13901-8

JPL. (n.d.-a). *NASA. Jet Propulsion Laboratory. GipsyX.* Retrieved May 7, 2021, from https://gipsy-oasis.jpl.nasa.gov/index.php?page=data

JPL. (n.d.-b). *The Automatic Precise Point Positioning Service of the Global Differential GPS System*. Retrieved April 23, 2021, from https://gipsy-oasis.jpl.nasa.gov/index.php?page=data

Karaim, M., Elsheikh, M., & Noureldin, A. (2018). GNSS Error Sources. *Multifunctional Operation and Application of GPS*, *May*. https://doi.org/10.5772/intechopen.75493

Langley, R. B., Teunissen, P. J. G., & Montenbruck, O. (2015). An Introduction to GNSS. In *Springer Handbooks* (2nd Editio). https://doi.org/10.1007/978-3-319-42928-1_1

Li, X., Tan, H., Li, X., Dick, G., Wickert, J., Schuh, H. (2018). Real-Time Sensing of Precipitable Water Vapor From BeiDou Observations: Hong Kong and CMONOC Networks. *Journal of Geophysical Research: Atmospheres*, *123*(15), 7897–7909. https://doi.org/10.1029/2018JD028320

Li, Wang, X., Wu, S., Zhang, K., Chen, X., Zhang, J., Qiu, C., Zhang, S., & Li, L. (2021). An Improved Model for Detecting Heavy Precipitation Using GNSS-Derived Zenith Total Delay Measurements. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *14*(May), 5392–5405. https://doi.org/10.1109/JSTARS.2021.3079699

Li, Z., Muller, J. P., & Cross, P. (2003). Comparison of precipitable water vapor derived from radiosonde, GPS, and Moderate-Resolution Imaging Spectroradiometer measurements. *Journal of Geophysical Research Atmospheres*, *108*(20). https://doi.org/10.1029/2003JD003372

Liu, C., Zheng, N., Zhang, K., & Liu, J. (2019). A new method for refining the GNSS-derived precipitable water vapor map. *Sensors (Switzerland)*, *19*(3). https://doi.org/10.3390/s19030698

Lou, H., Zhang, J., Yang, S., Cai, M., Ren, X., Luo, Y., & Li, C. (2021). Exploring the relationships of atmospheric water vapor contents and different land surfaces in a complex terrain area by using doppler radar. *Atmosphere*, *12*(5). https://doi.org/10.3390/atmos12050528

Ma, L., Sun, Y., Zhang, Y., Han, B., Wang, Y., & Li, L. (2019). GNSS/MET Station Equipment Maintenance and Product Application. *Journal of Geoscience and Environment Protection*, *07*(09), 105–113. https://doi.org/10.4236/gep.2019.79008

Manandhar, D. (2018). *Introduction to Global Navigation Satellite System (GNSS) Module: 1*. http://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/09_M1.pdf

Marini, J. W. (1972). Correction of Satellite Tracking Data for an Arbitrary Tropospheric Profile. In *Radio Science* (Vol. 7, Issue 2, pp. 223–231). https://doi.org/10.1029/RS007i002p00223

Meteostat (2019). *Abuja _ Weather History _ Meteostat.Retrieved January 25, 2022, from:* https://meteostat.net/en/station/65125?t=2019-06-01/2019-06-15

Mobolade, T. D., & Pourvahidi, P. (2020). Bioclimatic approach for climate classification of Nigeria. *Sustainability (Switzerland)*, *12*(10). https://doi.org/10.3390/su12104192

Niell, A. E. (1996). Global mapping functions for the atmosphere delay at radio wavelengths. *Journal of Geophysical Research B: Solid Earth*, *101*(2), 3227–3246. https://doi.org/10.1029/95jb03048

Onyeka, E. C. (2006). *Relating the Nigerian Reference Frame and AFREF*. 1–13. https://fig.net/resources/proceedings/fig_proceedings/accra/papers/ws01/ws01_03_onyeka.pdf

Pacione, R., Araszkiewicz, A., Brockmann, E., & Dousa, J. (2017). EPN-Repro2: A reference GNSS tropospheric data set over Europe. *Atmospheric Measurement Techniques*, *10*(5), 1689–1705. https://doi.org/10.5194/amt-10-1689-2017

Qiu, C., Wang, X., Li, Z., Zhang, S., Li, H., Zhang, J., & Yuan, H. (2020). The Performance of Different Mapping Functions and Gradient Models in the Determination of Slant Tropospheric Delay. *Remote Sensing*, *12*(1), 130. https://doi.org/10.3390/rs12010130

Sanderson, R. (2014). An introduction to remote sensing. *GeoJournal*, *6*(3), 1–35. https://doi.org/10.1007/BF00210657

Shipley, S. T. (2005). GIS applications in meteorology, or adventures in a parallel universe. *Bulletin of the American Meteorological Society*, *86*(2), 171–173. https://doi.org/10.1175/BAMS-86-2-171

Shivers, S. W., Roberts, D. A., McFadden, J. P., & Tague, C. (2019). An analysis of atmospheric water vapor variations over a complex agricultural region using airborne imaging spectrometry. *PLoS ONE*, *14*(12), 1–28. https://doi.org/10.1371/journal.pone.0226014

Shukla, A. K., Shukla, S., & Ojha, R. (2017). Geospatial Technologies for Rainfall and Atmospheric Water Vapor Measurement over Arid Regions of India. In *Sustainable Water Resources Management* (Issue August 2019, pp. 263–292). https://doi.org/10.1061/9780784414767.ch10

Steenson. (2019). *The history of Geographic Information Systems (GIS) _ BCS. Retrieved May 11, 2021, from:* https://www.bcs.org/articles-opinion-and-research/the-history-of-geographic-information-systems-gis/

Stepniak, K., Bock, O., & Wielgosz, P. (2018). Reduction of ZTD outliers through improved GNSS data processing and screening strategies. *Atmospheric Measurement Techniques*, *11*(3), 1347–1361. https://doi.org/10.5194/amt-11-1347-2018

Teromovigo (2019). *TeroNet Platform* (pp. 2–26). https://teromovigo.ubi.pt/wp-content/uploads/2019/10/TeroNet-Users-Manual-English-version-20191031.pdf

TeroNet (2021). *TeroNet - GNSS Data Management Platforms. Retrieved April 14, 2021, from:* https://teronet.nignet.net/

UNAVCO (2021). *GAMIT_GLOBK_TRACK _ Software _ UNAVCO. Retrieved March 10, 2021, from:* https://www.unavco.org/software/data-processing/postprocessing/gamit/gamit.html.

Verbatim (2019). *The Cause of Incessant Flooding in Lokogoma District _ Verbatim Nigeria News Network. Retrieved June 30, 2021 from:* https://verbatimnigeria.org/2019/06/09/the-cause-of-incessant-flooding-in-lokogoma-district/

Won, J., Park, K. D., Ha, J., & Cho, J. (2010). Effects of tropospheric mapping functions on GPS data processing. *Journal of Astronomy and Space Sciences*, *27*(1), 21–30. https://doi.org/10.5140/JASS.2010.27.1.021

Zhang, F., Barriot, J. P., Xu, G., & Yeh, T. K. (2018). Metrology assessment of the accuracy of precipitable water vapor estimates from GPS data acquisition in tropical areas: The Tahiti Case. *Remote Sensing*, *10*(5). https://doi.org/10.3390/rs10050758

Zhang, Q., Ye, J., Zhang, S., & Han, F. (2018). Precipitable water vapor retrieval and analysis by multiple data sources: Ground-based GNSS, radio occultation, radiosonde, microwave satellite, and NWP reanalysis data. *Journal of Sensors*, *2018*. https://doi.org/10.1155/2018/3428303

Zhang Y. & Drake W. (2014). *Geographic Information Systems (GIS). In: Michalos A.C. (eds) Encyclopedia of Quality of Life and Well-Being Research. Springer, Dordrecht.* https://doi.org/https://doi.org/10.1007/978-94-007-0753-5

Zhao, Q., Yao, Y., Yao, W., & Li, Z. (2018). Real-time precise point positioning-based zenith tropospheric delay for precipitation forecasting. *Scientific Reports*, *8*(1), 1–12. https://doi.org/10.1038/s41598-018-26299-3

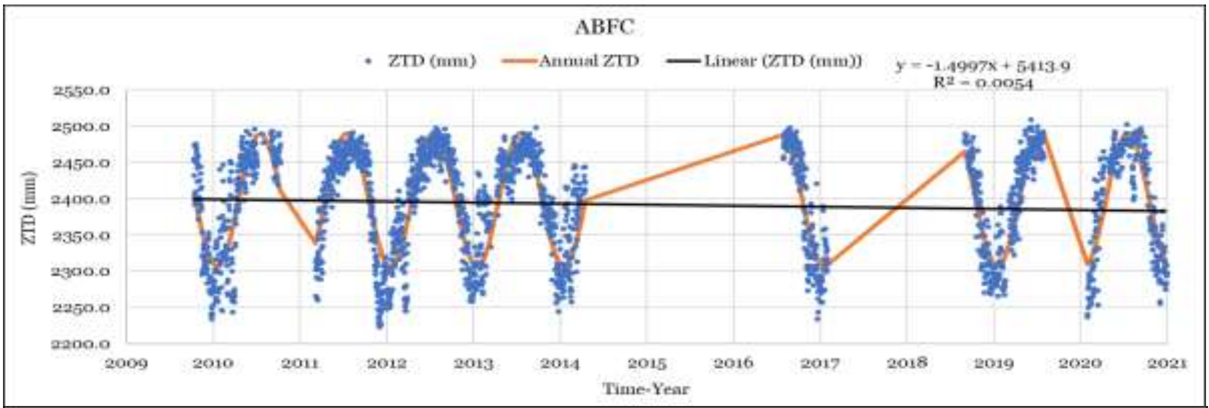
Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., & Webb, F. H. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research: Solid Earth*, *102*(B3), 5005–5017. https://doi.org/10.1029/96jb03860

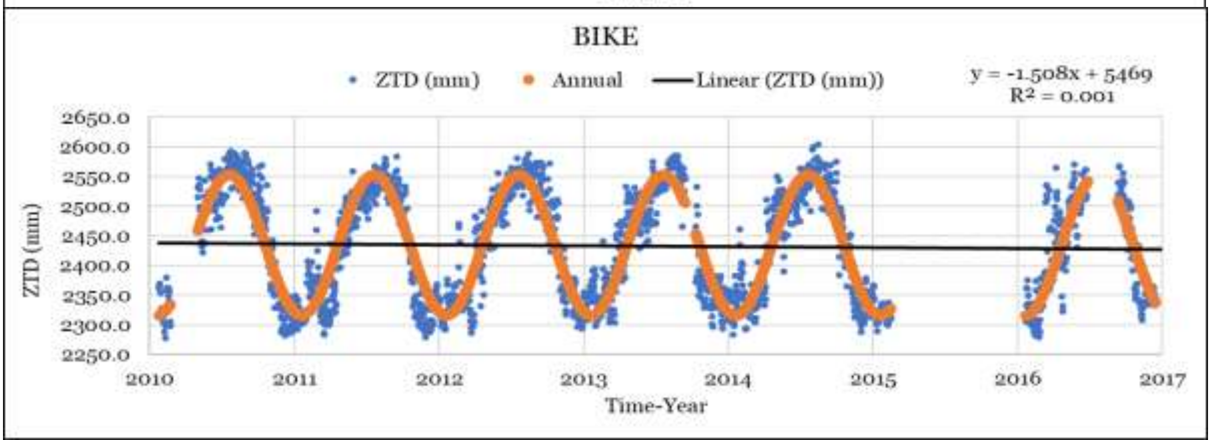
Appendix

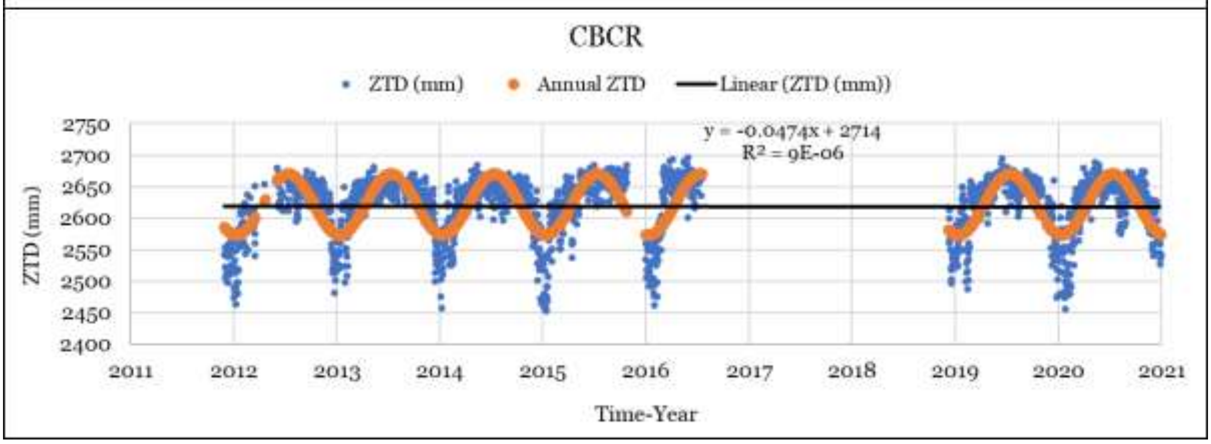
Appendix A

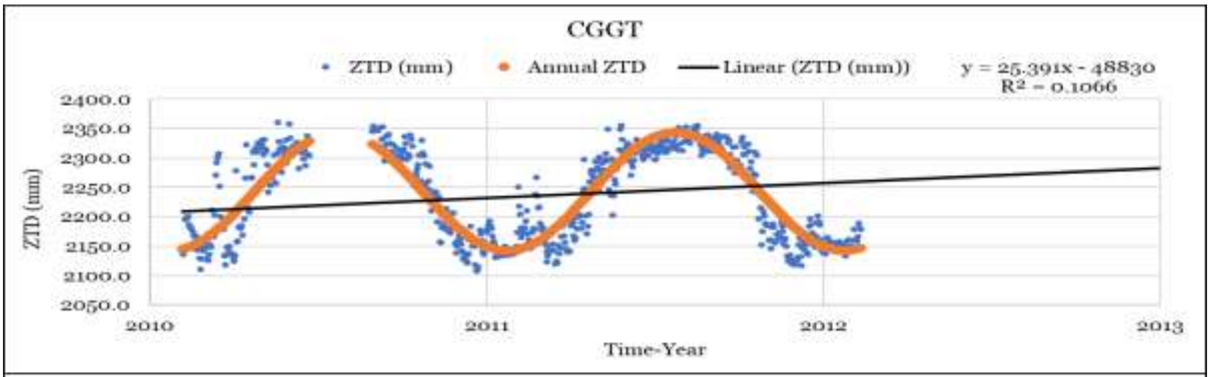
Here we present the graphs of the time series of each of the fifteen GNSS stations with annual variation used for this research.

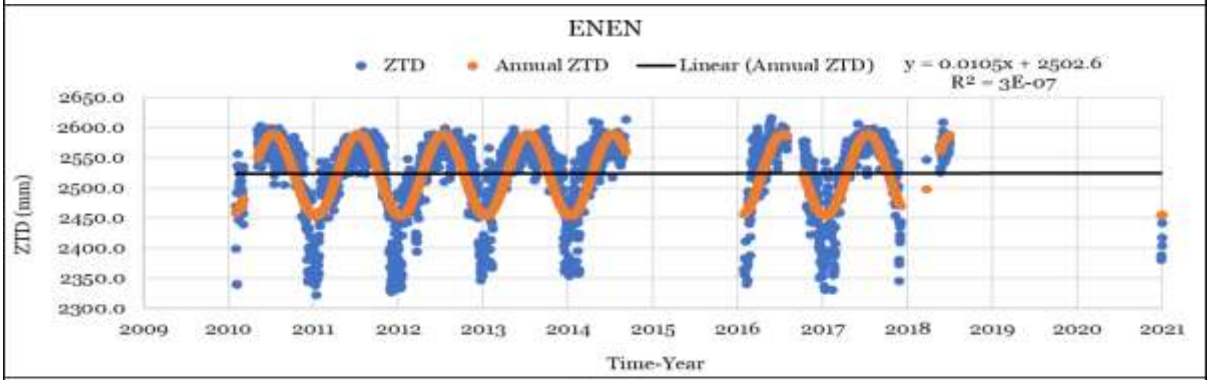
A1: 15 GNSS Stations used for the study in Nigeria

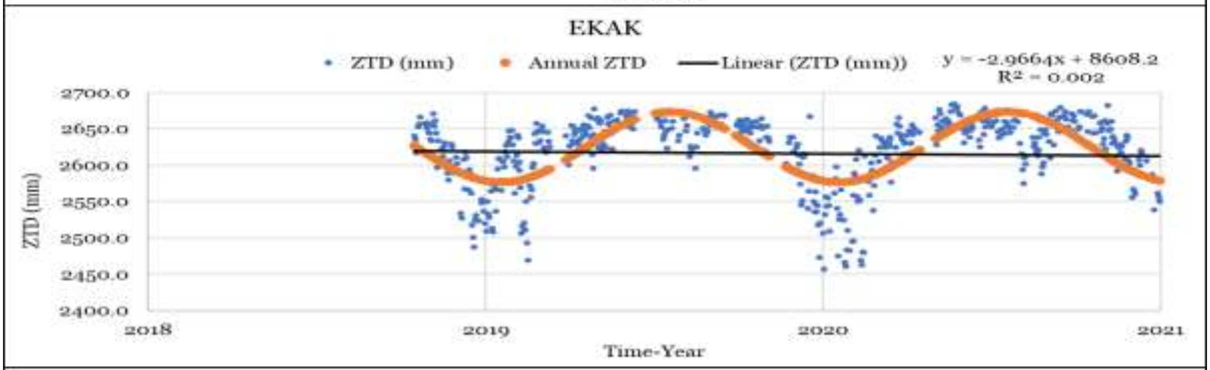


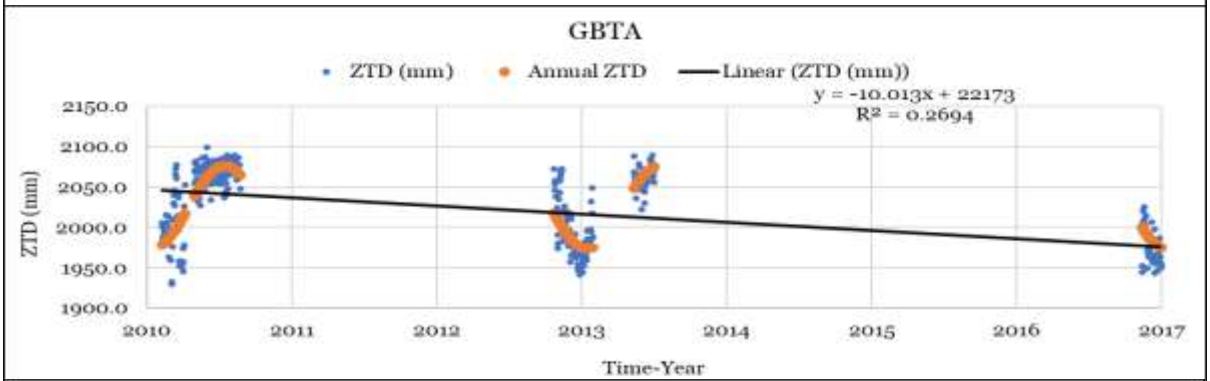


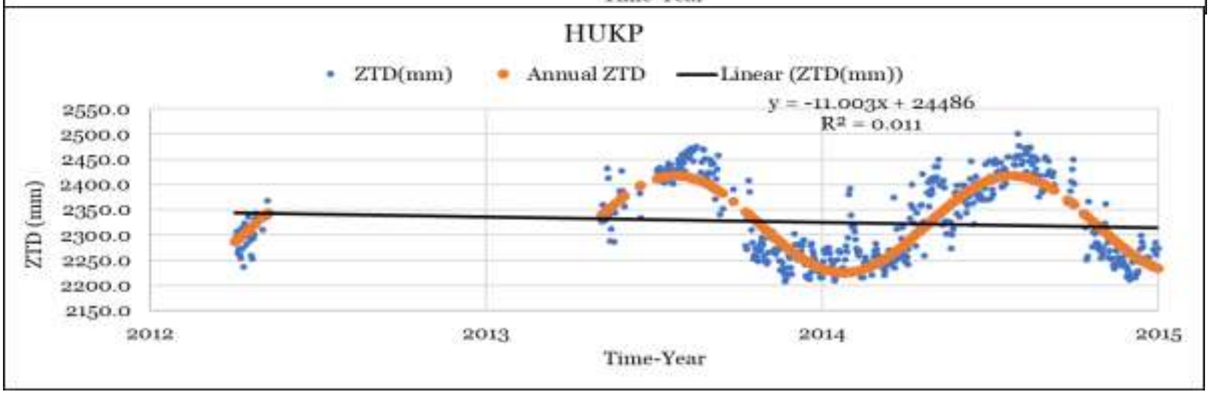


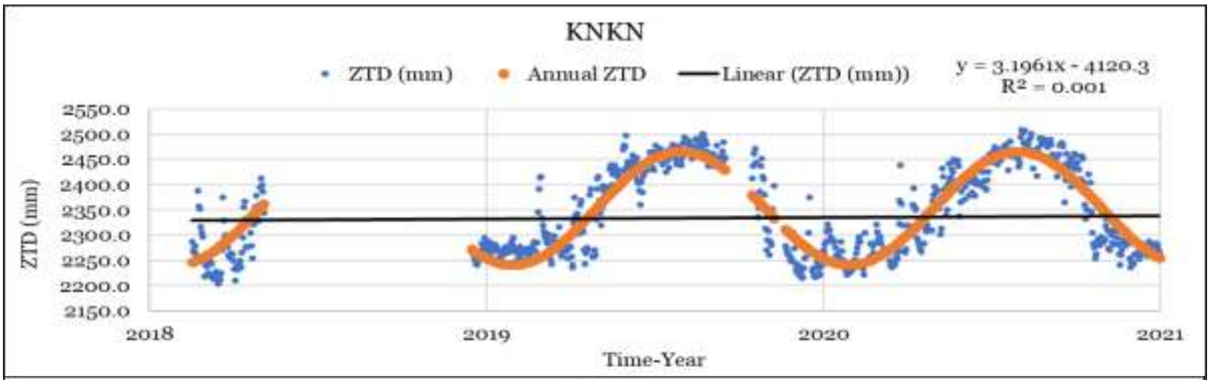

CGGT
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = 25.391x - 48830
R² = 0.1066
ZTD (mm)
Time-Year

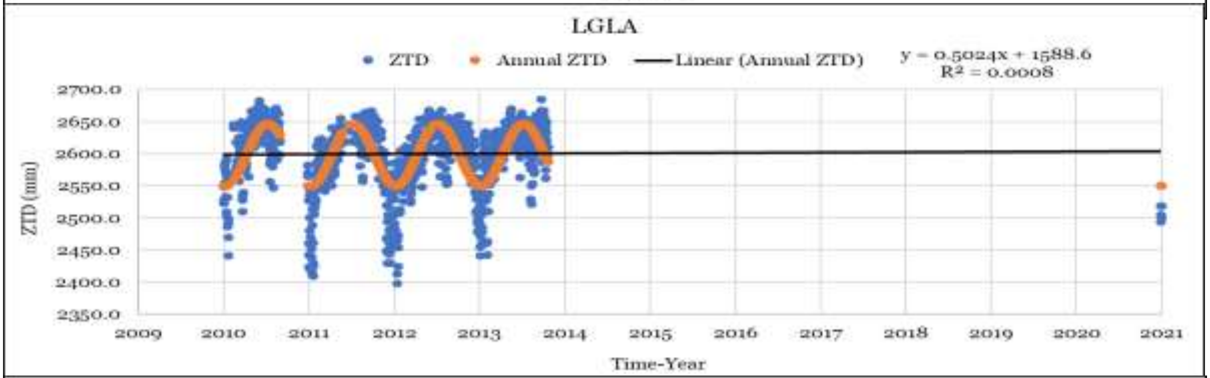

ENEN
ZTD
Annual ZTD
Linear (Annual ZTD)
y = 0.0105x + 2502.6
R² = 3E-07
ZTD (mm)
Time-Year

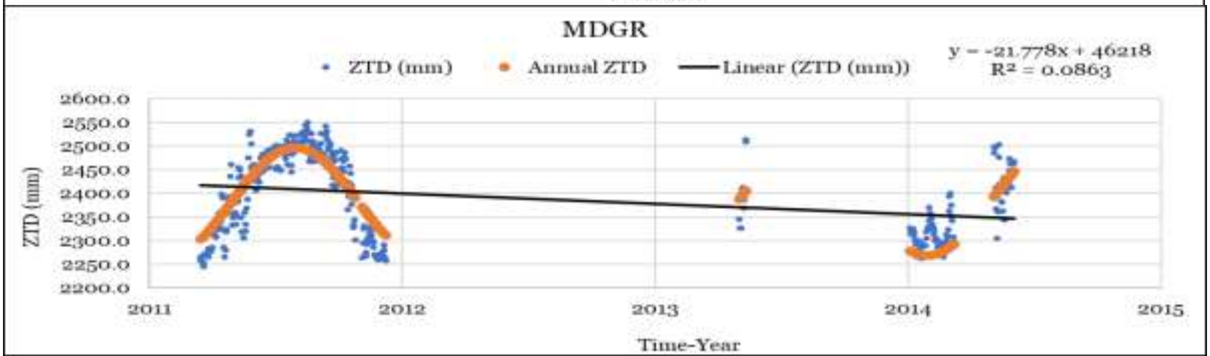

EKAK
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = -2.9664x + 8608.2
R² = 0.002
ZTD (mm)
Time-Year

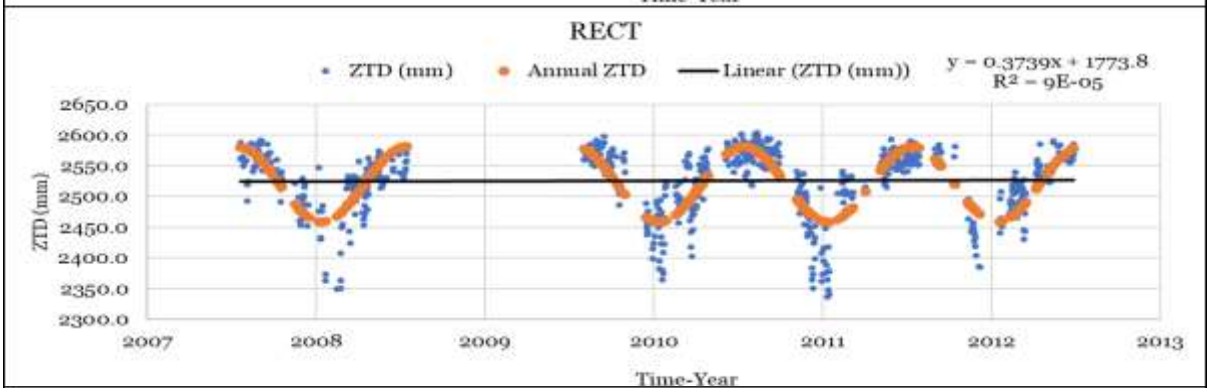

GBTA
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = -10.013x + 22173
R² = 0.2694
ZTD (mm)
Time-Year

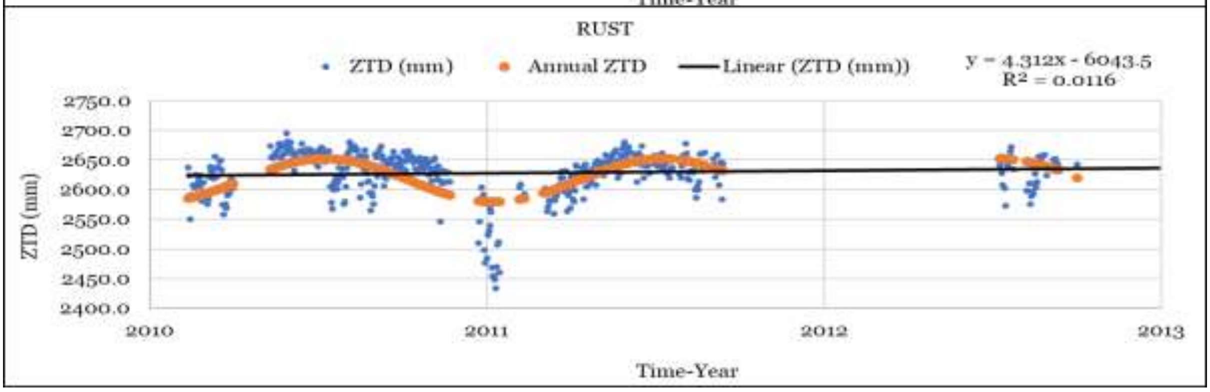

HUKP
ZTD(mm)
Annual ZTD
Linear (ZTD(mm))
y = -11.003x + 24486
R² = 0.011
ZTD (mm)
Time-Year

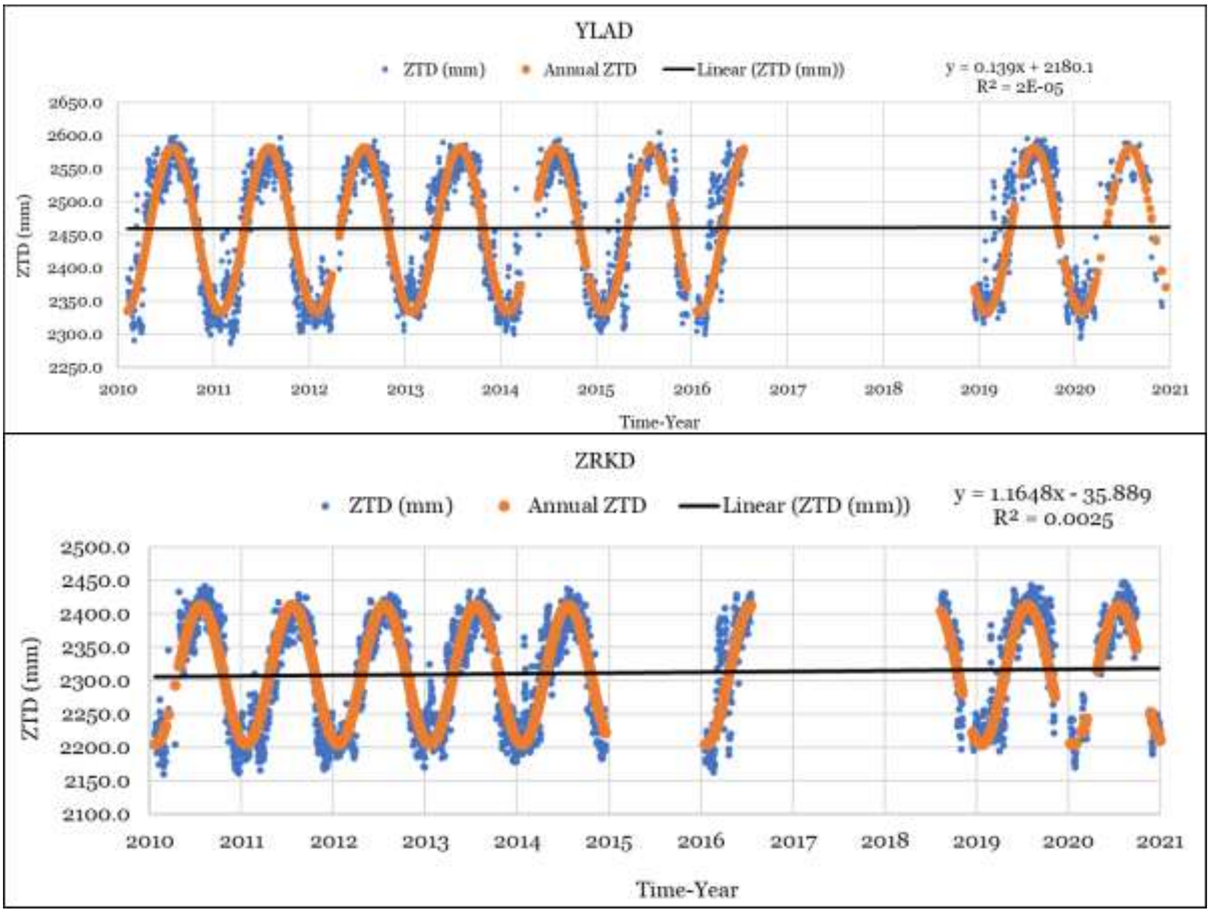

KNKN
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = 3.1961x - 4120.3
R² = 0.001
2550.0
2500.0
2450.0
2400.0
2350.0
2300.0
2250.0
2200.0
2150.0
ZTD (mm)
2018
2019
2020
2021
Time-Year


LGLA
ZTD
Annual ZTD
Linear (Annual ZTD)
y = 0.5024x + 1588.6
R² = 0.0008
2700.0
2650.0
2600.0
2550.0
2500.0
2450.0
2400.0
2350.0
ZTD (mm)
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Time-Year


MDGR
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = -21.778x + 46218
R² = 0.0863
2600.0
2550.0
2500.0
2450.0
2400.0
2350.0
2300.0
2250.0
2200.0
ZTD (mm)
2011
2012
2013
2014
2015
Time-Year

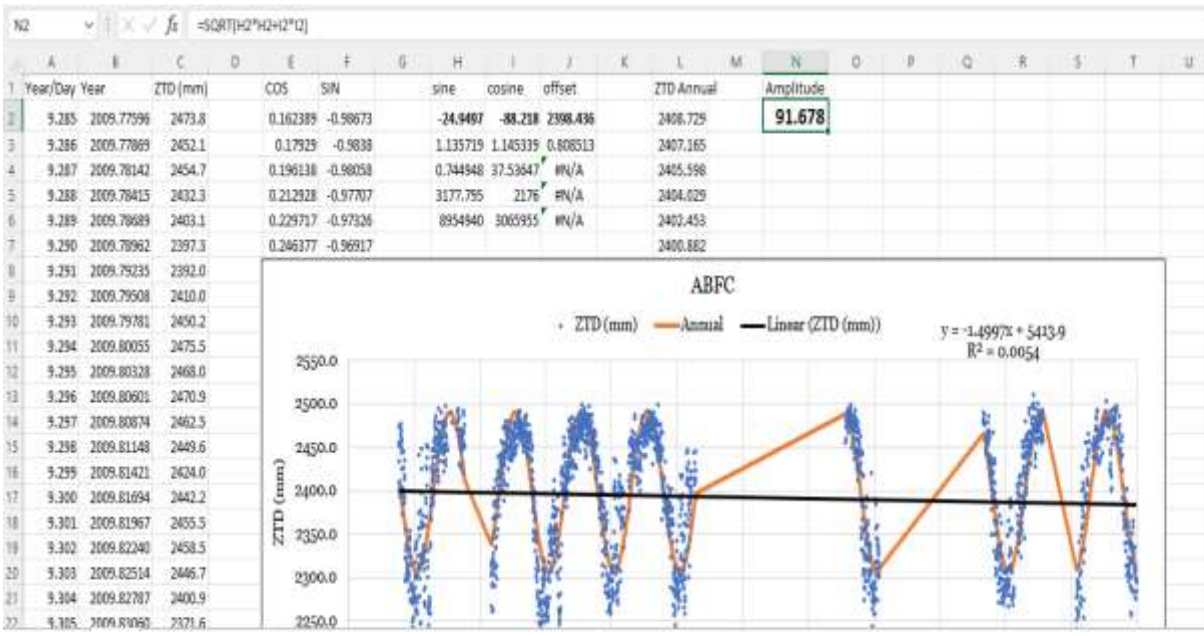

RECT
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = 0.3739x + 1773.8
R² = 9E-05
2650.0
2600.0
2550.0
2500.0
2450.0
2400.0
2350.0
2300.0
ZTD (mm)
2007
2008
2009
2010
2011
2012
2013
Time-Year


RUST
ZTD (mm)
Annual ZTD
Linear (ZTD (mm))
y = 4.312x - 6043.5
R² = 0.0116
2750.0
2700.0
2650.0
2600.0
2550.0
2500.0
2450.0
2400.0
ZTD (mm)
2010
2011
2012
2013
Time-Year



A.2 Amplitude Calculation

The Figure below depicts the Annual variation at ABFC station and most importantly the amplitude of variation. This calculation method was applied to the other GNSS stations.



Appendix B

B.1 Precipitation Chart

The figure below shows the precipitation chart derived from Abuja weather history that correspond with day 6th (day of year 157) of June 2019 under investigation. The daily averages of ZTD correlation with the precipitation was observed to be very small. Thus, averaging makes the peak disappear. Hence the plotting of the daily rain which shows the peaks corresponding to days of the ZTD epoch with heavy rain.