ASSESSMENT OF GNSS-BASED INTEGRATED WATER VAPOUR OVER NIGERIA CORS NETWORK

Water vapour is a very dynamic component of the atmosphere. It greatly influences the atmospheric stabilization mechanism. Hence, it is very difficult to measure or model using classical meteorological systems or models. Tropical atmosphere holds the largest amount of water vapour, thus its characteristics of high climate uncertainty. Interestingly, geodesists have devised methods for estimating the extent to which signals propagated from GNSS satellites to ground-based GNSS receivers are delayed by atmospheric water vapor. This delay is parameterized in terms of a time-varying zenith wet delay (ZWD) which is retrieved by stochastic filtering of the GNSS data. Given surface temperature and pressure readings at the GNSS receiver, the retrieved ZWD can be transformed with very little additional uncertainty into an estimate of the integrated water vapor (IWV) overlying that receiver. Therefore, this study is to assess the integrated water vapor over NIGNET CORS using GPS data. Three specific objectives were set for the study which was conducted in three phases. The first objective assessed the Zenith Path Delay (ZPD). The highest and the lowest ZPD estimates are respectively 2731.104mm at station ULAG and 2129.924mm at station CGGT and the analysis showed good correlation with the IGS (ZPD). The average correlation (R^2) of 70% was obtained showing a very strong agreement with IGS estimation. The second objective was the estimation of IWV. Surface temperature and pressure data were utilized to obtain the integrated water vapor (IWV). The surface temperature and pressure data of the NIGNET CORS were not readily available, therefore the GPT2w_1 model was used to generate the surface temperature and pressure. The surface temperature and pressure were then used to compute the weighted mean temperature which was combined with the ZWD to obtain IWV. Spatial and seasonal variation of IWV value over the NIGNET CORS was performed and it was found that the highest IWV values were obtained over the southern stations just as the rainy season presents the period of high IWV values over all stations. The estimated IWV was validated with IWV generated from ECMWF ERA-5 interim data and it shows a considerable correlation with the estimated NIGNET IWV, the average correlation of 0.6 was obtained. It was deduced from the study that GPS-based IWV properly captured the IWV trend over Nigeria. It is strongly recommended that assessment of IWV over all the NIGNET CORS should be extended for longer years for better spatial and temporal analysis.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the study

Water vapour is the most dynamic component of the atmosphere, and it also plays a key role in atmospheric processes. Water vapour has a very significant impact on GNSS data operational analyses (OA) in term of precision. Therefore, it is important that the amount of water vapour in the atmosphere is experimentally quantified accurately (Choy *et al.,* 2015). More so, atmospheric water vapour is the dominating greenhouse gas, and so estimating the quantity of water vapour feedback of global warming is of great importance. Indeed, numerical experiments suggest that this effect is substantial. As the climate is warming due to increasing carbon dioxide and other anthropogenic greenhouse gases, water vapour is expected to increase rapidly as models broadly conserve relative humidity (Soden *et al.*, 2005).

However, commencement of studies on atmospheric water vapour through ground-based GPS technique started in 1992, Bevis *et al*. (1992) which has been on a continuously increasing curve of improvement and evaluation Tregoning *et al.* (1998) because of its significance in operational weather forecasting, climate management and monitoring, atmospheric exploration, among other vast applications. In addition to the GNSS data, site dependent surface pressure and weighted mean temperature values are unavoidable parameters to derive the precipitable water vapour (PWV) from the atmospheric delay, which can be obtained from a collocated meteorological sensor. The meteorological sensor records the surface pressure and temperature data concurrently at the GNSS site to an acceptable degree of accuracy (Wonnacolt, 2005). The required Tm values for PWV estimation can be estimated from the surface temperature using models turned to the specific area and season (Davis *et al.*, 1985; Bevis *et al.*, 1992, 1994; Mendes *et al.*, 2000; Schueler *et al*., 2001; Musa et al., 2017). In absence of collocated meteorological sensors these station-specific meteorological parameters can be derived from the available numerical weather prediction (NWP) models' predicted meteorological data using a variety of interpolation techniques (Opaluwa *et al.,* 2014b). (Bevis *et al*. 1994) have given a simple ratio for PWV/ ZWD = Q 0.15 (where ZWD is zenith wet delay), but the actual values of Q can vary to a magnitude as much as 20% with respect to location, altitude, season, and weather. Availability of the aforementioned parameters has to some extent eliminated the need of ***Tm*** values to retrieve PWV from ZWD. Osah *et al.* (1996) investigated the possibility of using global meteorological data from the National Centres for Environmental Prediction (NCEP) to derive the surface pressure at a few International GNSS Service (IGS) tracking stations by interpolating upper level atmospheric fields in order to eliminate the use of high-precision barometers. For this research the GPT model is used for the interpolation of temperature and pressure which are used for the computation of IWV data using the ZPD data computed from Bernese 5.0 software.

Tropical atmosphere holds the largest amount of water vapour; thus, it is characterized with high climate uncertainty (Opaluwa *et al.,* 2014b). Unfortunately, available meteorological systems and models have challenges in properly capturing the atmospheric dynamics due to poor temporal and spatial resolutions. Interestingly Geodesists have devised methods for estimating the extent to which signals propagating from GNSS to ground-based GNSS receivers are delayed due to atmospheric water vapour. Hence, a GNSS-based estimate of atmospheric water vapour has become a valuable input parameter for Numerical Weather

Prediction (NWP) (Bock *et al.*, 2007). Thus, assimilation of the GNSS Integrated Water Vapour (IWV) into Numerical weather models has become popular recently across the globe and has greatly improved weather outlook. This is valuable for flood inundation modelling and prediction. However, flooding has assumed a disaster status in most part of Nigeria recently but availability of GNSS infrastructure in Nigeria is relatively new, hence, adopting GNSS for meteorology. Subsequent section presents a review of the integrated water vapour from GNSS data over Nigerian Continuously Operating Reference Stations (CORS).

1.1.1 Global Navigation Satellite System (GNSS)

A GNSS is an ensemble of satellites gyrating about the Earth, constantly transmitting signals that provide three-dimensional (3D) positions globally to the users with a GNSS signal receptor/sensor. Over years, US Global Positioning System (GPS) has been the only fully operational GNSS system. In December 2011, the Russian GLObal NAvigation Satellite System (GLONASS) was reinstated to full operation. The Chinese COMPASS and BEIDOU, European GALILEO and EGNOS systems (Sarkar *et al.*, 2018). The Japanese MSAS, QZSS and SBAS and the Indian IRNSS are currently under development, notwithstanding BEIDOU commenced preliminary operating service (Phase II) in December 2011. Principle of GNSS positioning is based on solving a fundamental geometric problem, consisting of the distances (pseudo-ranges) of points on Earth to a group of at least four (4) GNSS satellites with well-known coordinates. The ranges and coordinates of satellites are computed by the user’s receiver using navigation data and signals transmitted by the satellites; the determined coordinates can be computed to an accuracy of several meters. Nonetheless, centimeter-level positioning is feasible and realizable using more advanced techniques (Fisher & Raquet., 2011).

1.1.2 GPS Meteorology

GPS meteorology otherwise, GPSMET is a state-of-heart application of GPS to climatological and meteorological studies. It takes its basis in the fact that navigational signals passes through the atmospheric layers before they are received by the GPS receivers located on or near the earth surface. The signals in their process of transmission, carry diverse information about the atmosphere among others; the zenith path delay, the water vapour. The zenith path delay is a very useful parameter to the meteorologists as it can be decomposed into zenith dry delay (ZHD), and zenith wet delay (ZWD). ZHD is a function of pressure content of the atmosphere while the ZWD is a function of atmospheric temperature (Niell *et al.,* 2001).

These components are key parameters in atmospheric science and weather prediction can be measured or estimated with GPS in a near real time sense, this give even a large sensitivity to the use of GPS in meteorology (Stensrud, 2009).

1.2 Statement of Research Problem

Water vapour is a very dynamic composition of the atmosphere. It greatly influences the atmospheric stabilization mechanism (Opaluwa *et al.,* 2014a*)*. Hence, it is very exhaustive to measure or model using classical meteorological systems or models. Tropical atmosphere holds the largest amount of water vapour, thus it characterizes high climate uncertainty (Opaluwa *et al.,* 2014b). Interestingly, Geodesists have devised methods for estimating the extent to which signal propagating from GNSS to ground-based GNSS receivers are delayed by atmospheric water vapour.

Nigeria as a tropical nation is also faced with the challenges posed by the dynamics of atmospheric water vapour. Unfortunately researches into understanding the characteristics of this highly variable greenhouse gas has been limited to the use of data from meteorological tools and models from synoptic and satellite remote sensing. However, these data sources are known to be subjected to atmospheric influence such as cloud cover and others have poor spatial and temporal resolutions due to high cost of deployment. In 2010, Nigerian Government in collaboration with African Reference Frame (AFREF) project established a network of GNSS CORS across the country and it is being developed further. The capacity of GNSS for meteorological applications has been widely affirmed in literature (e.g. Vey *et al., 2010,* Opaluwa *et al.,* 2014b, Bevis *et al.,* 1994) but yet to be explored in Nigeria. Hence, this study seeks to explore the applicability of GNSS data for estimation of atmospheric water vapour.

1.3 Aim and Objectives of the study

The aim of this study is to assess the integrated water vapour from GNSS data over Nigerian Continuously Operating Reference Stations (CORS) for a period of one year (2011). The specific objectives are to:

i. Estimation of Zenith Path Delay (ZPD) over NIGNET GPS CORS using Bernese 5.0 software
ii. Estimation of GNSS-Based Integrated water vapour (IWV) over Nigeria
iii. Validation Analysis of the estimated water vapour using integrated water vapour (IWV) from Meteorological observation with Numerical Weather Model (NWM).

1.4 Justification for the study

The application of GPS in meteorology and other area of space and atmospheric study has offered a more flexible and prompt access to atmospheric data. Tropospheric delay is a function of local temperature, pressure and relative humidity. Therefore, the current practice across the globe is the use of the GNSS data to support meteorology to improve weather outlook and climate studies (Opaluwa *et al.*, 2017). This is important to capture the dynamics of tropical climate. Unfortunately, Nigeria as a tropical nation is not well studied as regards GNSS meteorology, available studies have based their findings on few days to few weeks GNSS data (e.g. Dodo *et. al.*, 2015). Also, the seasonal and annual trend of this highly dynamic parameter over Nigeria is yet to be known, hence the justification for this study. The availability of the expanded GNSS CORS provide a robust platform for continuous R and D of GNSS meteorology

1.5 Scope and limitation of the study

1.5.1 Scope of the study

This research work focuses mainly on estimation of water vapour content using a GNSS technique. A year span of GPS data was acquired across Nigeria over the Nigerian Geodetic Network and processed using Bernese GPS software version 5.0 in the estimation of ZPD. Then data from IGS stations were downloaded for validation of the estimated ZPD values using appropriate statistical tools. Also, Global Temperature and Pressure wet model (GPT2W_1) was adopted in the estimation of local temperature, pressure at the respective GPS stations. Sofware like panoply was utilized in visualization of the atmospheric data in the NETCDF format. Also MATLAB program was developed and utilized in the estimation of ZHD, ZWD and IWV. A Numerical Weather Model data was downloaded for the validation of the estimated IWV and a statistical approach was adopted in the validation of the results.

1.5.2 Limitations of the study

Due to the inaccessibility of the latest version of the GNSS scientific software (Bernese 5.2), the previous version was employed in this research. The archive data of NIGNET 2011 was employed in this research due to the unavailability of the NIGNET website as at the time of this research for current data. The success of GNSS data processing using Bernese GPS Software 5.0 is largely dependent on the Bernese processing engine (BPE) and the BPE also on Central Processing Unit (CPU) of the computer system. The CPU should possess quite high specification properties for a successful GNSS data processing (e.g. the processor's speed of above 2.0 GHz, the RAM capacity of at least 8 GB, the hard disk's memory space of not less than 500GB).

1.6 Significance of the Study

The result of this research will be of great benefits to the geodesists in their practice considering the fact that the importance of accuracy/precision in survey cannot be over emphasized. The existence of integrated water vapour (IWV) in the atmosphere (medium of signal transmission) poses a serious challenge in our observation knowing fully the role it plays in precise point positioning (PPP) of GNSS positioning. This study therefore, will be of great use to the surveying and other geodetic studies and researchers. It will similarly be a great improvement to the meteorological communities in retrieval of data for examining the state of the atmosphere in a near real time sense for weather prediction and other applications.

1.7 Study Area

The study area, Nigeria, lies between latitudes 4°and 14°N and longitudes 2°and 15°E, and is located in the western part of Africa. The total area of the country is about 923,768km^2

making it the thirty-second (32nd) largest country in the world. It shares about 4,047km borders with four (4) countries (Benin Republic to the west, Niger Republic to the north, Chad to the north east and Cameroon to the east). It has a coastline of at least 853 km stretching along the Atlantic Ocean in the southern border. Figure 1.1 depicts the map of Nigeria and the location of NIGNET CORS.

Nigeria has a varied landscape; to the southwest of the Niger is a rugged highland and to the southeast of the Benue is the Mambilla Plateau, which forms the highest Plateau in the country. The highest elevation point in Nigeria (2,419metres above sea level) is located in Chappal Waddi in the Northern State of Taraba. The country has two major rivers, namely; the River Niger and River Benue that converged in a “Y” shaped valley in Lokoja, and emptied its waters into the Atlantic Ocean in the Niger Delta area of the southern part of the country.

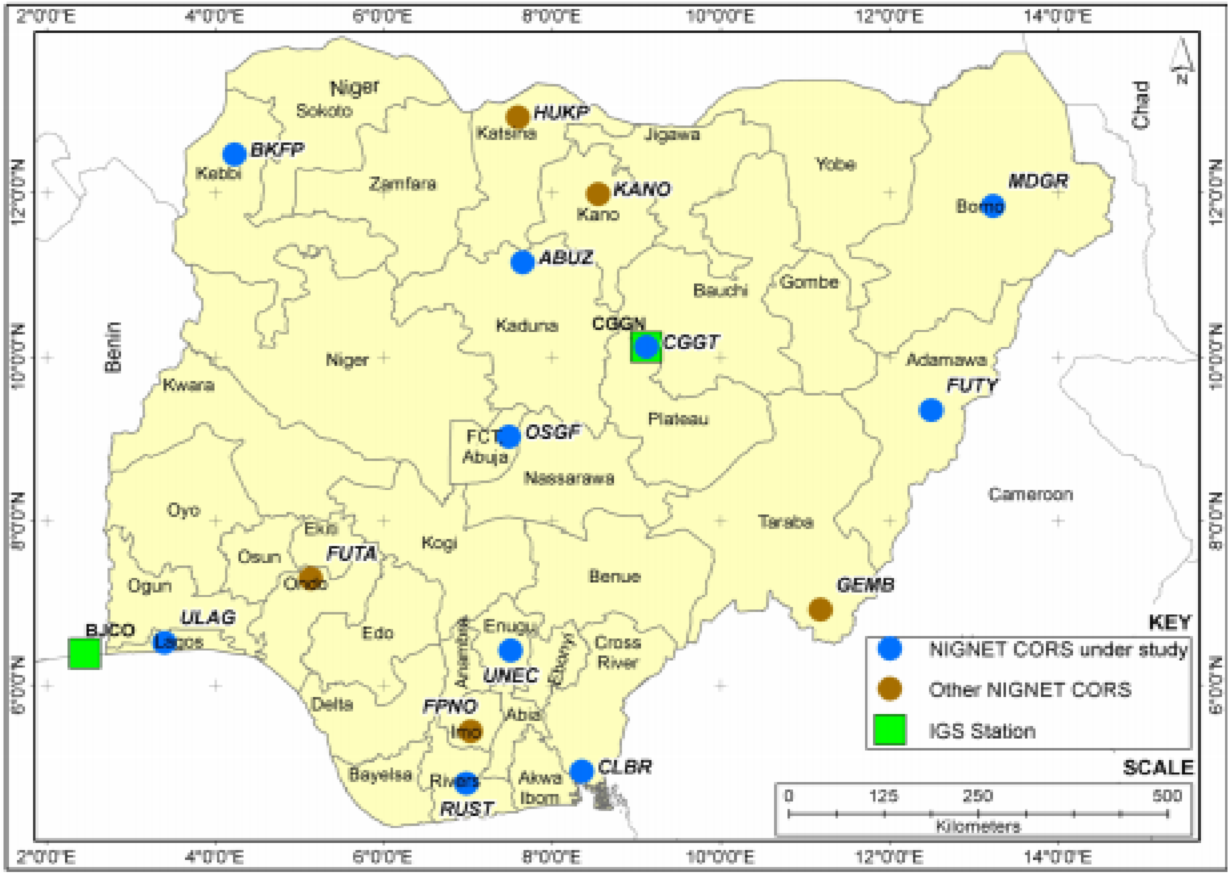


Figure 1.1: Nigeria map showing the GNSS stations available in Nigeria
Source: (Ayodele, *et a.*, 2019)

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Ground-Based GPS Meteorology

GNSS radio waves are delayed by the neutral atmosphere, which results in a positive bias in the range measurements. This delay is one major error source in GNSS processing and is traditionally known as the “tropospheric delay.” This error must be dealt with appropriately to achieve precise positioning. In GPS processing, the tropospheric delay can be computed as zenith path delay (ZPD) (often used inter-changeably with “zenith tropospheric delay” abbreviated as ZTD). The equations (1) up to (4) are used in the computation of ZPD, ZHD and PWD as documented by (Hajj *et al.*, 2004).

$$ZPD = (mf\mathrm{h}(\theta^{o}) * HD) + (mfw(\theta^{o}) * WD) \qquad (1)$$

Where, m_h (θ^o) and m_w (θ^o) are the dry and wet mapping functions respectively while, HD and WD are the dry and wet delay thus, and we have:

$$ZPD = ZHD + ZWD \qquad (2)$$

From ZPD, ZWD can be obtained by subtracting ZHD from ZPD. If the surface pressure (Ps) at the station is known as well as the station latitude ($\emptyset$) and height (h), thus, ZHD can be computed by

$$ZHD = \frac{(2.27688 \pm 0.0005)P_s}{1 - 0.00266cos20^o - 0.00028h} \qquad (3)$$

Where Ps is the surface pressure ZHD is the Zenith hydrostatic delay. ZPD is defined as the sum of the hydrostatic (ZHD) caused by the atmospheric gases such as nitrogen, oxygen, argon and carbon dioxide, and non-hydrostatic or wet (ZWD) delays, which is mainly contributed by water vapor contained in the atmosphere, as shown in

ZHD is generally very stable and is easily determined using an empirical model such as the Hopfield models (Hopfield *et al.*, 1969) and constitutes more than 80% of the total path delay. ZHD can reach up to about 2.3m in the zenith direction and up to 30m for a slant path close to the Earth's surface (Jennifer *et al.*, 2003). Given surface pressure measurements, it is usually possible to model and remove the hydrostatic delay with accuracy of a few millimeters or less, at the zenith the Hydrostatic is direct and opposite which is -90 ZHD and +90 ZHD. On the other hand, the ZWD delay is more spatially and temporally variable and is more difficult to eliminated than the ZHD. The ZWD can be as small as a few centimeters or less in arid regions and as large as 35 cm in humid regions it is actually 10%. As it is impossible to accurately measure the wet delay from surface meteorological measurements, GNSS scientists determine the hydrostatic delay from surface measurements and then attempt to estimate the wet delay as part of the data processing. ZWD may be converted to PWV via a dimensionless conversion factor (Π)

$$PWV = ZWD.\Pi \qquad (4)$$

2.2 Zenith Path Delay

The Global Positioning System (GPS) is an important tool for the estimation of atmospheric water vapour. The GPS signals traveling from satellite to receiver propagate through the atmosphere. The signals are delayed due to the amount of dry gases and water vapour in the troposphere layer as the result of refraction and diffraction. This increase the time taken for the signal when it travels through the troposphere. The effects are called tropospheric refraction, tropospheric path delay or simply tropospheric delay (Hirahara, 2000). The tropospheric delay can be divided into dry and wet components. The dry component is caused by the dry air gases in the atmosphere such as nitrogen (78%) and oxygen (21%) with only small concentrations of other trace gases. The wet component however depends on the humidity content of the troposphere and contains significant levels of water vapor (Bevis *et al.*, 1992). The total delay in the GPS signal is known as the slant path delay, or in zenith direction known as Zenith Total Delay (ZPD) or Zenith Path Delay (ZPD). The ZPD also consists of the hydrostatic and wet component which are known as the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD) also known as zenith non hydrostatic delay, respectively. The ZWD can be expressed in terms of Integrated Water Vapor (IWV) and the IWV was realized as a useful quantity for meteorological applications (Bevis *et al.*, 1992). In a study by Musa *et al.* (2011), the ZPD estimation was conducted from two CORS networks – the Australian Regional GPS Network (ARGN) and the Malaysian Real-Time Kinematic network (MyRTKnet), which stretches from the low latitude to the mid latitude region. Moreover, the IGS (International GNSS Service) stations were included in the ZPD estimation process so as to provide an opportunity to assess the estimated ZPD against the IGS derived troposphere products. The estimated ZPD are expected to be valuable for a wide variety of climate and weather applications.

2.2.1 Zenith Path Delay (ZPD) Estimation

$$\Delta L = \int_L n(s)ds - G \qquad (5)$$

Where $n(s)$ is the refractive index as a function of position s along the curved ray path L, and G is the straight-line geometrical path length through the atmosphere. Equation (1) is further re-written as (Opaluwa *et al.*, 2014).

$$\Delta L = \int [n(s) - 1]ds + [S - G] \qquad (6)$$

Were s is the path length along L the first term on right is due to slow bend and the second term is due to refraction in the signal propagation.

Thus;

$$N = k_1\left(\frac{P_d}{T}\right) + k_2\left(\frac{P_v}{T}\right) + k_3\left(\frac{P_v}{T^2}\right) + k_4\left(\frac{P_c}{T^2}\right) \quad (7)$$

WhereP_d , P_v , and P_c are the partial pressure of dry air, water vapour and carbon dioxide respectively (in millibars) and T is the absolute temperature (in Kelvin). While k_1, k_2, k_3 and k_4 are the refraction coefficients given (Opaluwa *et al.,* 2014). Since the troposphere is neutral and non-dispersive, its refractive index depends on temperature, pressure, humidity, compressibility and electric characteristics of the molecules (Opaluwa *et al.,* 2014b).

However, the total tropospheric delay depends on the zenith distance or elevation angle of the satellite. If zenith distance is z then the propagation path delay is proportional to $\frac{1}{cosz}$. The interactions between the GPS radio signal and the atmosphere is depicted in figure 2.1

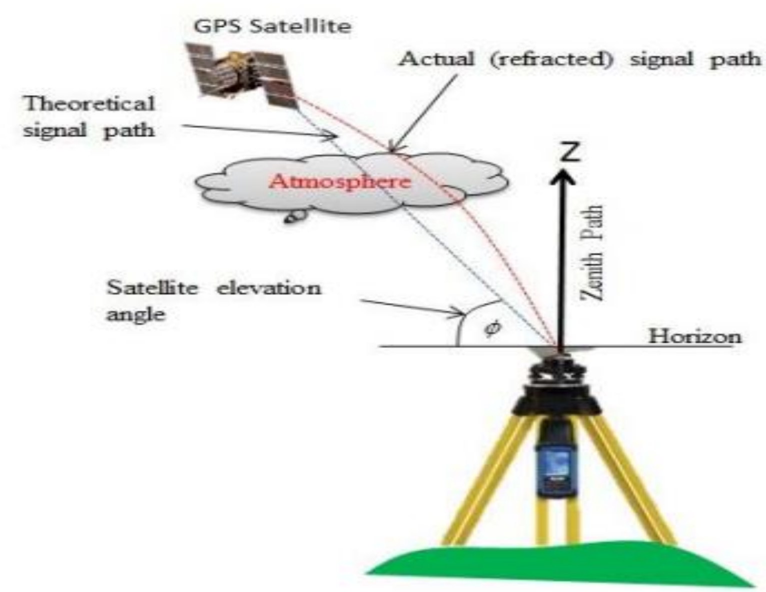


Figure 2.1: Atmospheric effect on GPS signal
Source: (Opaluwa *et al.,* 2014).

$$z = 90^o - \emptyset \qquad (8)$$

Hence, $$\frac{1}{cosz} = \frac{1}{sin}\emptyset \qquad (9)$$

Where $\emptyset$ is the satellite elevation angle, this angle help to estimate tropospheric delay zenith direction in the GPS computation separately including station coordinate and the receiver clock delay? The zenith path delay (ZPD) consist of two component which are the zenith hydrostatic delay (ZHD) and the zenith non-hydrostatic delay also known as the zenith wet delay (ZWD) in computing zenith total delay also known as the zenith path delay (ZPD) is given by the equation. (2). It then means if zenith path delay (ZPD) can be estimated and the zenith hydrostatic delay (ZHD) which is the dry delay then zenith wet delay can be computed. Thus the zenith hydrostatic delay (ZHD) is about 90% of the zenith path delay (ZPD); it varies smoothly with surface pressure which means that at the zenith ZHD is equal and opposite therefore, it can be effectively modelled as given in equation. (10) and (11) by (Wickert *et al.,* 2012).

$$ZHD = (2.2779 \pm 0.00024)\frac{P_s}{f(\emptyset, h)} \qquad (10)$$

Where P_s is the total pressure (in millibars) at the Earth's surface, and

$$f(\phi, h) = (1 - 0.00266cos2 * \phi - 0.00028h) \qquad (11)$$

2.3 Integrated Water Vapour (IWV)

Water vapour, the most variable of the major constituents of the atmosphere, plays a key role in atmospheric processes and also it has a significant impact on radio propagation at millimeter wavelengths. Therefore, it is important that the amount of water vapour in the atmosphere is experimentally quantified accurately, with frequent sampling and under all weather conditions. For instance, the knowledge of water vapour field comes usually from radio-soundings and ground or space based water vapour radiometers (WVR). Radiosonde observations (RAOB's) produce accurate measurements of the water vapour profile, but the availability of data does not meet the requirements of frequent sampling of such parameter, taking into account the high degree of variability. Ground-based microwave radiometers are able to work continuously for the retrieval of integrated precipitable water vapour (*IPWV*) with a high temporal resolution, but providing measurements not reliable during rainfall.

Considering the growing employment of Global Positioning System (GPS) ground-based receivers as a microwave (LBand)

Remote sensing tool for the estimation of integrated precipitable water vapour, *IPWV* becomes available with high temporal and spatial resolution, taking into account that GPS estimates are not affected by rainfall, and GPS can therefore be considered an all-weather system.

2.3.1 Water vapour modelling

The information about content of water vapour (2-D model) above GNSS stations, represented by Integrated Water Vapour (IWV), is obtained directly from ZWD. The relation between ZWD and the water vapour content in the atmosphere is expressed by IWV (Bosy *et al.*, 2012) and given by the equation

$$IWV = \frac{ZWD}{10^{-6} . R_w} \left(k_2' + \frac{k_3}{T_M} \right)^{-1} \qquad (13)$$

Where R_w = specific gas content for water vapour K_1, k_2 are the refractive content of the water T_M is weighted mean water vapour temperature atmosphere T_0, is the surface temperature. The ZWD is derive from equation (14)

$$ZWD = ZPD - ZHD \ or\ IWV = ZPD - ZHD \quad (14)$$

ZHD are derived from Saastamoinen model (1972). The input parameters for ZHD computation are surface meteorological parameters (temperature, pressure) interpolated for Nigeria CORS. Therefore, it is possible to derive IWV for any location inside the NEGNET network as presented in equation (18) (Bosy *et al.,* 2012).

2.3.2 The Estimation of Integrated Water Vapour from GPS ZWD

This process involves the conversion of the GPS derived ZWD to the IWV. The two parameters required are the weighted mean temperature (*Tm*) of the atmosphere and the conversion parameter (K) thus, if the surface pressure and temperature at the GPS stations are known, the *Tm* parameter can be obtained as (Davis *et al.*, 1985):

$$Tm = \frac{\int \left(\frac{e}{T}\right) dz}{\int \left(\frac{e}{T^2}\right) dz} \quad (15)$$

Where *e* is water vapour pressure, *T* is as defined earlier.

The commonly used global *Tm* parameters are usually derived from radiosonde and surface temperature (*Ts)* in Kelvin (K) using linear regression technique. (Opaluwa *et al.*, 2017): derived the global *Tm* parameters as:

$$T_m = 70.2 + 0.72T_s \quad (16)$$

$$While \ \ K \ is \ given \ as:$$

$$K = \frac{10^6}{\left(\left({K_3}/{T_m}\right) + K_2\right) R_v} \qquad (17)$$

Where Rv, is a gas constant for the water vapour, P_w is the partial water vapour K_2 and K_3 are as defined earlier while, *Tm* is the weighted mean temperature of the atmosphere. Then the IWV can be derived as given in equation 18 (Opaluwa *et al.*, 2017):

$$IWV = K(T_m).ZWD \qquad (18)$$

This procedure as detailed in this section summarized the fundamental background for the GPS meteorology especially, using the ground-based GPS observations. Therefore, developments in ground-based GPS meteorology are subsequently examined.

2.3.3 Water vapour observing techniques

Concerning its important role in the climate system as well as high spatiotemporal variability, tremendous efforts based on a variety of platforms, like ground-based remote sensing techniques, have been made for sensing the atmospheric water vapour. In this section, an overview of several commonly used water vapour observing techniques, apart from GNSS, are presented. This includes the radiosondes, water vapour radiometers, Very Long Baseline Interferometry (VLBI), Doppler Orbitography Radio positioning Integrated by Satellite (DORIS), and numerical weather models.

2.3.3.1 Radiosonde

Traditionally, radiosondes are considered as the predominant upper air observing systems. Radiosondes are balloon-borne instruments equipped with different sensors that measure temperature, pressure, humidity, and wind velocity and transmit the results to the ground station using radio signals. The radiosonde profiles provide atmosphere information up to an altitude of approximately 30 km. The radiosonde balloons are launched every 12 or 24 hours per day in most cases. The atmospheric water vapor can be retrieved from the integration of the vertical absolute humidity profiles given by the radiosonde profiles. A global network consisting of more than 1300 radiosonde stations has been deployed, including in ocean areas, where the radiosonde observations are taken by about 15 ships equipped with automated shipboard upper-air sounding facilities (Kawatani *et al.,* 2016).

2.3.3.2 Water vapor radiometer

The water vapor radiometer (WVR) is able to measure the background microwave radiation emitted by the atmospheric water vapor, so as to infer the wet tropospheric delays and integrated water vapor from the measurements (Pacione *et al.,* 2001). Normally, the spectral line of water vapor is centered at 22.235 GHz. The sky emission at a frequency close to this line can be observed by WVR, which is then used to infer the wet delay. Meanwhile, the WVR is capable of providing the integrated water vapor (IWV) along the line of sight, with a considerably good temporal resolution. Typically, two different frequencies are performed in WVR in order to distinguish the contribution of water vapor from that of liquid water. One frequency that is more sensitive to water vapor is about 22.2 GHz, while the other one that is sensitive to the liquid water is usually close to 30 GHz (Teke *et al*., 2011). Based on the measurements of sky brightness temperature at two frequencies, the wet tropospheric delay can be calculated (Elgered, 1993). The accuracy of a WVR is determined by the choice of frequencies as well as the absolute accuracy of brightness temperature. Calibrations are always required for the sake of derivation of atmospheric water vapor with high accuracy.

The most obvious advantage of a WVR is its capacity of providing almost continuous water vapor measurements (Diedrich, *et al.,* 2016).

2.3.3.3 Numerical weather models

The numerical weather prediction (NWP) aims to providing weather forecasts, especially for the short-term severe weather events and precipitation. In NWP, a couple of non-linear partial differential equations that describe the change of the atmospheric conditions including pressure, temperature, humidity, wind etc. are considered as the principal factor, along with the numerical solutions with regard to these equations (Gutman and Benjamin, 2001). The realization of NWP models is accomplished after solving the initial value problem, i.e. the initial conditions or state of the atmosphere. This process is referred as the so-called data assimilation, while the resolved atmospheric state is named as an analysis. The numerical weather models (NWM) use a large variety of meteorological observations to describe the atmospheric dynamics and compute weather forecasts. They are largely dependent on the thermodynamics, conservation laws, and the physical laws of fluid dynamics. Unlike the existing observation systems, no new observations are generated from a NWM. Instead, the NWM assimilates a great number of different meteorological observations into a prediction based on the model background provided by atmosphere physics. They are able to provide the whole information for describing the neutral atmosphere, from which the meteorological parameters like temperature, pressure, humidity and wind velocity can be obtained at any location and at any time by applying interpolation, within the area and time window considered by the model (Pany *et al.*, 2001). In addition, the information of tropospheric delays and horizontal gradients, as well as the precipitable water vapor or integrated water vapor at a given location can also be supplied by a modern NWM.

2.4 Global Navigation Satellite System (GNSS)

The Global Navigation Satellite Systems (GNSS), including the US's Global Positioning System (GPS), Russia's GLONASS, EU's GALILEO and China BEIDOU (also known as COMPASS). There are several regional navigation satellite systems, this satellite systems can be characterized as a more precise, continuous, all-weather and near real-time microwave (L-band) technique with signals through the Earth's atmosphere. These characteristics of GNSS shows more and wider applications and potentials. Each GNSS satellite continuously broadcasts radio signals in two or more frequencies in L-band (1–2 GHz) with wavelength around 20 cm, the direct signals are been used for navigation, positioning and timing. The refracted signals from GNSS Radio Occultation satellites together with ground GNSS observations can provide the high-resolution tropospheric water vapor, temperature and pressure, troposphere parameters and ionospheric total electron content (TEC) and electron density profile as well. (Khojasteh *et al* 2016).

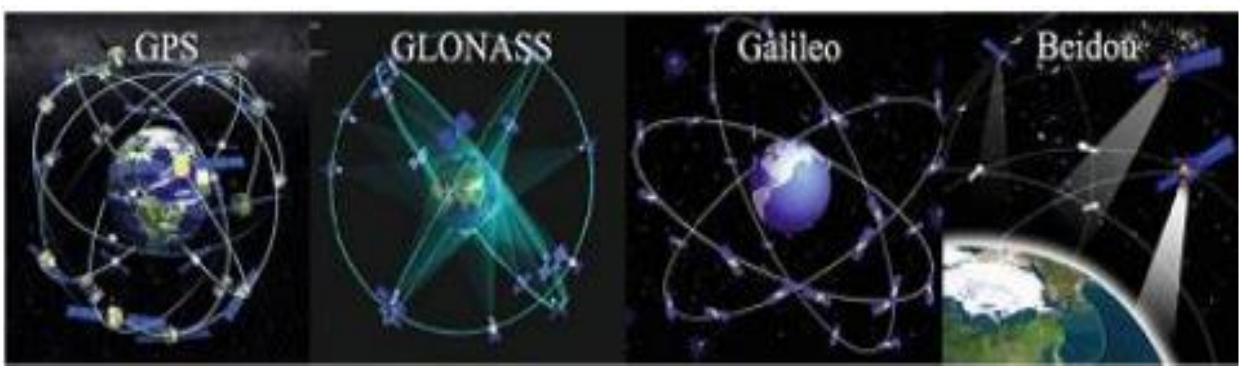


Figure 2.2: Global Navigation Satellite Systems (GNSS).
Source: (Khojasteh, *et al* 2016)

2.4.1 GNSS Signals

GNSS signals are summarized in Table 2.1 (Hofmann-Wellenhof *et al.* 2007). For instance, GNSS satellites continuously broadcast right-hand circularly polarized signals with both the navigation message and ranging codes modulated on two L-band microwave carrier frequencies, i.e., the L1 (f1=1.57542 GHz, λ1≈19.0 cm) and L2 (f2=1.2276 GHz, λ2≈24.4 cm). Starting from 2006, as part of GPS modernization effort, two new GPS users use signals L2C (L2 frequency, C denoting user) and L5 (fL5=1.17645 GHz, λL5≈25.5 cm) were broadcasting on the new generation GPS satellites. Also another user use frequency L1C is down the road in the near future. The navigation message includes the ephemeris data, used to calculate the position of the individual GPS satellite in orbit at the time of signal transmission, and the almanac data with the information about the time and status of the entire satellite constellation. On the other hand, the ranging code enables the user's receiver to determine the transit (or propagation) time of the signal and thereby determine the satellite-to-user range (Khojasteh *et al.,* 2016.)

Table 2.1: GNSS Signals (Khojasteh, 2016)

SYSTEM	**CARRIER**	**MODULATION**	**MULTIPLE ADDRESS**
GPS	L1/L2/L5	BPSK/MBOC/QPSK	CDMA
GLONASS	L1/L2/L3	BPSK/QPSK	FDMA/CDMA
Beidou	B1/B2/B3	MBOC/BOCAlt BOC QPSK	
Galileo	E1/E5/E6 E5a/E5b	BOCc/CBOC Alt BOC BPSK	CDMA

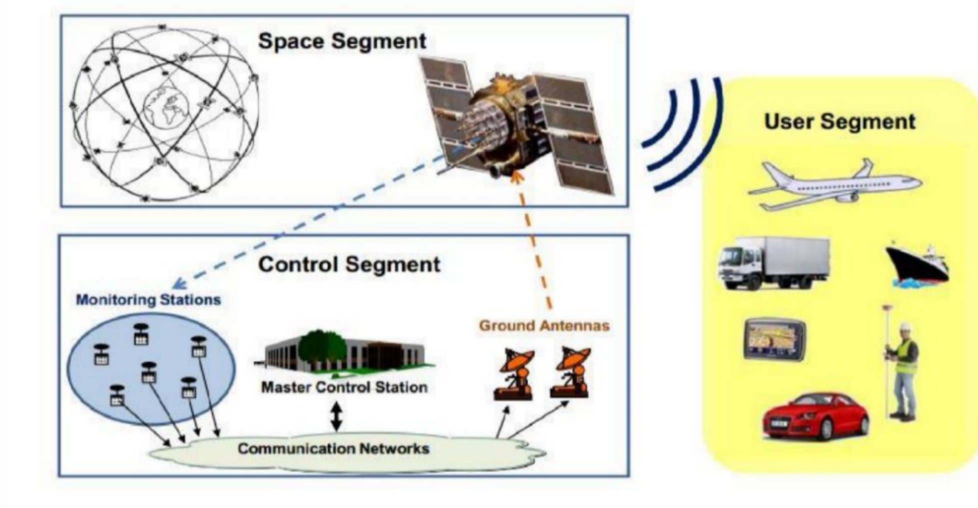


Figure 2.3: GNSS Architecture and segments
Source: (Subirana, 2011)

GNSS satellites constantly transmit navigation signals at two or more frequencies in Lband. These signals consist of ranging codes and navigation data allowing users to compute the travel time from the satellite to the receiver and the coordinates of satellites at any epoch. The primary signal components are illustrated as follow:

i. Carrier: Sinusoidal Radio frequency signal at a given frequency.
ii. Ranging code: Sequences of zeroes and ones allowing the receiver to compute the travel time of the radio signal from the satellite to the receiver. They are referred to as Pseudo-Random Noise sequences or Pseudo-random Noise codes.
iii. Navigation data: A binary-coded message supplying information on the satellite ephemeris (Pseudo-Keplerian elements or satellite position and velocity), clock bias parameters, almanac (with a reduced-accuracy ephemeris data set), satellite health status and other complementary information.

As GNSS signal travels from the satellite in space to the receiver on the earth's surface, it is influenced by a number of factors (Figure 2.2) that affect the precision of the final coordinates.

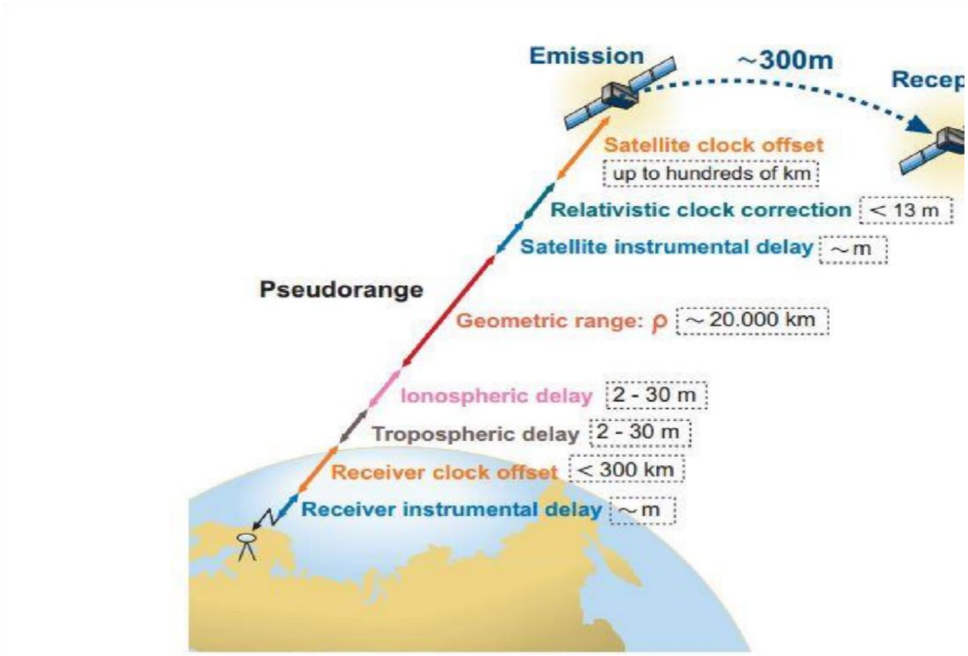


Figure 2.4: Reception and emission of satellite signals with the errors in observables Source: (Subirana, 2011).

2.4.2 GNSS Errors

2.4.2.1 GNSS Constellation Satellite Error

GNSS constellation satellite error mainly includes inherent orbital position error of the satellite and clock error. The former is mainly caused by influences of various perturbative forces, number of monitoring station and spatial distribution, number and precision of orbital parameters, and non-real-time property of ephemeris, and the range error caused thereby is approximately within 1.5 m–7.0 m; (Khojasteh *et al. 2016*) influences on range error are tried to be weakened generally through simultaneous observation to work out the difference or method of orbit improvement to limit it within the error scope of 1 m. The latter refers to the nonsynchronous deviation between satellite clock and GNSS standard time due to frequency offset and frequency drift between clock of GNSS constellation satellite and GNSS standard time; total quantity of such deviation may reach 1 ms, and equivalent range error caused thereby may reach 300 km; the deviation may correct the clock error model through continuous measurement of the ground station to limit the equivalent range error within 6 m; if residual error of GNSS constellation satellite clock is further weakened, it may be realized through differential technology. GNSS Signal Propagation Error (Khojasteh *et al.*, 2016).

2.4.2.2 GNSS signal propagation error

This type of error mainly includes ionospheric refraction, tropospheric refraction, multipath error, etc.

i. **Ionospheric refraction error:** Ionospheric refraction error is in direct proportion to atmospheric electron density and inversely proportional to the penetrated electromagnetic wave frequency. (Khojasteh *et al.*, 2016). Atmospheric electron density varies with radiation intensity of the Sun and other celestial bodies, season, time, geographic position, etc. For GNSS constellation satellite signal, randomness of solar activity is large, so the difference of impact of ionospheric refraction on GNSS navigation and positioning error is large, and it is impossible to establish precise mathematical model for it. During GNSS navigation and positioning, methods may be generally adopted to weaken the impact of ionosphere on the precision of GNSS navigation and positioning includes: (Khojasteh *et al.* 2016) correction through double frequency observation; (Hoffmann-Wellenhof & Walse, 2007) correction through simultaneous observation value to work out the difference, i.e., relative positioning method.

ii. **Tropospheric refraction error:** Tropospheric refractive index is irrelevant to frequency or wave length of electromagnetic wave, and reduces gradually with increase of altitude; it is also closely related to atmospheric pressure, humidity, and temperature. Since atmospheric convection is intensive and changes of pressure, humidity, and temperature are complicated, it is difficult for precise modelling, and range error generally caused thereby may reach nanometer. An effective method to reduce influence of tropospheric refraction on navigation and positioning error is to estimate the propagation delay of electromagnetic wave in the troposphere. Measures commonly taken at present mainly include working out the difference through simultaneous observation to effectively reduce or even eliminate influences on delay of troposphere; (Hoffman-Wellenhof *et al.*, 2007) improving atmospheric model of troposphere through measured data nearby the monitoring station.

iii. **Multipath error:** Besides directly receiving signals sent by GNSS constellation satellite, GNSS receiver also receives GNSS constellation satellite signals bent for once or many times by buildings surrounding the receiver antenna, i.e., during actual measurement, signals received by GNSS antenna are signals superimposed by direct and reflected wave. Phase delay may exist between reflected and direct wave since the length of path passed by the two signals is different, and multipath error is thereby caused (Khojasteh *et al.,* 2016). It is difficult to establish accurate error model due to the uncertainty of reflection coefficient of reflector and the distance between it and the receiver antenna. Measures may be taken to reduce multipath error at present mainly include trying to make GNSS receiver antenna avoid object surface with large reflection coefficient; using GNSS receiver antenna with good directivity such as the choking coil antenna (Hoffmann-Wellenhof *et al.,* 2007).

2.4.2.3 Signal Reception Error

Such errors mainly include GNSS receiver measurement error, GNSS receiver clock error, antenna phase center error, etc. Among them, besides related to measurement resolution of software and hardware of GNSS receiver for constellation satellite signals, GNSS receiver measurement error is also related to installation precision of GNSS receiver antenna. GNSS receiver clock error is related to the receiver, so the clock error may be taken as an unknown parameter to estimate such error by working out the pseudo range equation; influences of such error may also be eliminated by working out the differential treatment through observation quantity. Antenna phase center error is caused by different incident angles, and equivalent range error may reach a few millimeters or even a few centimeters according to conditions of antenna performance.

2.4.3 GNSS Error Sources

GNSS User Errors are classified into the three segments of GNSS structure. The segments are space segment, control segment and the user segment. In space segment, the source of error can be satellite clock stability, satellite perturbations or selective availability (turned off in May 2001). The control segment the feasible error is ephemeris prediction and the user segment contain the major part of errors due to Ionospheric delay, Tropospheric delay, receiver noise, multi-path, indoor positioning or due to urban gorges. The following are the error sources.

i. Satellite and receiver clock errors
ii. Satellite orbit errors
iii. Atmospheric effects (ionosphere, troposphere)
iv. Multipath: signal reflected from surfaces near the receiver

v. Antenna phase centre

vi. Solar radiation pressure

vii. Satellite Geometry

viii. Relativistic Effects

ix. Receiver noise

x. Signal Obstruction

GNSS employs RINEX (Receiver Independent Exchange) format for storing and processing data.

The RINEX format consists of the followings:

- Observation Data File
- Navigation Message File
- Meteorological Data
- File GLONASS Navigation
- Message File
- Galileo Navigation Message File
- GEO Navigation Message File
- Satellite and Receiver Clock Date File
- SBAS Broadcast Data File
- Satellite Ambiguity file
- Satellite Velocity file

2.5 Continuously Operating Reference Station (CORS)

Nicholas. (2010) defined CORS as Continuously Operating Reference Station, which can take the place of a traditional base station used in differential GNSS positing. CORS can give an instant high positional accuracy of ±20 mm. CORS Network began in 1994 when NGS officially installed permanent GPS receiver in the National Institute of standards and Technology, Gaithersburg Campus, Maryland, and few months later in Colorado, which were later incorporated with three other continuously operating GPS stations that are originally part of CIGNET to become the first five stations in CORS Network. By 2000, more than 200 CORS stations are installed and incorporated into the NGS' CORS Network. By the first quarter of 2014, the CORS network increased to more than 1,900 sites, which is why it is now regarded as the primary source for geodetic survey community to access National Spatial Reference System (NSRS) data. CORS networks are now established in different countries and by different organizations due to its high geodetic data accuracy (±20 mm). The development of CORS networks are categorized into three tiers as noted by (Rizos & Satirapod, 2011). These are as follows;

i. Tier 1 stations are the stations with International Global Service (IGS) grade 1 standards
ii. Tier 2 stations as National Geodetic Network, and
iii. Tier 3 stations are networks established by private institutions, state and local agencies.

The Tier 1 stations are high accuracy stations (±20 mm) with class 1 geodetic receivers and well stabilized antenna monument capable of tracking any Regional Navigation Satellite System (RNSS) and GNSS signals (Naibbi and Ibrahim, 2014). These stations are used to define and establish global reference frame and are also used in scientific research and geodetic sciences. Similarly, the Tier 2 are also high accuracy stations, but are maintained at state and national government levels. They are also equipped with good quality geodetic receivers and their antennas are stationed on a stabilized monument. They can also track signal broadcast from GNSS and RNSS (Snay & Soler, 2008). These stations are mostly established for the purpose of national geospatial reference frame (geocentric datum). Conversely, the Tier 3 are high stations but with minimum requirements compared to tier 1 and 2 stations. The Tier 3 stations are mostly established by local government, state, private organizations and agencies for positioning purposes. They are also referred to as “fit for purpose” stations (Schwieger *et al.*, 2009). They are equipped with receivers that can track interoperable GNSS and RNSS signals. CORS stations are now established as networks that define regions at local, continental and global level due to its stability, continuity and effectiveness (Rizos & Satirapod, 2011). However, associations of scientists, geodesists and other earth observing bodies that form the first global reference frame (consisting of GNSS sites) established specifications for establishing CORS stations across the globe through the ITRF. The ITRF reference systems are made to be a standard for all geodetic and earth science fields. The main task of the ITRF is to*”* maintain the stability and to provide open access to the geometric and gravimetric reference frames as well as time series of data and products, by ensuring the generation of uninterrupted state-of-the-art global observation*”.* It should be noted that all the stations are situated in open accessible areas (see Figure 2.5) to provide security and less obstruction to the sky by tall buildings and trees, which may cause multipath errors and reduces accuracy (Naibbi & Ibrahim, 2014).

Plate I: Nigeria GNSS CORS mounted
Source: (Onoriode *et al.*, 2017).

CORS technology has been used in the oil and gas industry to establish primary (geodetic) control pillars, as-built surveys and large-scale seismic acquisition project with significant cost savings and reduced HSSE exposure. The deployment has enabled geodetic data integrity, data harmonization, reduced turnaround time, and HSSE exposure which have eased project delivery within the difficult terrain of the Niger Delta. The implementation of GPS CORS technology obviously is a game changer in survey service delivery within the oil and gas industry, and should be extended to developing Land information system speedily throughout Nigeria and cost effective, quick and accurate update of Nigeria utility infrastructure (Onoriode *et al.*, 2017).

Traditionally, most Survey activities in the Nigeria Oil industry are executed using conventional methods involving the use of Theodolites and Total stations which require extensive control pillar search and in-situ checks in often difficult terrain, with significant costs and serious Health, Safety, Security and Environment (HSSE) exposures. Also, projects executed with conventional methods are prone to coordinate inconsistences across oil fields, due to discrepancies in control origins. Hence, need to re-strategize and deploy the Continuously Operating Reference Station (CORS) Geographic Positioning System (GPS) technology to address these issues. These permanent, unmanned, automated and highly precise reference stations (standalone or networked) continuously collect and store Global Positioning System (GPS) data to provide precise spatial positioning, data harmonization that enables assured geodetic data integrity.

Generally, in order to improve positional accuracies of GPS observations to sub centimeters, a relative positioning technique is employed. Relative GPS positioning involves the collection of observables by a GPS reference station whose position is known. These data are then combined with data collected by other receivers, whose positions are to be determined. This process may be performed real-time where corrections are applied instantaneously or in a post-processed mode with relative positioning accuracy in sub-centimeter (Onoriode *et al.,* 2017).

2.5.1 Contributions of GNSS CORS to national Development.

The impact and contribution of GNSS-based geodetic reference frame to national and local development programmes cannot be overemphasized because so many problems today which became difficult to resolve, with the advent of the GNSS CORS are been solve. In recognition of this, the implementation strategy of the cross cutting spatial data infrastructure (SDI) initiative at every level has placed great emphasis on geodetic controls and frames by dedicating working groups for them. (Kufoniyi 2016).

- The United Nations Global Geospatial Information Management (UN-GGIM) initiative has a working group on Global Geodetic Reference Frame (GGRF), created in January 2014 to develop a global geodetic roadmap for the GGRF among other activities

- The African cluster of the GGIM (UN-GGIM: Africa) has African Geodetic Reference Frame (AFREF) as one of its working groups. The GGIM: Africa declaration further encourages Member States to adopt unified national geodetic reference frames that are consistent with the African Geodetic Reference Frame (AFREF) and the Global Geodetic Reference Frame (GGRF).
- The ECOWAS Geospatial Data Infrastructure (EGDI) has geodetic controls as part of the terms of reference of its working group on Geospatial Datasets.
- GNSS play the role of weather prediction in other to predict the amount of rainfall so as to enable the government plan and allocate project.
- Now-casting is weather forecasting on a very short term or near real time broadcasting of information about weather and natural disasters.

Nigeria's NGDI has geodetic control as one of the infrastructure's ten fundamental datasets and has a working group devoted to it .Mobile technologies are now playing, and will continue to play a big role in the use of geospatial information for sustainable development and daily human activities. Many of the mobile phones now come with geospatial solutions such as GNSS-based location.

The regional contribution of the GNSS CORs are however listed below

- Spatial Data Infrastructure Development
- Aerial and Satellite Mapping
- Water Resources Management
- Regional Development Initiatives

- Volunteered Geographic Information (VGI)
- Contribution to Earth Sciences
- Application in Systematic Land Tenure and Registration

2.6 Nigerian Permanent GNSS Network (NIGNET)

In recognition of geodetic network as an essential framework dataset for the implementation of Spatial Data Infrastructure (SDI) at any level, the country has included it as one of the ten fundamental datasets of Nigeria's National Geospatial Data Infrastructure (NGDI), even before the advent of AFREF. Until the year 2006 when the first continuously operating reference station was established in the Regional Centre for Training in Aerospace Surveys (RECTAS) as part of AFREF, all the survey controls in the national geodetic network were passive. As at 1997, there were 600 passive GPS controls, 550 other passive conventional geodetic controls and unspecified number of (many) lower order controls. In an effort to provide a unified national geodetic frame for surveying and mapping as well as other national and regional developmental projects, the Office of the Surveyor General of the Federation (OSGOF) commenced the establishment of the Nigerian Permanent GNSS Network (NIGNET) in 2008 and by 2011 the Office has established 11 GNSS Continuously Operating Reference Stations (CORS). By May 2013, the country already has 16 zero-order CORS comprising one established by the Regional Centre for Training in Aerospace Surveys (RECTAS) for AFREF in 2006 and 15 NIGNET stations 11 by OSGOF and three (Enemark 2013) by the Presidential Technical Committee on Land Reform) all strategically located in different parts of the country. The NIGNET stations are shown in figure 1.1 (Edozie *et al.*, 2013). Many other State Governments have established or are also planning to establish

CORS in their respective states as part of their mapping and GIS projects; these include one (1) by Lagos State Government and three (3) by the Osun State Government.

2.6.1 NIGNET (Nigerian GNSS Reference Network)

Continuous Operating Reference Stations (CORS) use the Global Positioning System (GPS) technology to provide precise spatial positioning, data harmonization, and enables geodetic data integrity assurance with real-time data streaming and management in a network mode with Leica Spider software to extend the data coverage and enables real time field crew monitoring. Usually, most survey activities in Nigeria are executed using conventional methods which require extensive control pillar search and in-situ checks in often difficult terrains with significant costs and serious health, safety, security and environment (HSSE) exposures. The survey is also prone to coordinate inconsistences between fields due to discrepancies in control origins. Hence, a compelling reason to establish CORS technology to address these issues. Leveraging the GPS technology, site were selected (see Figure 2.6), installed with GPS system and configured to acquire process and transmit differential corrections on a continuous basis to reference survey projects (Onoriode *et al.*, 2017).

Figure 2.6: Distribution of the NIGNET stations. Yellow – stations already installed (December 2009). Red – stations being installed in January/February 2010. Source: (Paolo *et al., 2020*).

2.6.2 The Nigeria geodetic datum system

Minna datum which happen to be in Niger State Nigeria, assuming to be the point of intersection between the geoid and ellipsoid therefore selected to be the reference datum station Nigeria (Minna datum (L40), but then it is not compatible with satellite derived positioning system, suggests that the new geocentric datum (CORS networks) should be adopted. This need prompted the Office of the Surveyor General of Nigeria (OSGOF) to initiate the NIGNET project in 2008 that derive the establishment of the 11 CORS stations in various locations in the country. These stations are coordinated by nine international

Global Navigational Satellite System (GNSS) and IGS that are part of the International Terrestrial Reference Frame (ITRF2008). However, since the establishment of the 11 CORS stations in the country covering only 25% of the country, no attempt has been made to upgrade and extend their coverage. Conversely, developed countries with more CORS stations focuses on both improving the integrity of their CORS stations as well as improving the distribution and density of the spatial coverage of these stations. Such countries include Australia with about 250 CORS stations at regular intervals of between 50km to100km, United States of America with over 1,350 stations (as of 2008) at an average spacing of 70km between stations, and United Kingdom with about 110 stations at an average spacing of 60km. Naturally, the availability and spatial coverage of the stations increases the number of IGS stations globally to strengthen the ITRF. Overall, geospatial applications are better with higher spatial coverage (density of the stations), because higher density provides good reception coverage for positioning results, prediction and monitoring of natural disasters. In 2007, prior to the establishment of CORS by OSGOF, the GPS team of OSGOF obtained the WGS 84 values of L40 (Nigerian Datum) by repeated GPS measurements using differential positioning techniques on the station (L40). A mean of means was obtained from the measurements and the value was used for adjusting a nationwide surveying campaign that commenced from Minna in Niger state, Nigeria. By the end of 2007, the Regional Centre for Training in Aerospace Surveys. RECTAS established the first permanent reference station (CORS) in Ile Ife, Ibadan, Nigeria, which consist of a receiver, an antenna, operating software, site server software for quality control and data analysis. This was done in line with the African Reference Frame’s (AFREF) project initiative (Naibbi and Ibrahim, 2014).

The 11 CORS networks in the country are linked with ITRF2008 by acquiring GPS data from nine International GNSS Service stations (IGS). NIGNET, which is a tier 1 station, was set up with up-to-date geodetic equipment. The data from these stations are processed at the central station located in Abuja where it is corrected, computed and provided to the users. The optimization of efficiency is a priority to the system and their location, which are mostly positioned on concrete rooftops for security reasons and signal obstruction. The objectives of creating the 11 CORS stations by the OSGOF is to cover the country with a relatively homogenous distribution of CORS stations in order to increase the spatial coverage of the networks and to provide an up to date networks that are compatible with

GNSS, GIS and ITRF based datum. Overall, the existing 11 CORS stations in Nigeria (with an average spacing distance of over 300km apart) seems inadequate given the size of the country (about 923,768km^2) as compared with the less than 100km spacing (based on the NGS's requirements) adopted in the USA and United Kingdom (Naibbi and Ibrahim, 2014). Therefore, increasing the number of the CORS network in Nigeria as suggested in various studies will improve the signal multipath issues, site issues, and signal environment issues experienced in the country. Also, sufficient and well-defined networks of geocentric datum (CORS) will provide among others; direct compatibility with GNSS measurements, mapping and GIS. It will also promote and optimize the use and application of spatial data through single user friendly data environment, thereby increasing efficiency in spatial data resource by reducing duplication and unnecessary translation (Naibbi and Ibrahim, 2014).

Table 2.2: The IGS stations used to establish NIGNET stations (Isioye *et al.*, 2015).

Station ID	**Station location**	**Country**	**Ellipsoidal height**
HARB	Pretoria	Republic of south Africa	1555.000
NKLG	Libreville	Gabon	31.4800
RABT	Rabat	Morocco	90.1000
RBAY	Richard bay	South Africa	31.7927
SUTH	Sutherland	South Africa	1799.7659
CAGZ	Capoterra	Italy	238.000
MAS1	Maspalomas	Spain	197.3000
NOT1	Noto	Italy	126.2000
SFER	Sanfernando	Spain	85.8000

The literature over Nigeria with emphasis on application of GNSS for Metrology in Nigeria. Were sourced from web-based archives such as Google scholar, web of science, IEEE-Xplore, Google. However, considering the fact that GNSS infrastructure became available in Nigeria from 2009, related literature from 2010 to 2019 in the region of Africa. The summary of this literature is given in Table 2.3.

Table 2.3: List of Publications on GNSS-Based Water vapour Estimation and related determinants in Africa Between 2010 to 2019

S/N	Author(s)	Paper Title	Technique Used	Focus Area	Country/ Year	remark
1	A.A.Acheampong, C. Fosu, L. K. Amekudzi, and E. Kaas (2015)	Comparison of precipitable water over Ghana using GPS signals and reanalysis products	radio occultation technique	delayed signals due to tropospheric and stratospheric effects was used retrieved atmospheric Integrated Water Vapour (IWV)	Ghana/2015	retrieved atmospheric Integrated Water Vapour (IWV)
2	Acheampong, A. A., Fosu, C., Amekudzi, L. K., Kaas, E. (2017)	Precipitable Water Comparisons Over Ghana using PPP Techniques and	PPP Techniques	highly precise tool for water vapor sensing based	Ghana/2017	the study results indicate that with a more densified network of GNSS base stations the retrieved PW or IWV will greatly improve numerical weather predictions in Ghana
3	Joseph D. DODO, Tahir, A. YAKUBU, Lazarus	Determination of the best-fit Tropospheric Delay Model on the	Saastamoinen model	Determination of the best-fit	Nigeria/2013	The longer the baseline; the more the effect of the troposphere. The refined Saastamoine

	M. OJIGI, and Samuel TSEBEJE. Nigeria (2013)	Nigerian Permanent GNSS Network (NigNet)				n model gives a better result
4	Dodo Joseph Danasabe, Ojigi Lazarus Mustapha , Tsebeje Samuel Yabayanze (2017)	Determination of the best-fit Tropospheric Delay Model on the Nigerian Permanent GNSS Network	The Refined Saastamoinen Model	Determination of the best-fit for Nigeria CORS	Nigeria/2017	This result is in agreement with. The longer the baseline, the more the effects of the troposphere. And Niell model gave a better result. .
5	Isioye A.O., Combrick L., Botai J. O., (2015)	Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria	PWV estimates from the different techniques	Precipitate water vapour	Nigeria/2015	The agreement between the various techniques was better at monthly and seasonal scales. In terms of bias, precision,
6	Ayodele, E.G, Okolie, C.J., and Mayaki, O.A. (2018)	An assessment of the reliability of the Nigerian GNSS	Mahalanobis distance method of outlier detection and filtering	Displacement associated with the NIGNET CORS to understand reliability.	Nigeria/2018	88% of the network showed a high level of positional accuracy

		network data				
7	R. T. Wonnacott (2015)	The use of gps for the estimation of precipitable Water vapour for weather forecasting and Monitoring in south Africa	double differencing technique	estimation of PWV using GPS and meteorological data	South Africa/2015	South African network of permanent GPS base stations, TrigNet, is suitable for the operational estimation of PWV supersede all
8	Houaria NAMAOUI, Salem KAHLOUCHE, Ahmed Hafid BELBACHIR, Roeland Van MALDEREN, Hugues BRENOT, and Eric POTTIAUX (2017)	GPSWater Vapor and Its Comparison with Radiosonde and ERA-Interim Data in Algeria	Remote sensing	analyze the sensitivity of the GPS PW estimates	Algeria/2017	A good agreement is found between GPS-PW and PW calculated from radiosonde

In this study, about 31 publications were reviewed only 4 papers were for Nigeria and 8 for Africa on integrated water vapour and most of these papers did not focus on GNSS Based integrated water vapour (IWV) over Nigeria NIGNET CORS Table 2. 1 show the summary of literature carried out in Africa considering the fact that the estimation of integrated water vapour can make serious impact in monitoring flood over Nigeria but the amount of researches been carried out in Nigeria is not enough to give information for the control of flood in Nigeria. From table 2 which shows the number of publications across countries in Africa between 2010 - 2019, in this paper is been observed that 4 publications were for Nigeria, 1 publication was for South Africa, 1 publication was for Algeria, and 2 publications were for Ghana. A total publication for integrated water vapour (IWV) in Africa for papers reviewed were 8 and 4 were for Nigeria and out of this 4 papers only one by (Isioye *et al* 2015) who emphasis on Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria, these means that little effort have been put in, on integrated water vapour in Africa figure 2 shows a Graph showing numbers of publication in Africa and figure 2.3 shows pie chart showing the percentage of researches carried out in Africa.

Table 2.3: The summary of the number of publications done in some countries in Africa

S/N	Country	Number of research	Percentage of research %
1	Nigeria	4	50%
2	South Africa	1	12.5%
3	Algeria	1	12.5%
4	Ghana	2	25%
		8	100

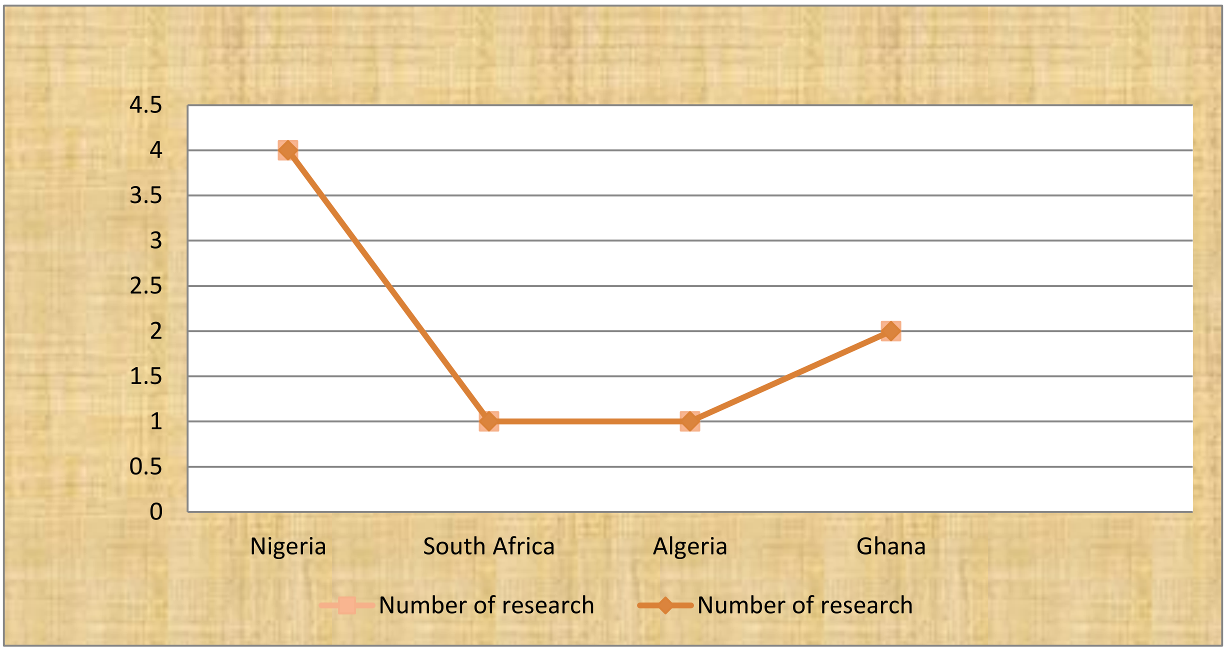


Figure 2.7: Graph showing number publications on GNSS water vapour per country in Africa

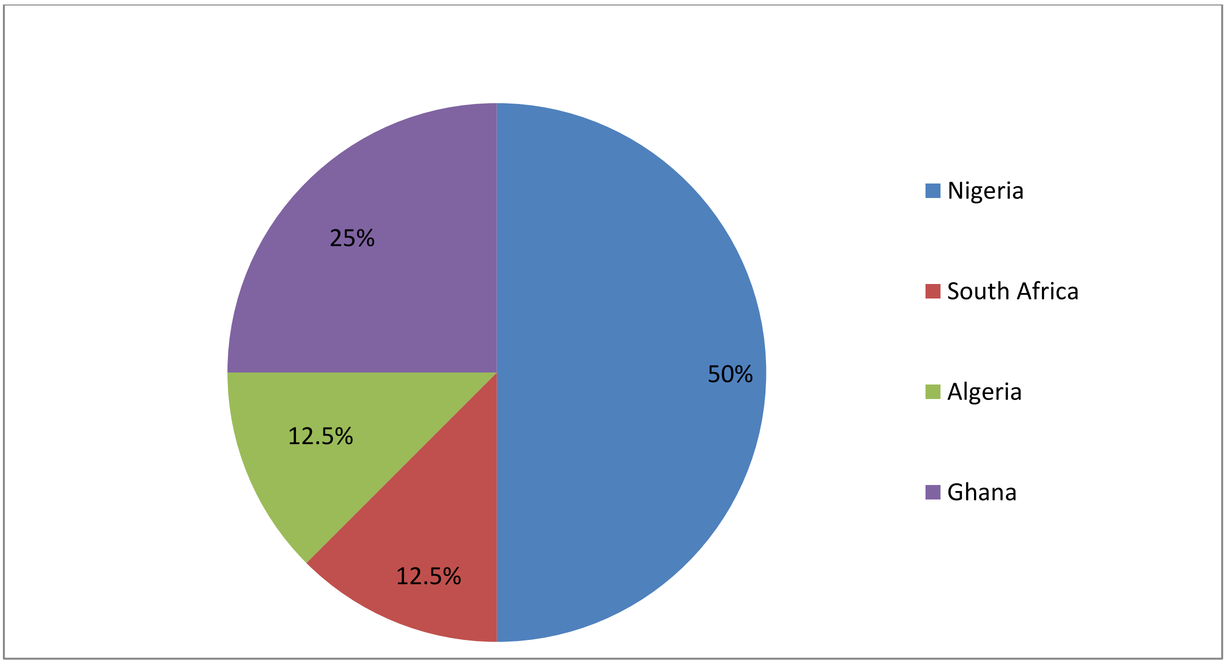


Figure 2.8: Pie chart showing percentage publications on GNSS water vapour per country in Africa.

In conclusion, GNSS-based water vapour estimation in Nigeria has been reviewed and it was discovered that little effort has been made in GNSS-based estimation of integrated water vapour (IWV) in Nigeria. The review revealed that it is difficult to estimate IWV using classical meteorological system and that there exist a relationship between atmospheric water vapour and prediction events.

However, GNSS-based method is to support aviation and weather but not the most efficient way, because GNSS receiver/antenna are for isolated points/vertical integrated water vapour and lacks spatial and temporal coverage that are possible with hyper spectral infrared and microwave satellite remote sensing. The Global meteorological /atmospheric precipitation/rain estimation are from specialized meteorological satellites; GOEs / NOAA, METEOSAT / CRYOSAT / MODIS (Behrangi *et al.*, 2014).

Thus, improving the knowledge of water vapour dynamics would be beneficial for weather monitoring and prediction in Nigeria. Therefore more researches are needed to be carried out in Nigerian on integrated water vapour using GNSS infrastructure (NIGNET CORS) which will enhance climate studies and weather outlook in Nigeria.

CHAPTER THREE

3.0 METHODOLOGY

This section presents the materials and methods employed in the process of this research. The methodology is classified into three major phases, thus: data acquisition, data processing and analysis of results. Figure 3.1 summarizes the phases of the methodology and procedures employed.

3.1 Flowchart and work planning

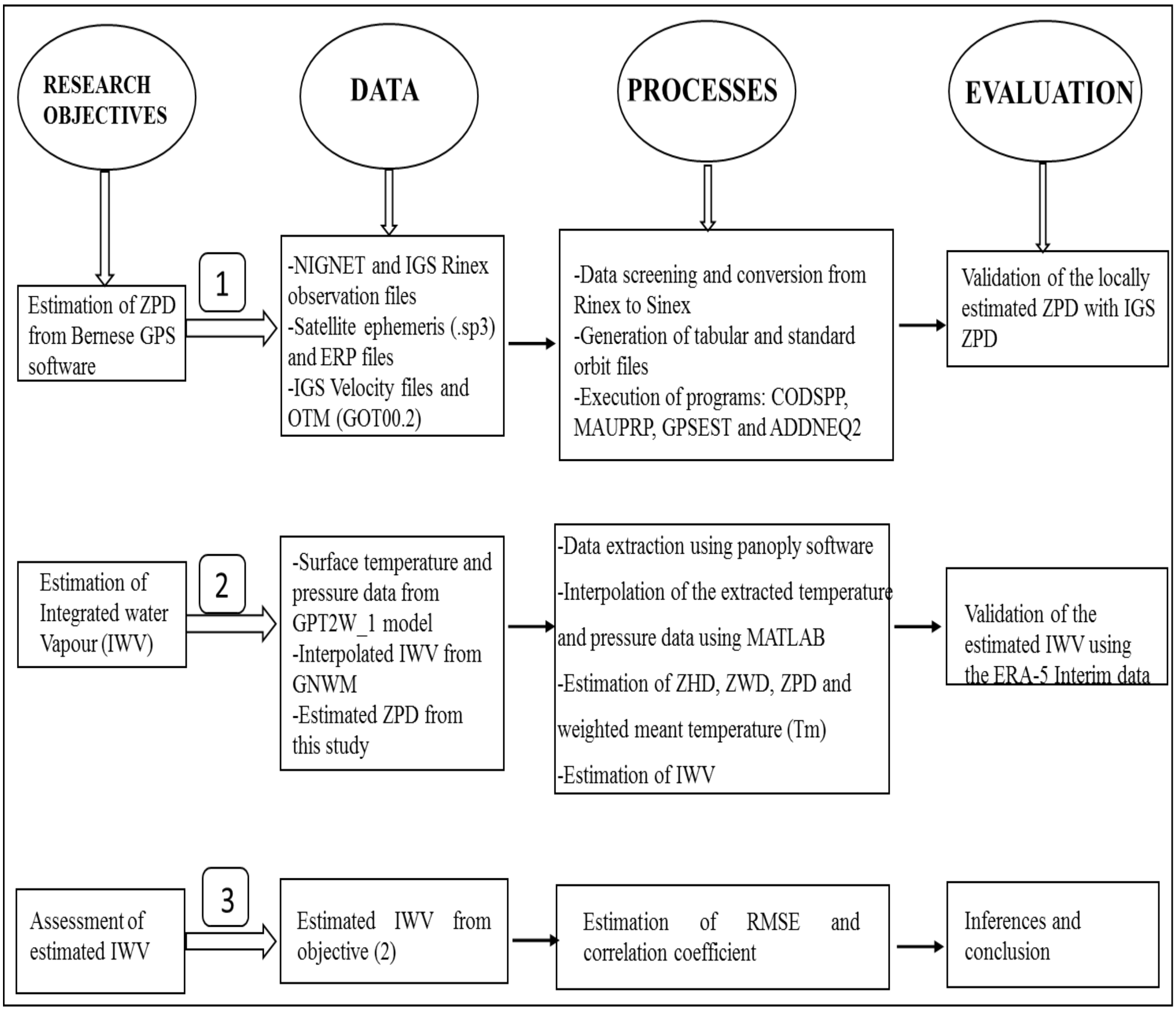


Figure 3.1: The adopted methodology for the study

The methodology adopted for this research is predominantly established on the opportunity offered by the expanded application of GNSS in meteorology. The study specifically looked into assessment of integrated water vapor (IWV) otherwise called total column water vapour through the GPS data over Nigerian geodetic stations. The Rinex observation data of these GPS (COR) stations were acquired and processed for the estimation of the Zenith Path Delay (ZPD) also called the Zenith Total Delay (ZTD) using Bernese GPS software package, version 5.0. In order to achieve a reliable result of this study, a year span data of 2011 Rinex observation was utilized. Apart from the CORS data, other data acquired for the processing are; the ephemerides data, the earth rotation parameters, the IGS station files, the IGS station velocity file, the ocean loading file and the IGS clock files.

The processing strategy, options, models and functions applied in the data processing are discussed in detail in subsequent sections. In order to estimate the IWV, the Nigerian COR stations were found not co-located with the weather stations i.e. with radiosondes otherwise meteorological sensors which measure or retrieve the weather parameters such as the temperature, pressure, relative humidity, vapour pressure, and the dew point for climatic studies and weather prediction. It was due to this challenge of non-availability of radiosonde data that the study resolved into using the Global Pressure Temperature wet (GPT2w_1) model which was built upon the climatological parameters from ERA-Interim model at a resolution of 1^0 by 1^0 latitude and longitude. The procedure for obtaining the mean weighted temperature, Zenith Hydrostatic Delay, the Zenith Wet Delay and the IWV were discussed in the second phase of the study and finally, the obtained result of IWV was validated using ECMWF numerical weather model data because of its high resolution. The phases and sub-phases or methods are as summarized and presented in figure 3.1 above.

3.2 Estimation of Zenith Path Delay from Bernese GPS Software V.5.0

Zenith path delay is an atmospheric phenomenon specifically, the troposphere that caused a delay in the arrival of navigational signals in positioning as a result of thickened layer of the troposphere. The delay effect is estimable by using a set of models and mapping functions to correct for the effect among which are saastamonien, Hopfield, marini-mur, Niell tropospheric models. The estimation of the ZPD involves three phases as stated in the previous section. They are discussed as follow:

3.2.1 Data acquisition

3.2.1.1 GPS Rinex observation files

In determining the ZPD values over the Nigerian COR (GPS) stations, the Rinex observations files of nine NIGNET stations were accessed through the NIGNET proprietary website at www.nignet.gov, but unfortunately, the site was found non-functional at the time of this study, this necessitated the utilization of the available archived data of the year 2011. It was unfortunate that none of the stations was coupled with a weather sensor such as thermometer and barometer for retrieval of temperature and pressure values.

IGS CORS are global network of geodetic stations established for the realization of the international terrestrial reference frames. These stations are of highest order of accuracy required in any geodetic positioning. Though, as at year 2011, none of such stations was established in Nigeria, therefore, a need for IGS stations around Africa for the corresponding year arose and five of the stations around African plate were adopted based on their proximity in consideration of the baseline lengths with a range of 90km for an accurate processing. Table 3.1 presents the five adopted IGS stations and their geographical locations thus:

Table 3.1: List of IGS stations used for the study.

S/N	IGS CORS ID	Geographical Locations
1	ADIS _31502M001	Ethiopia, Africa
2	BJCO_32701M001	Benin Republic
3	NOT1_12717M004	Italy
4	RABT_35001M002	Morocco
5	YKRO_32601M001	Coted’ivoire

Figure 3.2 shows the current distribution of IGS CORS around Africa. It is worth stating that after 2011, the station CGGT was included in the IGS CORS and became the only IGS station in Nigeria.

The observation files of the stations were downloaded using Rtklib software as it provides a means for multiple download and automatic conversion of the data from the compact Rinex format to the standard Rinex format.

Figure 3.2: The distribution of IGS CORS around Africa (IGS proprietary website)

Other data used are final orbit data (.sp3), Earth rotation parameter (ERP), and receiver code bias (DCB) which was all sourced online from Centre for Orbit Determination in Europe (CODE). Ocean loading parameter (.BLQ) was also obtained from Onsala Space Observatory website as discussed in the subsequent section.

3.2.1.2 Ocean loading parameters

Crustal deformation is a significant station displacement effect induced by the varying mass distribution resulted from marine tides (ocean tidal loading). The coefficients or magnitude of the ocean loading impact (amplitude and phase shift for the eleven most important constituents) were substituted at appropriate phase of data processing (i.e. programs GPSEST, GPSSIM, and CLKEST). However, the use of the file is not mandatory, its use is only encouraged, and otherwise vertical and horizontal displacement may not be corrected.

The ocean loading parameters of the CORS were computed by the ocean tide loading provider and sent to the submitted email (survddan4real@gmail.com). The mailed ocean loading parameters are then copied and saved in a notepad environment for subsequent data processing. For this research, Goddard Ocean Tide Model (GOT00.2) was adopted.

3.2.1.3 Satellite Ephemerides

The ephemerids files contain information about the status and health of satellite, and stability of the orbits. This file was used in correcting for any anomaly in the orbit and other external effects encountered by the satellites, in order to obtain accurate positioning information from the signals received. Orbit, station and satellite clock products are found in the standard product directories at the IGS proprietary website.

3.2.1.4 Earth Rotation Parameter (ERP)

Earth orientation parameters (EOP) are collection of parameters that describe irregularities in the rotation of the Earth. The effects are addressed in the processing software by using the IGS estimated corrections.

3.2.1.5 Preliminary velocity files

This file was used to estimate and compensate for the shift /displacement of the IGS stations in it becomes a strong necessity to supply the initial coordinates of stations, it is equally important to supply initial velocity information to the processing software (Bernese) which is also an input parameter in the processing phase. There are several agencies around the world that provides this information and among them are; the Scripps Orbit and Permanent Array Center (SOPAC), International GNSS Service (IGS), National Aeronautic and Space Administration (NASA) etc. The velocity files of the selected IGS stations data under consideration were downloaded with respect to the ITRF 2008 from the SOPAC website at http://www.sopac.com.

3.2.1.6 Satellite clock synchronization files

Satellite clock corrections are necessary in order to synchronize between the satellite clock and receiver clocks. The synchronization is performed in the data preprocessing step using program CODSPP.

3.3 Data Processing

The data processing procedures are discussed under data preparation, data preprocessing and final processing.

3.3.1 Data Preparation

This phase include the process of data filtering and conversion. After downloading the Rinex data, both the local and global data were combined and campaign was created for the processing on a monthly basis, altogether, a number of 14 stations per campaign. Each campaign was screened and filtered for any anomaly, incompletion or cycle slip, as reflected by the data file size. After the data treatment, campaign was created for the processing in the Bernese software, where station information was updated and coordinated a priori coordinate was generated with which the a priori velocity of the IGS stations were obtained from the SOPAC based on the ITRF 2008 as the proximal realization. The a priori coordinates was also used in the acquisition of the ocean loading correction (GOT00.2) which accounts for the site displacement as a result of crustal deformation due to ocean tide loading. The loading correction coefficient at each station was computed by the Onsala Space Observatory (online ocean tide loading provider) using green function. Goddard

Ocean Tide Model was adopted on the basis of the study by Abbas *et al*. (2019) on optimal choice of ocean tide model for processing GNSS data over Nigeria, where the model, GOT00.2 was reported with best performance over Nigeria. The phases of the processing are summarized in Figures 3.3, 3.4 and 3.5 respectively.

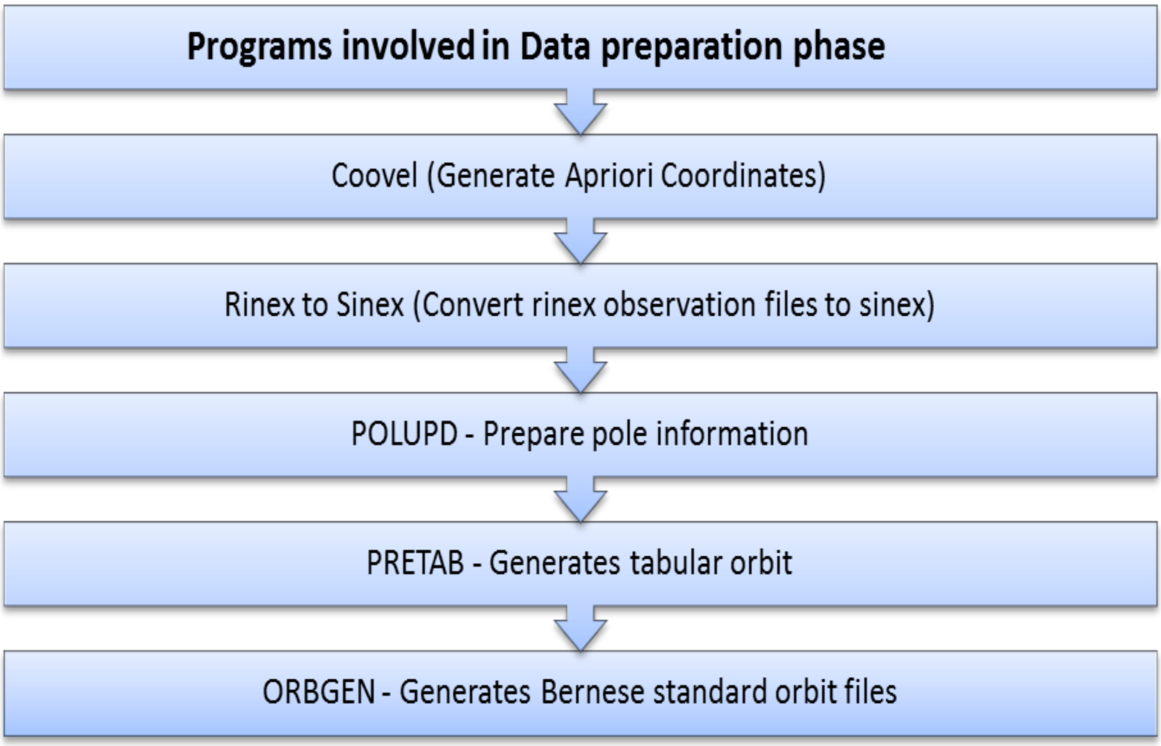


Figure 3.3: The procedures in data preparation

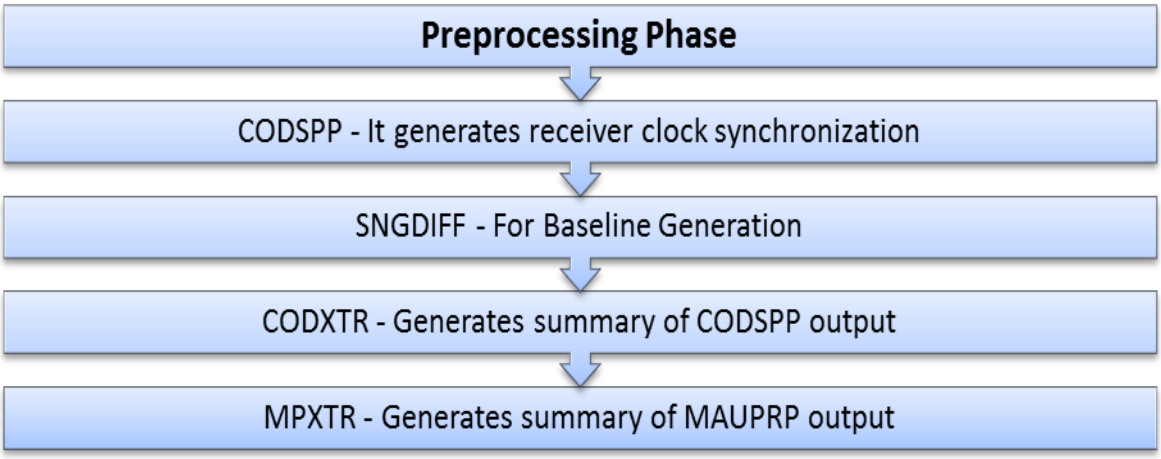


Figure 3.4: The procedures involved in data pre-processing.

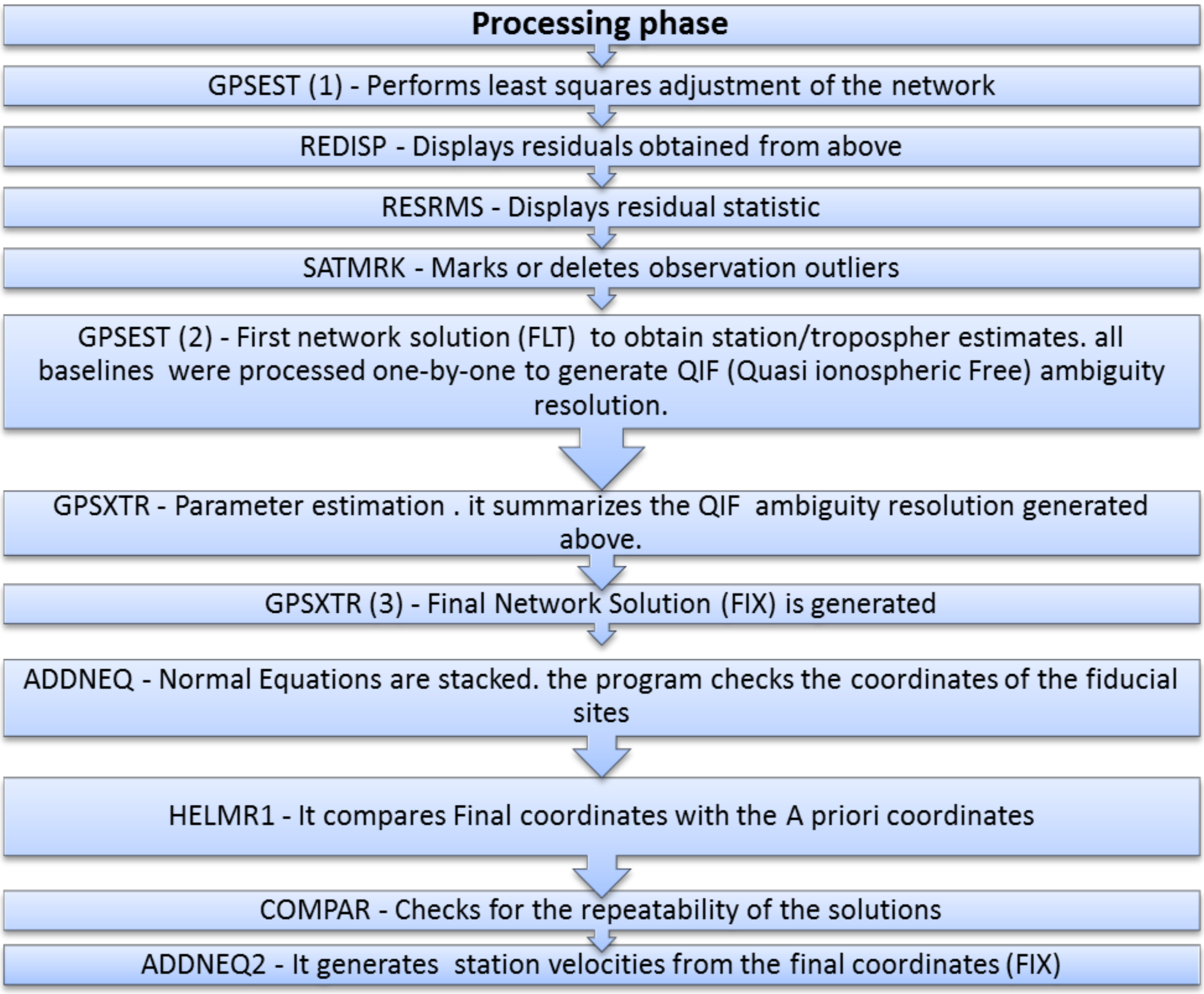


Figure 3.5: The data processing steps

3.3.2 Method of ZPD estimation

Using the foregoing procedures for data processing using Bernese 5.0 version, the NIGNET CORS data was processed. Option "Site-specific troposphere parameters" in panel "GPSEST 5.1: Setup of Parameters and PreElimination1" of the software was set to activate the estimation of the ZPD parameters. In panel "GPSEST 6.3.1: Site-Specific-Troposphere Parameters 1" selection was made of an appropriate mapping function, a priori tropospheric model and desired time resolution equivalent to the option "Parameter spacing" which in case of this study are: Niell mapping function, Saastamonien a priori model and 30-180 seconds respectively. The processing strategy employed, models, options and parameters adopted are summarized in Table 3.2

Table 3.2: The processing strategy adopted (Opaluwa *et al.*, 2017).

Parameters	**Processing Strategy**
Network design	OBS-MAX
Measurement type	Phase
Elevation cut-off angle	3^0
Weighting of GPS observations	$Cos^2(z)$; z = zenith angle.
Sampling rate	30-180s.
A priori sigma	0.01 meters
Orbits/EOP	IGS final Orbit and Earth Orientation parameters (EOP).
Station coordinates	Minimally constrained to the ITRF2008 reference frame.
Cycle slip screening mode	Combined L1 & L2 frequency
Outlier rejection	Enabled
Absolute antenna phase center Corrections	PHAS COD.I08, SATELLIT.I08.
Ocean loading model	Goddard Ocean Tides model (GOT00.2)
Ionosphere	Double-difference ionospheric-free (IF) linear combination.
Ionosphere model for ambiguity fixing	Global ionosphere model from CODE.
Gradient estimation	Horizontal gradient parameters: tilting at 24hrs interval.
A-priori model	A-priori Saastamoinen hydrostatic model with dry Neill mapping function.
Mapping function	Wet-Neill mapping function (1hr interval).
IGS Ref. Frame	ITRF 2008
Relative troposphere constraints	Loose.
ZPD estimates rate	Hourly (1hr).

The input data as mentioned earlier were plugged in to their respective directories and processing options set, and the BPE was run for the estimation. Thus, the station-specific tropospheric delay alongside their standard deviations as well as station coordinates was generated.

3.3.3 Validation of estimated ZPD

The estimated ZPD was assessed by comparing the most probable values of the daily estimate of ZPD for the IGS stations provided at every 5 minutes by IGS Analysis Centres (ACs) to their corresponding estimates from this study. Since ZPD estimated from a local campaign are strongly correlated, the IGS stations were processed together with the local stations to decorrelate the correlated ZPD (Opaluwa, *et al.,* 2017). The trend obtained in the validation of the IGS estimated ZPD was used to characterize the ZPD for the local stations in the absence of the external data source to compare them with and the stations were not equipped as well with meteorological sensors for retrieval of atmospheric data. The statistics of the comparison was computed i.e. the mean, minimum, maximum values of ZPD estimated, the Root Mean Square (RMS) and standard deviations are presented in chapter four.

3.4 Estimation of Integrated Water Vapour

In order to estimate the IWV which is the cardinal focus of this study, the pressure and temperature data were sourced from ECMWF global atmospheric Global Pressure Temperature 2 wet (GPT2w_1) model by Bohm *et al.* (2015). The model has a horizontal resolution of 1^0 in latitude and longitude over the globe which enhances valid interpolation of positions on the earth surface and accurate access to surface meteorological data of the location. The model assimilates its climatological parameters from monthly mean pressure level data of ERA – Interim which makes the model suitable to calculate slant hydrostatic and wet delays down to 3^0 elevation at any location on the earth surface. Validity of this model was examined by Opaluwa *et al.* (2017) and it was found that the model is reliable for sourcing surface meteorological data. The GPT2w_1 model unlike some other empirical weather model takes interested sites' geodetic latitude, longitude and ellipsoidal height as well as the day of the year as the input parameters. MATLAB codes were developed to implement the model for generation of surface meteorological data over the nine Nigerian continuously operating reference stations considered in this study. The date of the year has to be defined in a Julian mean date system as one of the constants input for the model and the geodetic latitude and longitude in radians. The model output are the coefficient of the wet mapping function, water vapour decrease factor and geoid undulation in addition to pressure and temperature which are the main output required in the further process of estimation of IWV.

The hourly estimated ZPD for the stations ABUZ, BKFP, CGGT, FUTY, MDGR, OSGF, RUST, ULAG and UNEC from the local data processing for the whole year as validated in the above section is a key parameter in the estimation of IWV though, data inconsistency of some of the stations posed a serious challenge to the program developed in the estimation of IWV.

Due to the volume of the data involved, a MATLAB code was developed implementing equations 1, 3, 6, and18 which respectively yield Zenith Total Delay (ZTD), Zenith Wet Delay (ZWD), Weighted Mean temperature (Tm) parameter and Integrated Water Vapour (IWV). Since this study focuses on estimation of IWV over the GNSS CORS over Nigeria. The estimated IWV were validated, analyzed and inferences made and discussed in the next chapter.

3.4.1 Evaluation of the estimated IWV

In order to accomplish the objective three of the study that is, validation of the estimated precipitable water vapour, a Global Numerical Weather Prediction Model (GNWPM) was adopted from the ECMWF reanalysis center. Climate re-analyses combine past observations with models to generate consistent time series of multiple climate variables.

Re-analyses are among the most-used datasets in the geophysical sciences. They provide a comprehensive description of the observed climate as it has evolved during recent decades, on 3D grids at sub-daily intervals. ERA5 data are available in the Climate Data Store on regular latitude-longitude grids at 0.25° x 0.25° resolution, with atmospheric parameters on 37 pressure levels.

The collection of earth orientation parameters is fitted to describe the observed rotation irregularities. Technically, they provide the rotational transform from the International Terrestrial Reference System (ITRS) to the International Celestial Reference System (ICRS), or vice versa, as a function of time.

The RMS misfit was computed on a daily basis for the estimated IWV. In ech case, the time series misfit was analysed based on the RMS of the ZPD values hence, the RMS was then computed as.

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{\left(x_{(i)} - y_{(i)}\right)^2}{n}} \qquad 19$$

where, $x_{(i)}$and $y_{(i)}$ are respectively, the hourly and mean IWV values, while n is the number of observations.

CHAPTER FOUR

4.0 RESULTS AND ANALYSIS

The results from this study include the ZPD and IWV estimates. These results are presented and discussed in this chapter.

4.1 Estimation and Assessment of GPS ZPD

The summary of the estimated ZPD is as shown in Table 4.1

Table 4.1: Summary of the estimated ZPD

STATIONS	***AVERAGE (m)***	***MIN (m)***	***MAX (m)***	***STDDEV (m)***
ABUZ	2310.239327	2181.104	2485.092	1.943175132
BKFP	2442.103158	2297.516	2650.216	2.073376238
CGGT	2251.168197	2129.924	2399.856	2.004981804
FUTY	2468.207491	2299.741	2651.268	2.101234933
MDGR	2432.694501	2271.576	2600.788	2.322702543
OSGF	2422.951122	2251.412	2538.736	2.05873861
RUST	2625.734182	2429.032	2725.38	1.88267607
ULAG	2603.830806	2408.168	2731.104	2.028874886
UNEC	2527.656282	2314.612	2649.772	1.952264213

The results of the estimated ZPD as shown in Table 4.1 indicated the least ZPD value (2129.924m) was obtained at station CGGT in the Northern part of Nigeria while, the highest ZPD value of 2731.104m was observed at station ULAG in the Southern part of Nigeria. This is justified by the proximity of these two regions to the equator. The southern region lies more proximal to the equatorial belt than the Northern regions which usually experience high humidity and as such, high ZPD values are expected.

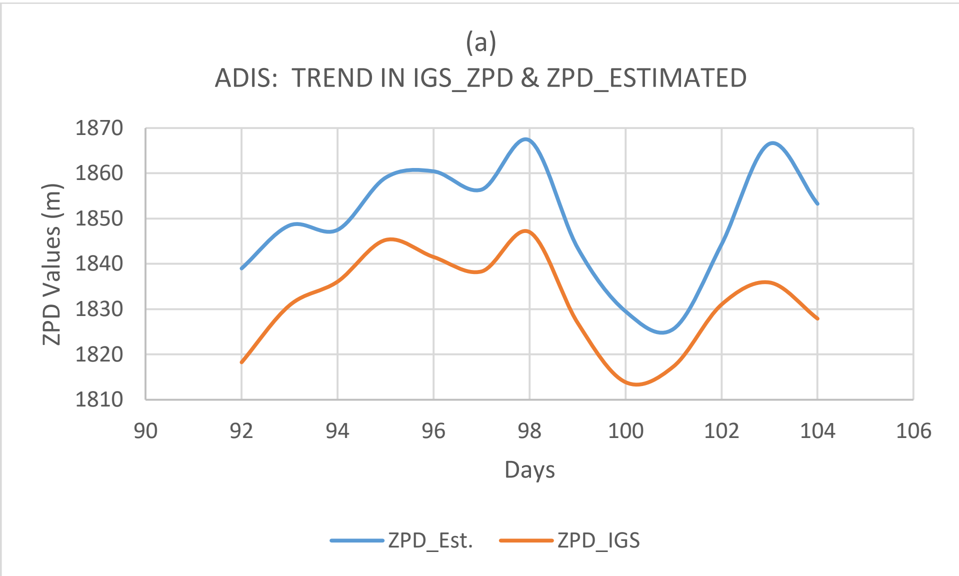
4.1.1 Validation of Estimated ZPD

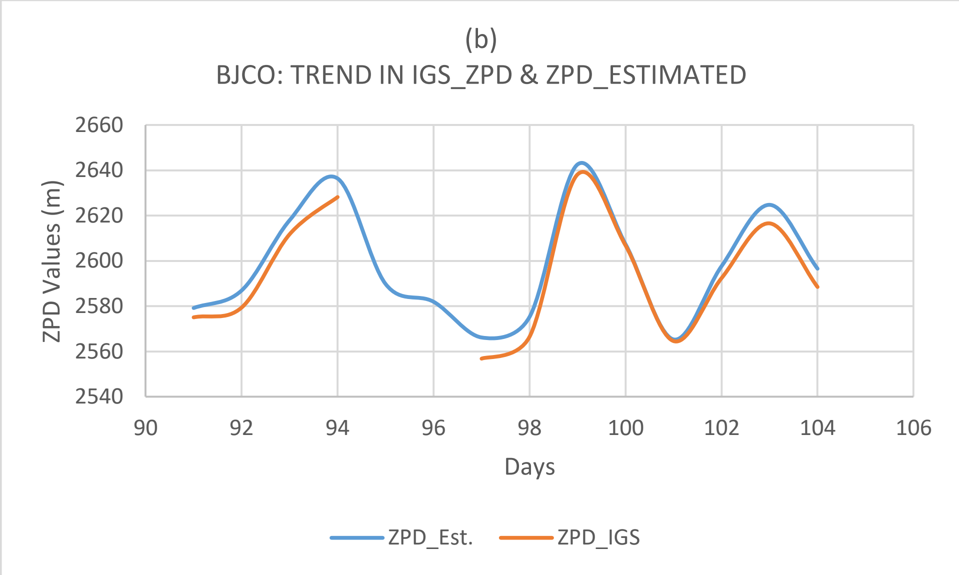
In order to validate the estimated ZPD over the local CORS, the estimated ZPD for the IGS CORS were compared to their corresponding values as archived by IGS analysis centers, hence, the comparative analysis. The summary of the comparative statistics is shown in Table 4.2.

Table 4.2: Summary of statistics of estimated ZPD

Stations	Mean diff. ($ZPD_{est} - ZPD_{IGS}$)	Min. Diff.	Max. Diff.
ADIS	17.7385	5.951236	37.0853
BJCO	5.951236	0.559167	9.355167
RABT	37.0853	32.738	43.688

Figure 4.1 depict a graphical representation of the trend or pattern of the estimated ZPD and IGS ZPD (ZPD_Est. and ZPD_IGS) for the year 2011.





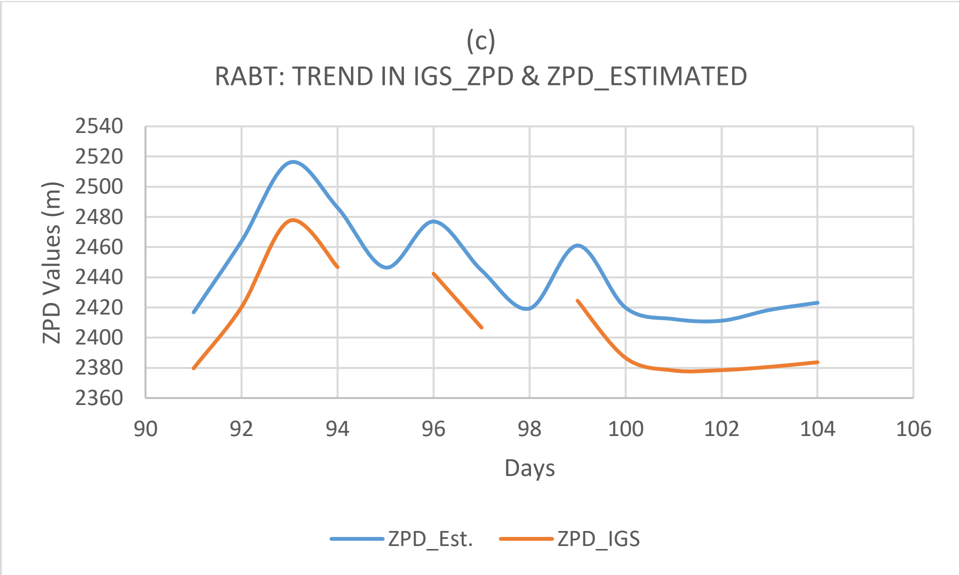


Figure 4.1: The trend of ZPD_Est. and ZPD_IGS for the year 2011.

The comparison was conducted as presented in Figure 4.1 (a), (b), (c) respectively and a perfect correspondence was observed. It was also observed that the length of the baseline is a function of accuracy in the estimation. The shorter the baseline length the higher the accuracy and vice-versa. Station BJCO was found with least mean difference of 5.951236m , followed by station ADIS with mean difference of 17.7385m and lastly station RABT with the highest mean difference of 37.0853m. This result is in agreement with study by Wickert *et al.* (2014) that ZPD values are spatially correlated.

The result of the assessment gave room to the acceptability of the estimated ZPD for further processes in this study. Nevertheless, some of the weaker correlation (larger discrepancy) could be attributed to difference in elevation angle utilized as the study used elevation angle of 3^0 while the IGS analysis center uses elevation of 7^0 and the length of the baseline from each station.

This comparative analysis was found impossible for the NIGNET CORSs Since there were no meteorological sensors attached to the stations as at 2011. But the IGS stations included in the data processing were at a minimal baseline length. The minimum and maximum baseline length considered were 1000km and 9000km respectively to compensate for differential tropospheric effect. It was observed that station BJCO with an average baseline length of 698km show the least difference in comparison with IGS ZPD product. Subsequently, station ADIS with an average mean greater than that of BJCO and lastly station RABT with largest difference. Generally, a direct proportionality exists between the difference and the baseline length and more so, it is shown schematically in figure 4.1 that the locally estimated ZPD follows a similar pattern as the IGS estimated ZPD.

Conclusively, the results show a consistent and significantly common trend in the estimated ZPD with the IGS estimated ZPD. It was observed that the Bernese based estimated ZPD are larger than the IGS estimated which is a function of the elevation angles difference (i.e. 3^0 and 7^0 respectively). So the trend obtained for the comparison analysis of the IGS stations was adopted for local NIGNET COR stations.

4.2 Assessment of Integrated water vapour (IWV)

The summary of the estimated IWV are presented in Table 4.3. The minimum, maximum and mean IWV are presented for January, the other months are contained in the appendix.

Table 4.3: Estimated IWV for January, 2011

STATIONS	MEAN (kg/m^2)	MIN (kg/m^2)	MAX (kg/m^2)
ABUZ	10.70474271	7.1639515	19.20694
BKFP	11.88173553	8.4959035	17.59606
CGGT	10.33193417	7.1360949	17.73192
FUTY	29.60908944	17.114794	42.95044
ULAG	37.89081	25.45482	52.56353
UNEC	27.78556	17.77152	45.29188

As discussed in chapter 3, the ZWD recovered from the ZPD were used to estimate the IWV and the trend over each NIGNET CORS for the year 2011 as shown in Figure 4.2.

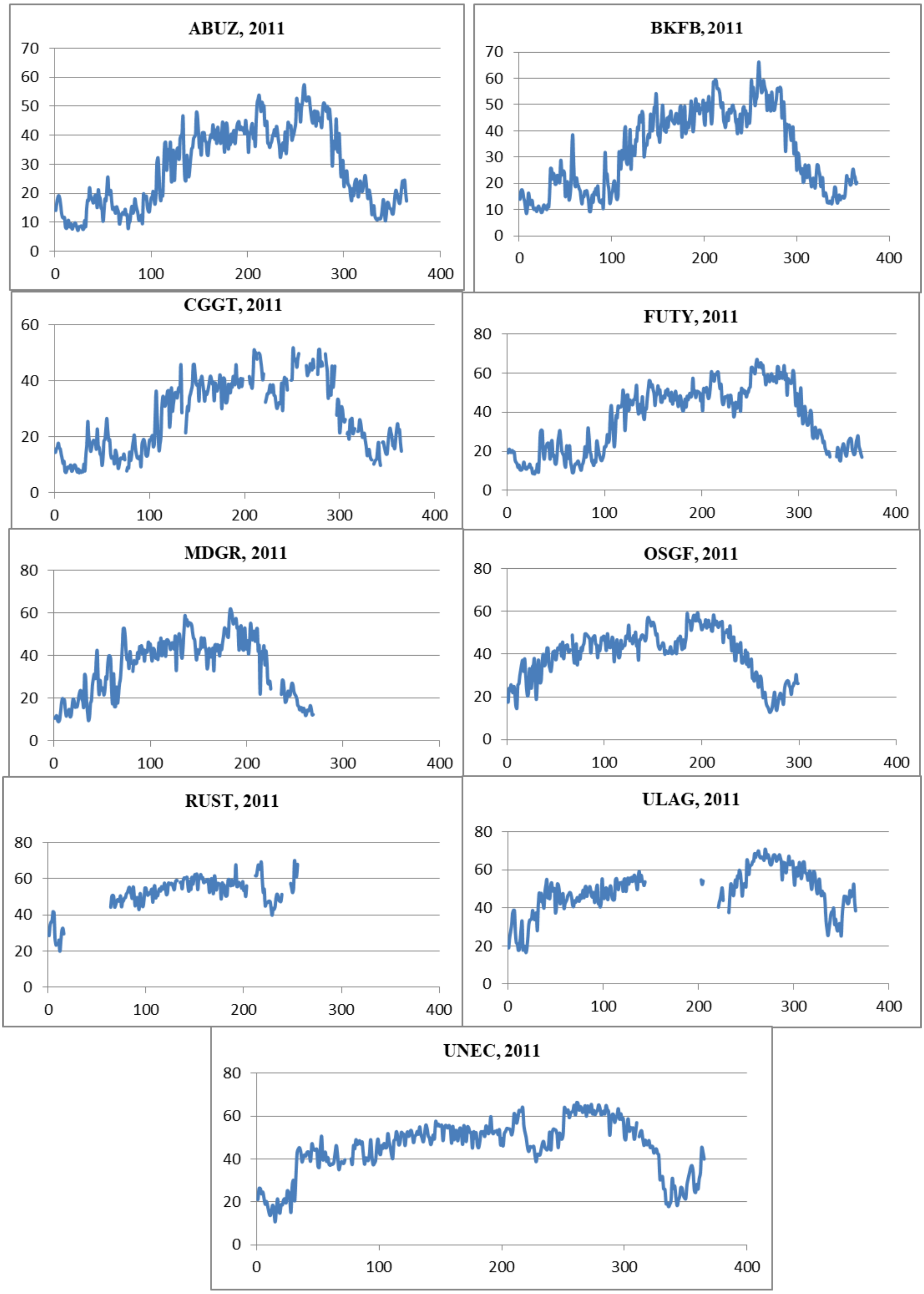
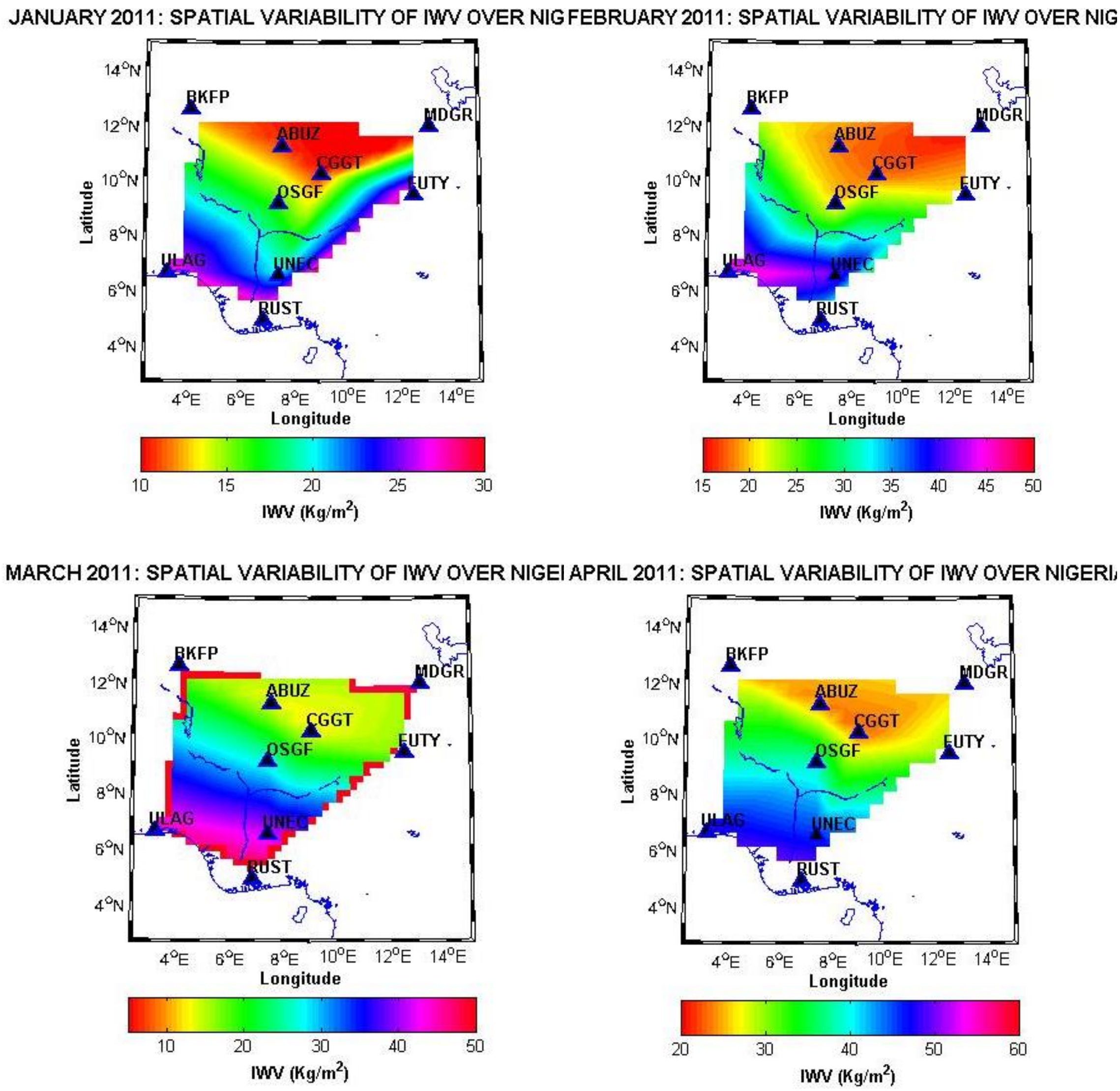
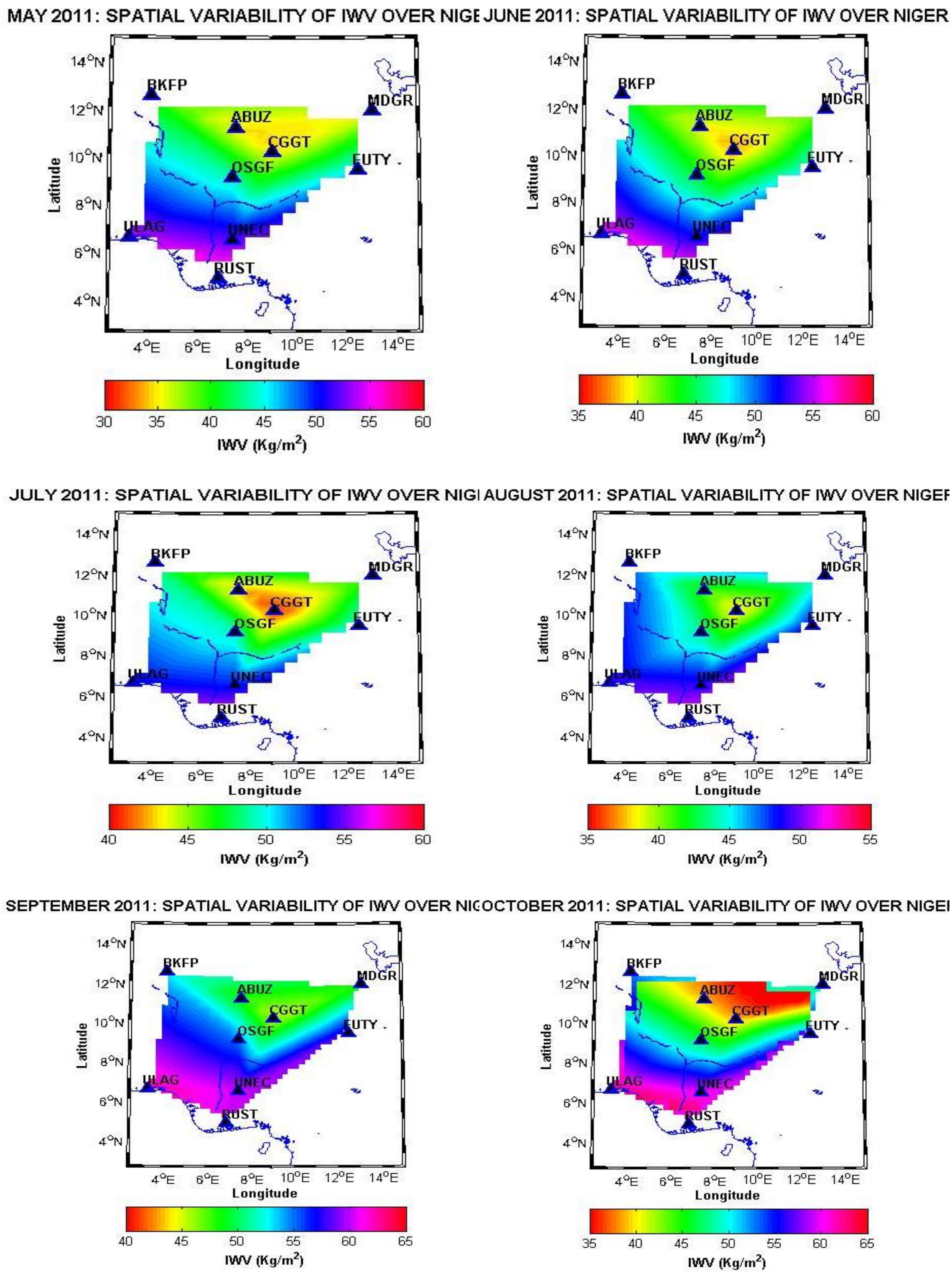


Figure 4.2: IWV mean daily estimates over NIGNET CORS from DOY 001 to 365 in 2011.

The time-series IWV trend as generated from the mean daily IWV estimates was considered all through the year for the IWV time series plot, showing its temporal dynamics. This is evident in Figure 4.2 as low IWV value were noticed for the first and the last three months of the year which represent dry season over Nigeria. In order to further appreciate the spatial characteristics of the GPS IWV estimate, IWV map over Nigeria were generated from the mean daily estimates as shown in Figure 4.3.




MAY 2011: SPATIAL VARIABILITY OF IWV OVER NIGE
JUNE 2011: SPATIAL VARIABILITY OF IWV OVER NIGER
JULY 2011: SPATIAL VARIABILITY OF IWV OVER NIG
AUGUST 2011: SPATIAL VARIABILITY OF IWV OVER NIGEF
SEPTEMBER 2011: SPATIAL VARIABILITY OF IWV OVER NI
OCTOBER 2011: SPATIAL VARIABILITY OF IWV OVER NIGEI
BKFP
ABUZ
MDGR
CGGT
OSGF
EUTY
ULAG
UNEC
RUST
Latitude
Longitude
4°N 6°N 8°N 10°N 12°N 14°N
4°E 6°E 8°E 10°E 12°E 14°E
IWV (Kg/m2)
30 35 40 45 50 55 60
35 40 45 50 55 60
40 45 50 55 60
35 40 45 50 55
40 45 50 55 60 65
35 40 45 50 55 60 65

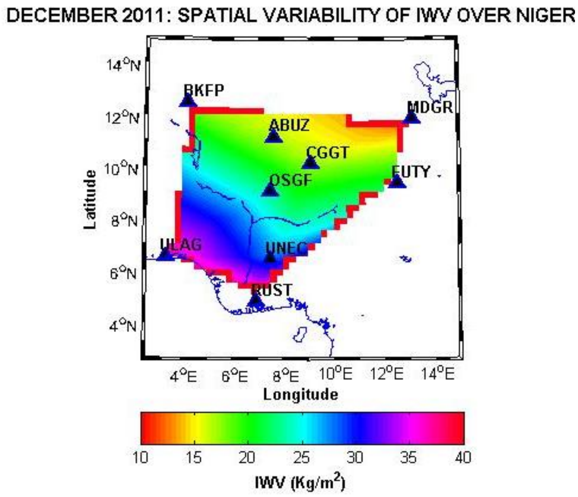


Figure 4.3: Spatio-temporal map of IWV distribution over NIGNET CORS in 2011

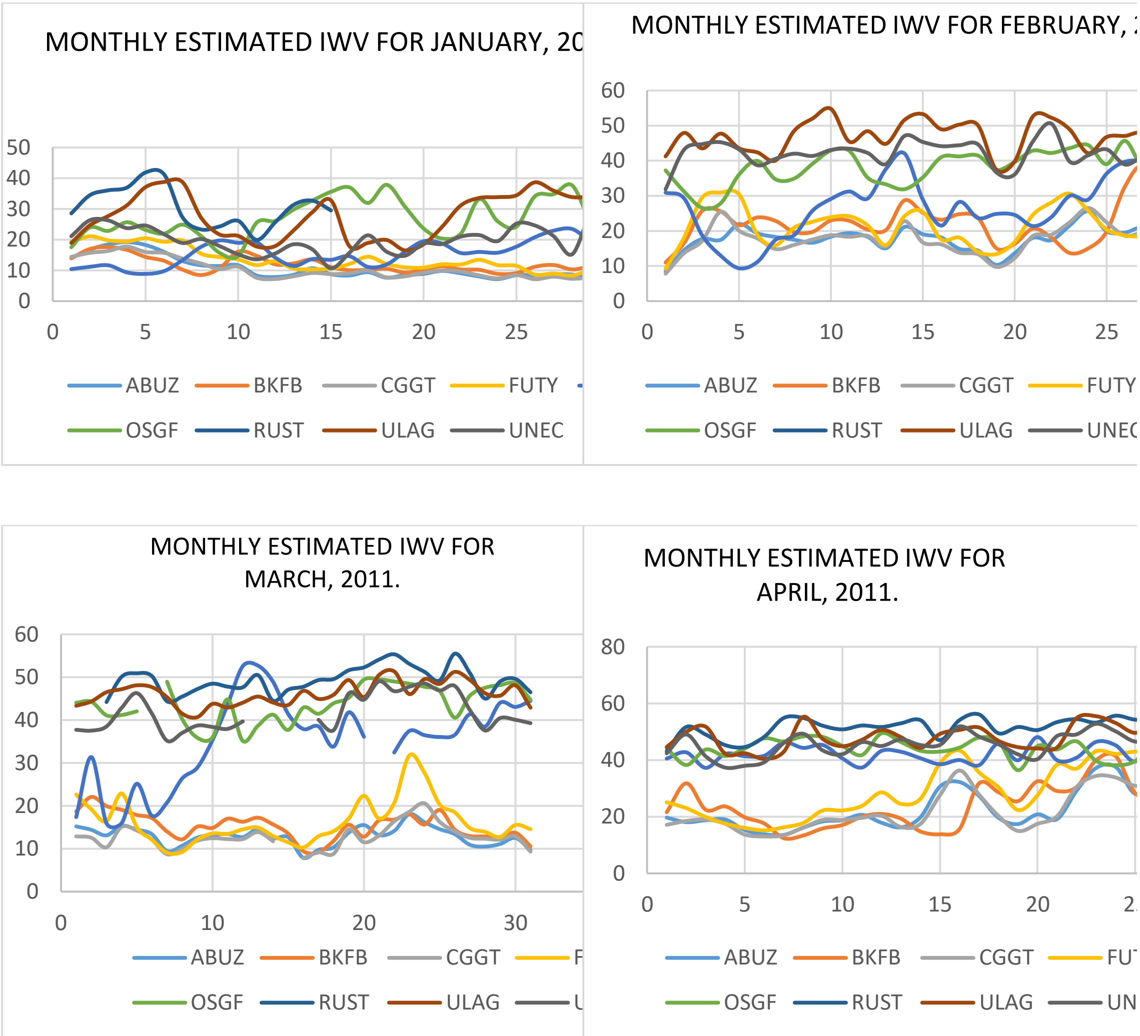
4.2 Analysis of Estimated IWV

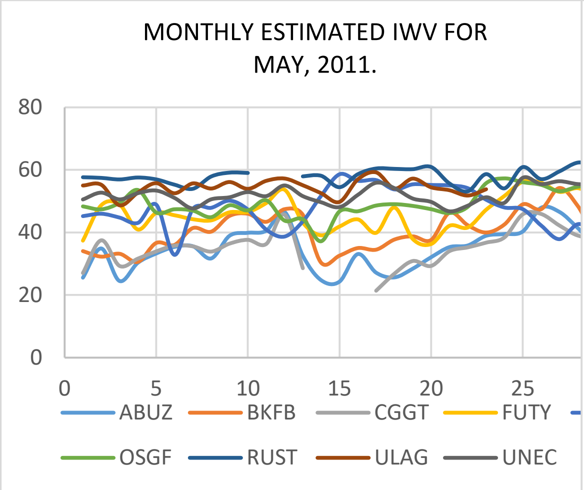
The analysis of the results from this study was performed under two considerations, these are: the spatial and seasonal analyses.

4.2.1 Spatial analysis:

A consistent high value of IWV values around locations of stations: RUST in Port Harcourt and ULAG in Lagos shows that the climate in those regions is ever damp (monsoon) and could be so due to their proximity to the equator i.e. low latitude regions. On the other hand, stations BKFP, CGGT, MDGR and ABUZ possess drastically low IWV value which as a consequence, low rainfall is expected in those locations as they are proximal to Sahara desert and the dry wind and high temperature consequentially dry up the water in the atmosphere, resulting in low IWV estimates.

The stations BKFP, CGGT and MDGR constitute the northern stations. This is justified by the fact that they possess the least IWV values. Averagely, the mean annual IWV estimates are: ABUZ: 31.83719416 Kg/m2, FUTY: 40.26014 Kg/m2, BKFP: 35.84606838, UNEC: 48.77747 Kg/m2, MDGR: 38.05527, OSGF: 43.16578, RUST: 55.36414, ULAG: 52.68024, FUTY: 40.26014 Kg/m2 respectively. A significant rise in the IWV values indicate the shift in climatic condition of stations OSGF, FUTY and ABUZ, as they were found in the middle belt region with a lower temperature and higher IWV. And lastly, the highest magnitude of IWV was observed in the southern region which is characterized with cool climate over the region. Figure 4.4 summarized the results with the IWV values on the ordinate and the days of the month on the abscissa.




MONTHLY ESTIMATED IWV FOR MAY, 2011.
0
20
40
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80
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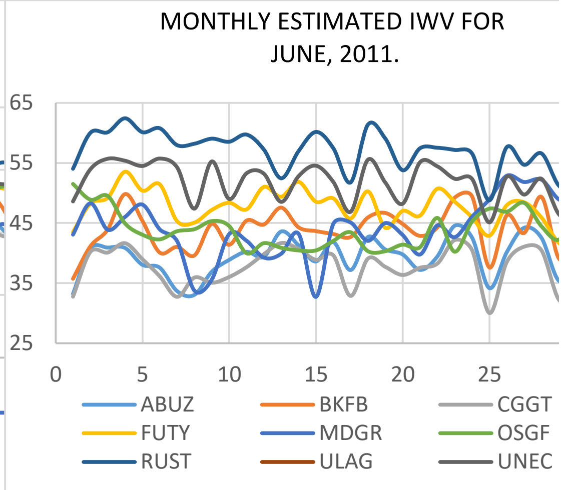
5
10
15
20
25
ABUZ
BKFB
CGGT
FUTY
OSGF
RUST
ULAG
UNEC


MONTHLY ESTIMATED IWV FOR JUNE, 2011.
25
35
45
55
65
0
5
10
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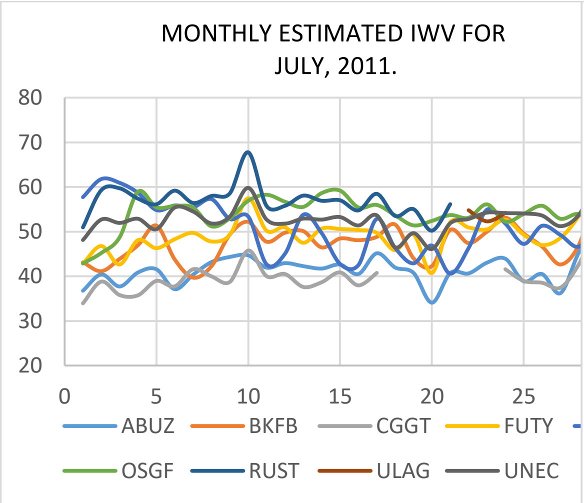
20
25
ABUZ
BKFB
CGGT
FUTY
MDGR
OSGF
RUST
ULAG
UNEC


MONTHLY ESTIMATED IWV FOR JULY, 2011.
20
30
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50
60
70
80
0
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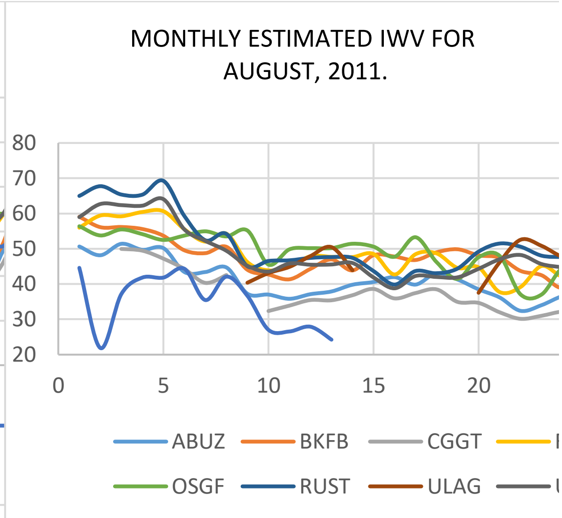
10
15
20
25
ABUZ
BKFB
CGGT
FUTY
OSGF
RUST
ULAG
UNEC


MONTHLY ESTIMATED IWV FOR AUGUST, 2011.
20
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70
80
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5
10
15
20
ABUZ
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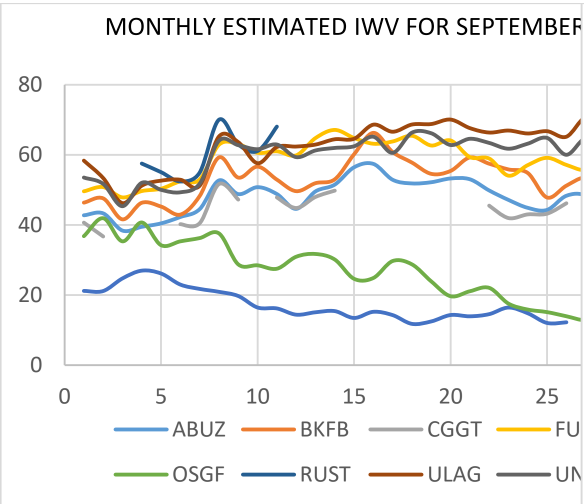
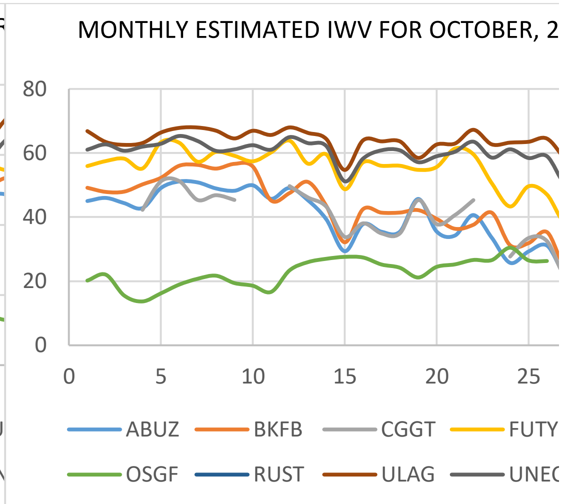
CGGT
OSGF
RUST
ULAG


MONTHLY ESTIMATED IWV FOR SEPTEMBER
0
20
40
60
80
0
5
10
15
20
25
ABUZ
BKFB
CGGT
OSGF
RUST
ULAG


MONTHLY ESTIMATED IWV FOR OCTOBER, 2
0
20
40
60
80
0
5
10
15
20
25
ABUZ
BKFB
CGGT
FUTY
OSGF
RUST
ULAG

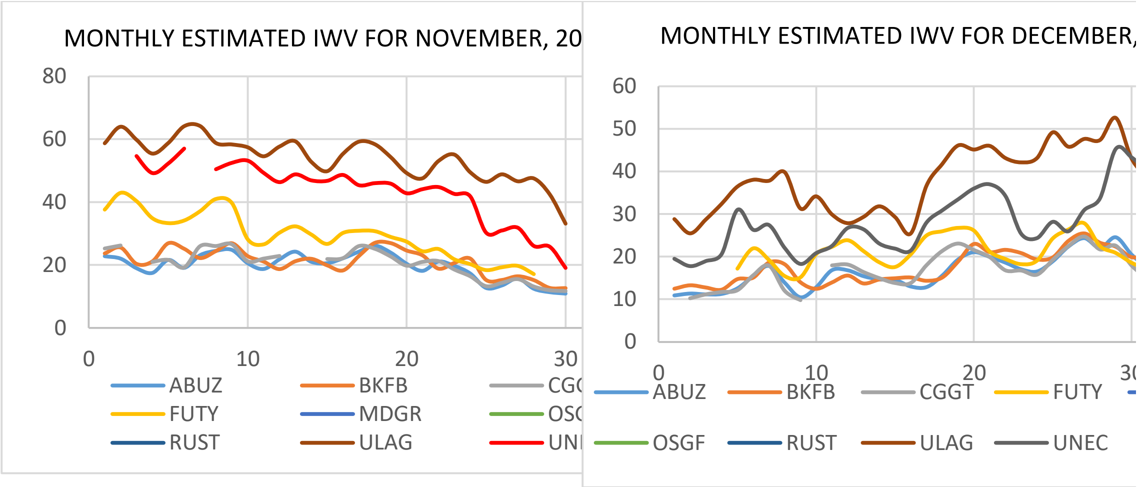


Figure 4.4: Spatial estimated IWV from January to December 2011.

4.2.2 Seasonal analysis

This section examined the seasonal behavior of the integrated water vapour (IWV). The IWV for the 12 months of the year were examined. It was found that for all the stations, there are consistently low IWV estimates during the first and the last three months of the year (Figure 4.2). Those periods of the year represent the dry season over Nigeria. On the other hand, a relatively high IWV estimates were noticed from April to October which represents the rainy season. This results pattern suggests that the atmosphere usually hold high vapour during the rainy than the dry season because of the frontal effect that usually precedes every rainfall. However, it can also be seen from Figure 4.2 that stations ULAG and RUST generally present some level of inconsistency in the pattern of the IWV time series due to the presence of monsoon system occasioned by their close-equatorial location.

4.2.3 Validation of the estimated IWV

In order to validate and assess the estimated IWV, the IWV from ECMWF re-analysis data was generated and compared to the IWV estimated from GPS data. The estimated GPS-based IWV were compared with the IWV obtained from the ECMWF re-analysis and the RMS were computed using equation 20. The summary of statistics for the mean monthly estimates for January and February are shown in Table 4.4. See appendix B for the other months.

Table 4.4: Summary of statistics of the mean monthly IWV estimates.

Station	Mean Diff. (kg/m^2)	RMS (kg/m^2)
	JANUARY	
ABUZ	5.396144	1.062605
BKFP	0.204126	0.337104
CGGT	8.168365	1.467082
FUTY	2.830501	1.137948
RUST	18.76307	3.369947
ULAG	-18.4986	3.322451
UNEC	-6.82578	1.255759
	FEBRUARY	
ABUZ	2.042842	5.8969
BKFP	1.506261	0.828227
CGGT	23.12556	4.370321
FUTY	28.45987	5.37841
ULAG	31.12826	5.882687
UNEC	20.33608	3.843157

The mean differences range from 10.3319kg/m^2 at station CGGT to 18.76307kg/m^2 at station RUST with corresponding RMS at a range of 0.337 kg/m^2 and 3.369947kg/m^2 which will translate to a minimal error (less than 4Kg/m^2) in IWV estimates (Musa *et al.*, 2011).

The GPS-based IWV estimates were compared to the ECMWF-based IWV, the results are as shown in Figure 4.5.

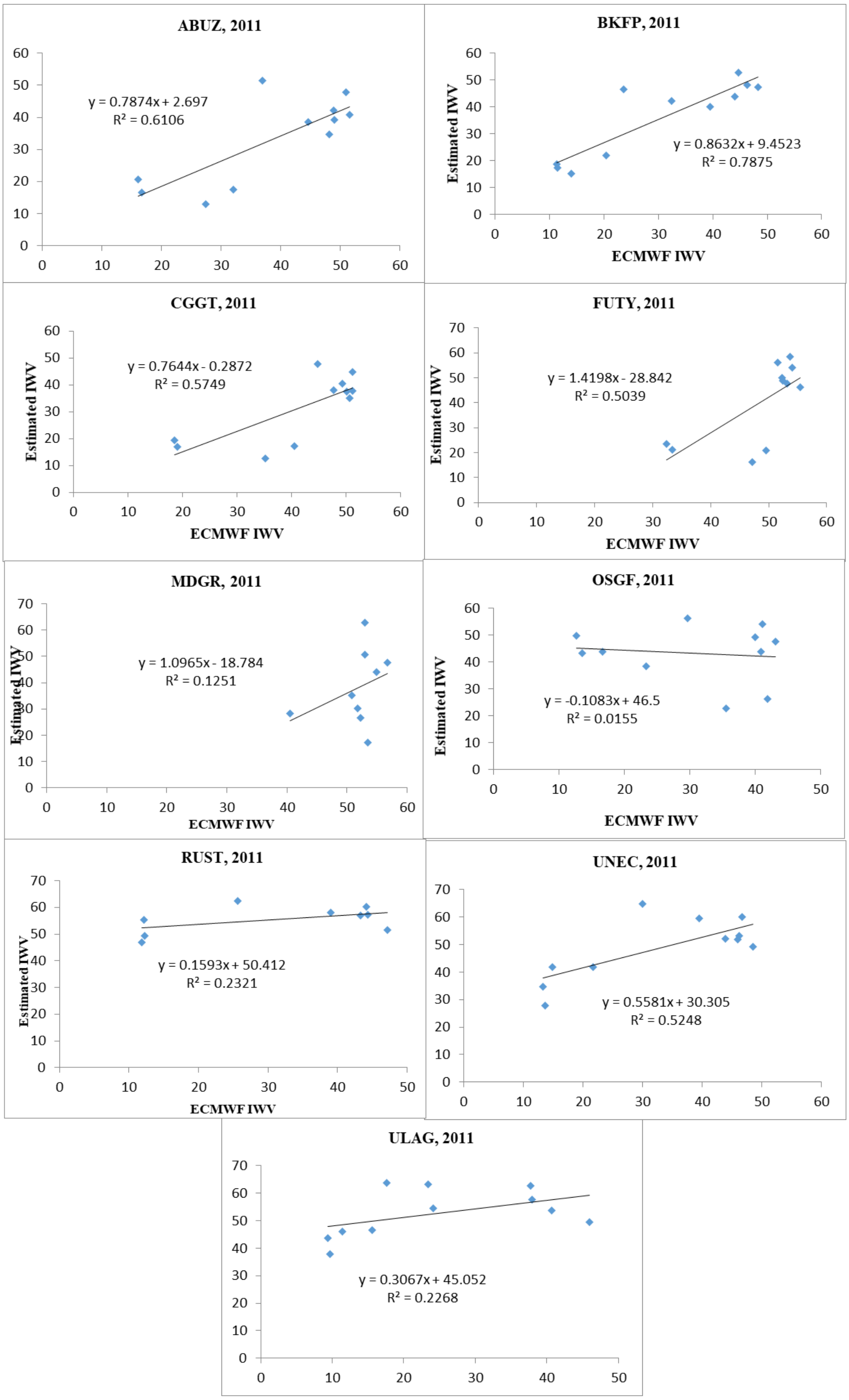


Figure 4.5: IWV scatterplot showing the correlation between GPS and ECMWF IWV Estimates.

From Figure 4.5, the R^2 (i.e. correlation coefficients) are respectively; *ABUZ: 0.6106, BKFP: 0.7875, CGGT: 0.5749, FUTY: 0.5039, MDGR: 0.1251, OSGF: 0.0199, RUST: 0.2931, ULAG: 0.2268, UNEC: 0.5248.* It was observed that stations ABUZ, BKFP, CGGT, and FUTY located in the Northern regions are having a relatively strong correlations except for MDGR and OSGF that show weak correlation. This could be attributed to the fact that the two stations have inconsistent data over the year and specifically no data for January, February and March. Similarly, stations RUST and ULAG in the Southern region present level of data inconsistency. Generally, an averagely correlation of 60% level was realized.

The mean monthly estimates of IWV from ECMWF and GPS at each station were generated and plotted as depicted in figure 4.6.

Figure 4.6: The mean monthly IWV estimates for the year 2011 from ECMWF and GPS showing the correlation pattern at each GPS station.

It can be seen from Figure 4.7 that the estimated IWV from the two concepts showed similar pattern at all the station except for OSGF, MDGR and RUST. This is found to be consistent with the correlation coefficient values as earlier shown in Figure 4.5.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

This research was executed in several phases to address three specific objectives stated in the previous section of the thesis.

The first objective i.e. estimation of Zenith Path Delay was achieved by processing GNSS data over NIGNET CORS using Bernese GPS software version 5.0. The Saastamonien ZPD model and Neil mapping function were adopted for estimation of the ZPD. The ZPD estimates as shown in table 4.1 indicated that Northern part of Nigeria experiences less delay along the zenith with the least ZPD value (2129.924m) at station CGGT (Toro, Bauchi State) while, the highest ZPD value of 2731.104m was observed at station ULAG (Lagos State) in the Southern part of Nigeria.

The ZPD obtained was validated by correlating the locally estimated ZPD values with the IGS archived ZPDs over the IGS stations adopted as fix stations (ADIS, BJCO, and RABT) in this study. The mean daily differences were computed as well as the RMSEs. The average difference obtained for the stations ADIS, BJCO and RABT are respectively; 17.7385m, 5.951236m, and 37.0853m. A perfectly similar pattern was noticed between the estimated ZPD and the IGS ZPD with an average correlation of 0.7.

It was realized that the ZPD is strongly a function of location. Station BJCO has the least baseline length 685km consequentially yield strongest correlation coefficient of 0.9596 while station RABT on the other hand has longer baseline length yielded low correlation coefficient of 0.45.

The second objective which is the estimation of IWV adopted the estimated ZPD coupled with the surface temperature and pressure obtained from GPT2w_model.

Furthermore, Spatial and seasonal variation of IWV value over the NIGNET CORS was performed and it was found that the highest IWV values were obtained over the southern stations just as the rainy season presents the period of high IWV values over all stations. The estimated IWV was validated with IWV generated from ECMWF ERA-5 interim data and it shows a considerable correlation with the estimated NIGNET IWV, the average correlation of 0.6 was obtained. It was deduced from the study that GPS-based IWV properly captured the IWV trend over Nigeria.

The estimated GPS-based IWV was validated with ECMWF ERA-5 Interim IWV, the RMSE obtained over the NIGNET stations ABUZ, BKFP, CGGT, FUTY, RUST, ULAG, and UNEC are respectively: 1.062604816 kg/m^2, 0.33710427kg/m^2, 1.467081633kg/m^2, 1.137948323 kg/m^2, 3.369947301kg/m^2, 3.322451441kg/m^2, and 1.255758948 kg/m^2.

5.1 Conclusion

In conclusion, this study has been able to assess a year span IWV over NIGNET using GNSS approach. The study has concluded on the following:

i. ZPD is a key input parameter in the estimation of IWV and as such it ought to be estimated as accurate as possible using an adequate validation strategy.

ii. Also, the most reliable data for validation of the estimated IWV are the meteorological data (surface temperature and pressure) observed by a sensor collocated with the CORS. This study used an ERA 5 hourly data as a proxy.

iii. The variation in IWV estimated was found to be dependent on location, baseline length and time as presented in section 4.1.

iv. This study found also that the atmospheric dynamics (variation of vapour in the atmosphere) are much affected (delayed) in the rainy season or much humid or cloudy weather than the dry season as evidenced by the seasonal analysis conducted in this study.

5.1.1 Problem encountered

Estimation of IWV as established in this study is a pure application of GNSS to meteorology, and due to the dichotomy in the nature and form of data used by the both practitioners, the challenge of data accessibility;

Data used by meteorological agencies is a large data format which requires a substantial computer memory for processing. In this vein, an hourly temperature and pressure data could not be accessed from ECMWF due to high system requirements which was not available to the researcher as at time of this study. Consequentially, a blind model GPT2w_1 model which is based on numerical modelling was adopted for retrieval of pressure and temperature data not the ECMWF nor a direct surface measurement.

Another major challenge in the study that influence the analysis is the gap in the GPS Rinex observation data stem from inconsistency of data over some stations. As a result of the gaps, it became mandate to be tracing the data epoch by epoch for coincidence in the estimated results and the standard values (IGS_ZPD and ECMWF data) adopted for validation.

NIGNET CORSs are not collocated with weather sensors which would have been the most accurate weather data based on measurement for validation of this study.

5.1.2 Contribution to Knowledge

The following are the contribution to knowledge

i. The IWV assessment was done for Nigeria NIGNET station for the the year 2011
ii. The IWV estimation depended on the location and help to know the value of estimate in the raining season and the dry season
iii. ERA 5 Eterim was us to validate the estimated IWV

iv. Regions closer to the tropical region are found to have higher integrated water vapour

5.2 Recommendations

This study is one of the earliest form of it in Nigeria, it is recommended by the author that subsequent studies in this area should consider the following:

i. A directly observed surface temperature and pressure data collocated with the GPS stations are recommended for validating the results from this study.

ii. More work should be done to assess accuracy of ECMWF numerical weather model and GPT2w_1 model using observed surface data from radiosonde in order to inform the coming researchers the best substitute for radiosonde data in the estimation and validation of results for their studies.

iii. Extended study should be conducted in developing a regional weighted mean temperature for Nigeria.

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APPENDICES

APPENDIX A: Time-series mean daily IWV estimates over the NIGNET CORS for the corresponding Day of Year (1 to 365).

	ABUZ	BKFB	CGGT	FUTY	MDGR	OSGF	RUST	ULAG	UNEC
1	14.06244	13.9257	14.41724	19.21769			28.55116	18.95092	21.11069
2	16.77864	16.96299	15.72718	21.10428			34.46535	24.676	26.32327
3	18.46023	17.59606	16.33838	19.77633			36.06441	27.72356	26.24703
4	19.20694	16.68614	17.73192	19.42445			36.94347	31.18208	23.75485
5	18.28076	14.38486	16.0002	20.44824			41.8602	37.08428	24.61151
6	16.02341	13.11877	15.71383	19.28124			41.27756	38.7826	21.75966
7	13.04672	10.24437	13.8584	19.73789			27.24729	38.70713	18.91466
8	11.66312	8.495904	12.257	15.43584			23.32752	27.14862	20.20435
9	11.43815	10.68649	10.41865	14.33121			24.30185	21.66947	17.9036
10	11.6825	16.12203	11.2066	13.56428				21.23358	15.21531
11	8.324892	14.73784	7.594532	11.71496			26.12642	17.76401	13.60865
12	7.849384	11.97285	7.210699	12.97202			19.92215	17.93937	15.52051
13	8.598416	12.29525	8.102076	10.56379			25.68719	23.11152	18.51987
14	10.70822	13.54755	9.180485	10.36959			31.37525	28.93223	16.83601
15	8.757501	11.10151	8.81644	10.60517			32.69542	32.80417	10.71183
16	8.352376	10.07416	9.045705	12.07677			29.50116	17.85945	15.74543
17	9.422838	10.21369	9.928281	14.4578				18.93842	21.42177
18	7.629298	10.53065	7.737448	12.10339				19.90544	16.10087
19	8.511603	9.302624	8.086236	11.00793				16.50847	14.78663
20	8.885593	10.28698	9.245822	10.95164				18.50607	18.77258
21	9.850381	11.36701	10.00383	11.98755				24.2225	18.58494
22	9.052597	10.31448	9.655807	11.92135				31.12898	21.01589
23	8.010071	10.19259	8.378607	13.4514				33.58176	21.4905

24	7.163951	8.868318	7.410073	11.71614				33.84474	19.55319
25	8.455654	9.139277	8.467661	11.47723				34.42443	25.22462
26	8.382681	11.17418	7.136095	8.629518				38.66529	24.62131
27	8.680336	11.75857	7.961062	8.974701				35.96355	21.17535
28	8.688447	10.31479	7.287734	8.373565				33.85454	15.21871
29	7.548813	11.11089	7.61618	9.906346				34.32921	27.94509
30	7.713759	9.983238	7.507291	10.06265				37.2903	30.04493
31	10.6173	11.82403	10.24849	13.4948				28.06331	20.47829
32	8.493065	11.01793	7.811296	9.227143			31.05735	41.23126	31.85487
33	14.47418	16.47115	13.63888	18.02229				47.92343	43.09831
34	17.72507	25.73658	17.19586	29.51641				43.50907	44.72735
35	17.46012	25.58488	25.44283	30.91601				47.71812	45.26256
36	21.93135	21.63378	20.05171	30.41698				43.53549	43.20385
37	19.29806	23.84861	17.87721	18.84884				42.36399	38.70237
38	18.27238	22.82408	14.8299	15.96686				40.10288	40.58468
39	17.49241	19.67283	16.03658	20.93712				48.50925	42.0127
40	16.6399	19.73061	17.55542	22.61097				52.02428	41.35506
41	18.35404	22.99016	18.75132	23.91593				54.7755	43.0695
42	19.37023	22.8982	18.33383	24.17219				45.42848	43.41991
43	18.31448	20.39982	18.60943	21.5856				48.41398	42.21043
44	15.06076	20.28255	15.60902	15.96103				44.82381	39.0657
45	21.12966	28.69493	22.79567	24.19728				51.58994	47.04776
46	19.06709	25.19137	16.72271	25.46111				53.27518	45.33976
47	18.14724	23.1687	16.17541	17.5705				48.96331	44.1469
48	14.86575	24.77975	13.79379	18.08703				50.28854	44.41367
49	14.41735	23.76742	13.35622	14.05814				50.10719	44.66489
50	10.33249	15.06348	9.753526	13.40589				37.45871	36.69539
51	13.64607	16.33343	12.27624	16.87226				39.82168	36.09839
52	18.03457	20.67236	18.58327	24.62193				52.65654	45.55169

53	17.37868	18.05464	18.94232	28.11569				52.2401	50.56223
54	21.56993	13.68551	22.48338	30.62804				48.88118	39.7237
55	25.62666	15.01665	26.54293	25.76753				42.14593	41.54136
56	19.93025	19.74635	22.48836	20.42503				46.73219	43.23969
57	19.51939	32.64491	18.62786	18.72584				47.06032	38.90777
58	20.93674	38.40387	19.03425	17.85913				47.54565	40.76266
59	17.05236	27.26156	14.15117	13.38794				39.80586	37.68395
60	14.44726	19.99058	12.3804	12.01872	10.42004	17.52655		42.24309	37.09877
61	15.20778	18.7077	12.88247	22.63735	11.17251	23.9504		43.34716	37.74648
62	14.41118	22.08723	12.57	19.19432	11.65314	22.85927		44.37486	37.55946
63	13.11988	19.95065	10.33631	16.40754	9.357659	25.67225		46.5262	38.5292
64	15.35302	19.0949	15.09581	22.90068	8.870389	23.18499	44.22342	47.22227	42.87184
65	14.46952	17.87232	14.2564	15.0461	9.778006	21.973	50.11918	48.13827	46.31785
66	13.39455	17.14543	12.10794	12.09677	13.34927	24.90183	50.93332	47.70837	41.53362
67	9.438781	14.01445	8.713334	9.069859	17.66616	21.18057	50.27321	45.3535	35.19393
68	10.70504	12.19618	9.950768	9.250586	19.73741	15.71835	44.40277	41.53119	37.02894
69	12.59981	15.16762	11.87603	12.16326	18.98227	14.67041	45.5032	40.70673	38.74599
70	13.16202	14.85513	12.45739	13.54609	19.10983	25.56416	47.25449	43.79941	38.41692
71	13.44879	17.01084	12.25252	13.45506	14.15884	26.10033	48.5084	42.93213	37.9665
72	12.7147	16.30605	12.25181	14.51741	11.45271	29.83998	47.82594	44.08409	39.70923
73	14.50154	17.2441	13.87336	14.94061	13.7016	32.73232	47.66411	45.50458	
74	12.47383	15.66618	11.75273	12.97145	13.44469	35.56413	50.51775	44.10891	
75	12.68786	13.52911		11.49188	14.61141	37.02158	44.53294	43.53918	
76	7.874604	9.400403	7.767872	10.29657	11.13858	31.93697	47.1129	46.84785	
77	9.746718	9.191734	9.144339	12.91362	11.91866	37.85831	47.80477	44.95736	40.07737
78	10.31492	11.83876	8.813825	14.1073	16.09704	30.69456	49.35757	45.92946	37.67183
79	13.77119	15.59175	14.51181	17.07013	19.49531	23.6105	49.58847	49.3546	46.25874
80	15.51988	12.79368	11.51472	22.35633	18.74344	20.37771	51.64622	45.36648	44.77763
81	13.16062	16.64829	13.08139	17.03685	15.66379	21.93467	52.31589	50.54943	49.06316

82	14.15878	16.80569	16.39456	20.67782	16.01017	33.20036	54.13777	51.36351	46.7581
83	18.06218	18.04389	18.61819	31.79115	15.77358	25.91869	55.36769	46.08048	47.80321
84	16.18462	15.63445	20.59945	27.68853	17.7263	24.23965	53.13114	49.59004	48.57736
85	14.56991	19.05537	16.27365	20.33065	20.81144	34.13872	51.27943	48.46006	46.93361
86	13.40793	14.44302	14.03402	18.47364	22.9271	34.79301	49.27151	51.27385	47.98655
87	10.91592	12.95032	12.53115	14.80569	23.49058	37.6933	55.51747	49.36788	42.33348
88	10.51651	12.88549	12.32443	13.93651	19.65378	25.79338	50.96059	46.27602	37.59991
89	11.11326	12.57912	12.12585	12.75825	18.53267	18.78997	45.02095	45.72572	40.50132
90	12.51299	13.7163	12.90901	15.52699	15.73717	26.7591	49.04259	48.12997	40.08115
91	9.703226	10.58928	9.311631	14.57031	30.92061	37.24759	49.62339	42.91674	39.29823
92	19.69504	21.59572	17.15851	25.12767	29.31737	31.26232	46.50925	44.65493	42.40437
93	18.09863	31.8143	18.4886	23.05012	18.67453	26.53903	43.11828	50.02816	49.06561
94	18.76499	22.46315	19.05478	19.91762	12.96067	27.87821	51.72349	51.79583	41.33866
95	19.01189	23.65948	17.51803	17.58334	9.356806	36.06166	49.01872	42.2333	37.37621
96	15.30523	19.7983	13.70303	16.05809	11.1841	39.95026	45.29404	42.43347	38.01734
97	13.81913	17.60736	13.04946	15.20019	17.51206	34.67228	44.63407	40.48303	39.276
98	13.59255	12.42076	13.44529	16.27472	18.81541	34.93088	48.25261	42.98126	46.08846
99	16.17069	13.39578	16.19284	17.82306	25.77029	39.1276	54.91523	55.31492	49.31365
100	18.3574	15.89372	18.89813	22.23649	29.1071	42.89942	54.88549	47.44381	43.40157
101	18.78127	17.07795	18.8483	22.23125	31.22046	42.81038	52.1367	44.93201	42.10593
102	20.67597	20.0312	19.62309	23.817	29.24913	35.16278	50.86735	47.17228	46.35044
103	17.9136	20.9977	20.39113	28.60069	37.68049	33.26563	52.23094	50.64882	44.99368
104	16.27093	19.31877	16.35933	24.53799	42.06823	31.88217	51.69783	48.1308	47.31946
105	19.81125	14.80342	17.47478	26.34172	28.95372	35.23625	53.01598	44.34339	45.33779
106	30.65323	13.81269	27.62266	38.92059	21.5211	40.98963	54.13379	49.26456	45.38262
107	32.26893	15.61904	36.34268	43.41194	28.27372	41.22445	47.04891	50.65964	51.88846
108	27.34772	31.76151	27.855	35.6756	23.67243	41.46465	54.14148	51.53831	48.33566
109	19.61307	28.65945	20.29743	30.37992	24.85019	37.3576	56.15548	46.81727	45.59345
110	17.41978	25.50208	14.99473	22.35941	24.55539	39.64024	49.48026	44.58349	42.0395

111	20.85131	32.53626	17.49406	27.5725	21.37575	42.88475	51.70245	44.14333	40.35864
112	19.15951	29.09049	20.17222	38.37759	23.95667	42.1908	50.62685	44.47316	48.52344
113	29.1898	30.49647	30.52766	37.00709	29.99239	43.5909	53.438	54.86765	49.09821
114	37.22411	39.99278	34.43622	43.14595	28.93906	44.44807	54.47549	55.52244	52.83833
115	37.61825	41.40483	33.8741	42.22606	36.30065	39.02264	53.26062	53.12365	50.18404
116	28.08996	28.3397	30.94094	42.99022	39.69566	45.67852	55.70202	49.63355	46.56096
117	31.57445	27.19824	32.1041	42.75721	39.8052	37.95959	54.29984	52.74818	47.95837
118	35.13538	30.734	34.25088	44.37943	38.2735	41.35381	54.54126	53.29161	52.45232
119	34.20879	33.12215	36.32164	51.38165	22.91832	43.8377	57.62458	52.9801	51.89698
120	37.32091	40.37041	36.51257	47.27409	17.38059	44.07307	54.80086	53.44347	51.47698
121	24.06375	25.41929	23.65308	30.89605	31.39613	44.30566	51.19246	48.75606	46.32474
122	25.54557	34.03631	27.03692	37.37639	15.95055	41.12474	52.06736	54.99456	50.53808
123	34.87903	32.26644	37.49178	48.69192	15.9714	41.20119	57.63364	55.24522	52.71837
124	24.47366	33.19109	29.30416	48.91161	25.17148	42.06293	57.43668	48.67521	50.56685
125	30.31274	30.60549	31.63675	40.93981	17.70422		56.93786	52.71629	52.54948
126	33.26961	36.63676	33.95183	46.22644	20.7752	48.96301	57.55348	55.75442	53.38859
127	35.37529	36.02903	35.80586	45.48923	26.39821	40.25463	56.94403	52.51208	51.01447
128	35.60253	41.39922	35.55777	44.22654	28.94678	35.89423	55.25834	55.67515	47.66177
129	31.69453	40.25465	33.8877	43.86023	35.33724	35.95953	53.94866	54.02543	50.57827
130	38.92859	45.27741	36.42298	46.4423	43.6302	44.85263	57.87732	56.10778	51.23924
131	39.88679	45.97235	37.6371	46.54401	52.60171	35.14717	59.11568	53.93021	52.90733
132	40.5316	43.3958	36.30222	49.38319	52.72968	38.69515	59.00936	56.48956	51.60249
133	46.57751	47.42725	45.72589	53.66942	48.94012	41.28004		57.23055	55.0136
134	32.53397	45.6213	28.57191	43.1443	41.43099	37.71748		55.07393	51.59221
135	24.73663	30.31754		39.07691	37.93748	42.93459	57.90942	52.52167	49.64176
136	24.28891	32.58284	25.98378	41.9009	38.54485	41.50349	58.10553	49.7537	48.09158
137	33.09029	35.00772		44.16806	33.83536	43.94578	54.45573	56.95391	51.9928
138	27.14192	34.49904	21.37668	39.88338	41.83529	45.2183	58.59914	59.18435	55.87652
139	25.6465	37.73377	26.83537	47.95858	36.13187	49.46009	60.43572	54.03354	54.14115

140	28.42993	38.75493	30.87455	37.89973		49.51135	60.31888	57.20163	50.82919
141	32.08345	37.59811	29.29848	36.29558	32.467	49.02573	60.21603	54.41781	49.75421
142	35.30989	46.29692	34.018	42.13089	37.48751	48.51685	60.91603	53.49671	46.74445
143	35.83829	42.30505	35.23489	41.5807	36.49479	47.78136	55.65951	51.78959	48.55325
144	38.93273	39.97579	36.74469	47.24054	36.07335	46.79726	53.11865	53.80386	51.2362
145	39.48735	42.54302	38.41474	51.66382	36.56475	40.57201	58.63421		49.46926
146	40.30038	48.97297	45.78909	56.19421	41.41	45.72903	54.09561		57.45647
147	47.8848	47.41157	45.91399	55.89511	38.50089	47.55857	60.88382		55.46718
148	46.55976	54.21452	42.21425	52.95738	44.08012	48.17948	57.02841		56.36926
149	41.42036	48.46855	39.01378	54.15896	43.08372	48.61036	59.51629		55.44584
150	35.77663	38.50466	38.38023	51.65213	44.49708	44.74809	62.31851		55.39296
151	36.76542	37.94125	38.71886	49.50372	40.57053	44.19268	61.57813		55.84618
152	33.21324	35.73198	32.75257	43.49211	42.75818	38.28912	62.59676		48.59821
153	40.81441	41.12599	40.19293	48.24686	37.27077	43.75544	54.02422		53.93895
154	40.92126	43.91507	40.09508	49.19395	42.22651	41.4768	59.99943		55.69127
155	40.85783	49.81772	41.64808	53.54083	41.39661	44.09073	60.09816		55.36338
156	38.05931	45.37479	38.99635	50.38418	41.56846	47.70615	62.42213		54.4882
157	37.57553	40.09094	36.14256	51.44133	46.22501	46.59587	60.10978		55.72446
158	33.68329	41.02528	32.73257	45.31303	44.32489	48.41102	60.76368		54.26411
159	33.06343	39.61149	35.93619	45.07309	45.34762	48.19613	57.95253		47.39391
160	36.91609	44.86543	35.06266	47.1796	40.61314	45.00085	58.19296		55.24822
161	38.86786	41.38058	36.02481	48.36707	37.38239	41.80935	59.03395		48.98526
162	40.2127	45.40107	37.65638	47.26821	43.25961	49.45099	58.52182		53.27158
163	39.39994	44.75574	39.82466	51.00686	42.94879	46.40829	59.71514		53.20579
164	43.59697	47.56748	41.67572	49.37451	40.67862	43.325	57.22113		48.5249
165	41.30171	44.28529	40.69611	51.85453	38.55391	43.01435	52.44006		52.79355
166	38.61158	43.6596	38.88768	48.54326	40.04429	44.41968	56.96536		54.53759
167	41.83488	43.17171	39.63233	49.1083	38.20923	47.94854	60.15241		51.84604
168	37.17889	42.67453	32.87813	45.74892	45.9254	46.5647	57.45268		46.86748

169	42.68218	45.93009	39.09626	50.26573	39.95417	36.42775	51.75884		55.5459
170	40.60307	46.67635	37.71144	44.2062	48.14462	45.00035	61.37415		51.72924
171	39.7706	44.84123	36.36113	47.01964	39.97069	43.78315	59.04851		48.21194
172	37.20269	42.86126	37.56687	46.23114	40.8831	46.63902	53.78062		55.1086
173	39.4476	44.2831	38.25938	50.70775	46.46047	39.74178	57.43433		54.42631
174	44.55853	49.22251	42.16945	48.54595	45.24948	38.215	57.5197		52.36517
175	42.57618	49.42554	40.4887	45.95759	39.52565	39.67932	57.15546	57.77557	52.33284
176	34.16876	37.6017	30.0373	42.89626	47.19831	46.45135	56.5582		45.11355
177	40.15726	46.27353	38.52647	47.96827	47.32561	42.76428	48.77308		52.71134
178	44.21721	43.34194	41.06975	48.45459	46.49496	43.41781	57.63376		49.73202
179	42.5342	49.35273	40.46362	45.92061	45.50474	44.27199	54.68754	57.79456	52.36236
180	35.40826	39.11939	32.26642	41.69159	42.76205	44.07188	56.58379		46.4813
181	37.44974	40.79934	32.14509	40.59372	45.20982	48.33354	51.23793		45.2522
182	36.75369	43.13403	33.92962	42.86119	45.97609	47.3815	50.31796		48.12365
183	40.41592	41.14019	38.80489	46.77246	44.74668	49.43713	50.96506		52.71788
184	37.72026	43.89088	35.78622	42.64223	43.04619	53.57167	59.30373		51.95632
185	40.86308	46.98398	35.7456	48.11587	48.88659	46.35691	59.70798		52.88304
186	41.57421	51.36028	38.96531	46.30326	32.83565	47.39909	57.38931		50.539
187	37.10715	43.76667	37.74923	48.31457	47.52125	46.97202	56.14145		55.41603
188	40.36758	39.68326	41.58488	49.72127	47.87158	44.88264	59.19026		54.51792
189	43.182	42.27173	39.97838	47.78926	50.15884	48.68104	56.42395		51.83052
190	44.32906	49.35083	38.74352	49.2989	47.3167	47.0517	58.0083		53.39506
191	44.70138	52.19909	45.77462	57.48609	40.92297	50.28902	58.59406		59.81722
192	41.93651	47.74036	40.02475	50.21438	38.68572	43.78924	67.78154		52.7021
193	42.94952	49.75779	40.50678	50.97329	43.52155	44.23547	55.75769		51.79909
194	42.2697	50.11144	37.6025	47.50253	51.73087	37.18451	55.79429		52.92636
195	41.72904	46.46826	38.66646	50.67745	58.58247	46.72963	58.08121		52.70748
196	42.62734	48.46907	40.86712	50.59239	56.50678	46.76017	56.91778		53.27153
197	40.51524	48.09203	37.96333	50.3752	56.72834	48.59564	57.0337		51.38835

198	45.1548	48.82427	40.75775	49.73838	53.74914	49.0285	54.76647		53.65541
199	41.96787	51.59848		45.82966	55.37737	48.47682	58.47664		46.50029
200	40.75833	44.03422	39.36171	49.37008	55.16725	47.42383	53.52192		49.66905
201	34.08289	42.27179		40.71056	55.02965	46.19734	55.04935		46.10542
202	40.73097	50.3907	38.70543	52.11153	54.14437	48.18575	50.2225		51.88314
203	40.64495	47.43032		50.93359	50.46101	55.72575	56.16069	54.80016	52.84813
204	43.05117	49.99138		50.50906	47.9778	57.26761		52.31194	54.26988
205	43.92743	53.12005	41.58524	52.67967	47.43467	56.04863		54.20351	54.16092
206	38.87405	49.57619	38.95989	49.30999	42.24651	55.21238			54.07101
207	40.50034	46.66524	38.55162	46.98954	37.85717	53.1664			53.61212
208	36.22503	42.645	37.45717	48.59638	42.63598	54.60222			51.2245
209	45.31825	46.97622	42.67372	53.50281	40.66043	54.95624			53.73385
210	51.16016	58.62697	50.96211	60.63374	42.46103	54.00417			61.16536
211	52.56861	57.94988	49.29856	59.02098	43.07017	51.50238			60.25324
212	53.81398	59.49983	50.04873	56.99079	48.28588	48.88927	61.73196		56.76589
213	50.64572	59.08303	47.7164	55.97848	43.88036	49.50709	61.67087		58.97433
214	48.15654	56.12642		59.43101	46.01884	44.93627	64.9879		62.69398
215	51.41017	56.17734	49.95241	59.20113	48.06894	43.06084	67.75369		62.38179
216	49.70084	55.60101	49.45899	60.43621	43.94806	42.28985	65.37742		62.22557
217	50.18651	53.69578	47.19805	60.66223	41.99741	43.63854	65.34924		64.07089
218	43.40355	49.55798	44.25889	55.5419	33.75694	43.98103	69.26885	59.43356	55.48046
219	43.40265	48.75263	40.32109	52.02366	35.59695	45.32546	59.29533		52.21692
220	44.69315	50.55845	42.54507	54.28464	43.15556	44.50379	52.39876		49.41776
221	37.25286	44.02971		46.21499	42.05892	39.98445	54.22174	40.36199	45.16291
222	36.99778	42.68291	32.33663	43.86315	39.25128	41.65653	45.05241	43.10231	43.54591
223	35.80481	41.33425	33.87438	44.93543	39.89122	40.88804	46.53328	44.86597	45.81628
224	37.11798	44.29449	35.45197	47.87207	43.22408	40.44612	46.72195	47.92435	45.47174
225	37.88781	46.97038	35.38255	47.70746	32.71708	40.45201	47.40728	50.46458	45.54005
226	39.79935	43.85537	36.81719	47.64338	44.85574	42.02868	47.63763	43.90071	45.96193

227	40.57134	48.17204	38.60672	48.52958	45.09606	43.46879	47.40821		41.87012
228	41.95457	47.79049	35.91174	42.70733	42.03219	40.31603	43.6749		38.77756
229	39.83692	46.80417	37.44333	48.45288	44.99542	40.31709	39.84694		42.2753
230	43.07446	48.99825	38.48456	48.68691	43.01369	41.41425	43.69107		41.99019
231	41.27581	49.85035	34.921	44.5538	39.76713	40.97842	43.04482		41.89653
232	38.47733	48.12901	34.64474	44.72594	44.61939	45.85174	44.38172	37.51416	44.31955
233	36.19342	47.47695	31.98821	37.73114	42.64986	40.23213	49.19589	46.14133	47.0104
234	32.38089	43.71459	30.12516	39.15665	46.05696	45.25832	51.48559	52.55905	48.23315
235	34.00717	42.48278	30.99425	45.11075	48.95446	47.39777	50.57641	50.81788	45.65362
236	36.58302	38.93103	32.17721	42.04167	52.86318	46.89098	48.03839	47.65746	44.75484
237	37.39397	44.38766	31.77501	42.58077	51.82466	48.35914	47.64016	46.59678	44.32956
238	34.88265	42.28866	32.25157	45.22325	52.21195	44.46151	47.39576	51.51302	45.93937
239	41.18702	46.38109	39.17301	49.74962	48.93747	42.24069	51.42706	54.79647	52.61616
240	33.69837	39.31128	29.34998	40.45112	48.50008	46.68183		50.9871	44.22153
241	38.02064	43.08545	38.12551	52.19069	57.73591	42.86214		56.79742	52.1949
242	44.42787	48.50999	41.24547	50.78747	61.78897	45.22735		55.77469	53.97983
243	43.59847	49.20261	39.16732	51.50993	60.93843	48.73895		59.84481	53.77119
244	42.73999	46.35407	40.64658	49.57854	58.69386	58.96665		58.3302	53.50528
245	43.28664	47.56122	36.70126	50.78493	54.83394	55.45502		53.35852	51.69003
246	38.38134	41.58097		47.84433	55.864	55.7525		46.21235	45.32968
247	39.46136	46.31146	37.91702	49.65263	55.47779	55.38624		51.18458	52.0083
248	40.4309	45.22814		50.32142	57.28847	51.18679	57.49109	52.6215	49.99875
249	42.26065	42.94501	40.20842	52.41674	52.82257	53.00323	55.03659	52.87699	49.30545
250	44.48979	48.23936	40.47189	52.94006	53.39207	56.92383	52.39351	51.16558	51.76785
251	52.6876	59.25165	51.65649	62.86379	42.67666	58.2722	54.92449	65.22477	64.00529
252	48.78577	53.49344	47.21606	63.0453	45.04061	56.71168	69.99939	63.5973	62.73729
253	50.76418	56.62172		60.56801	53.81826	55.55895	62.96667	57.58567	61.58983
254	48.80101	52.91424	47.83432	60.99446	49.66284	58.64499	61.07473	62.20244	62.92684
255	44.57453	49.61975	44.82212	59.8307	42.76089	59.2005	68.03079	62.34858	59.32801

256	49.54595	51.89869	47.97225	64.76079	42.51619	55.4216		62.90999	61.22951
257	51.49562	52.99876	49.77742	67.08676	52.88151	55.99145		64.42574	61.95572
258	56.42953	60.14131		64.79006	46.35186	53.64883		64.5637	62.4256
259	57.39812	66.25092		63.14826	42.9009	51.40628		68.59554	65.14669
260	52.86694	60.77952		63.79945	46.88676	52.41438		66.56655	60.54811
261	51.82904	57.77132	51.75269	65.4127	40.5917	53.71496		68.62964	66.30823
262	52.17126	54.55609		62.64452	46.33808	53.1116		68.77081	66.13702
263	53.2399	55.38916	49.8054	64.08076	54.92176	56.11852		70.03862	62.79219
264	53.01246	59.22797		59.32515	51.80528	52.2492		67.60739	64.56258
265	49.82345	57.45112	45.48944	58.92779	47.24944	53.97905		66.3436	63.37873
266	47.12368	55.82228	41.94875	54.04398	51.31436	55.79711		66.91455	61.72673
267	44.86461	54.80212	42.99574	57.04755	49.25797	52.8885		66.07525	63.17084
268	44.27164	47.81151	43.2028	59.1311	46.64322	53.95601		66.71944	64.80872
269	48.30575	51.18477	46.17116	57.11492	51.88838	51.02906		65.14571	59.99755
270	48.32372	53.53302		55.62829	52.63294	50.79187		70.75018	64.74107
271	43.14085	51.03591	43.85297	58.20414	41.87281	58.14273		69.30685	62.44595
272	48.14372	47.63617	47.72031	59.73528	44.58201	56.3897		66.35758	61.97366
273	47.722	54.78771	44.63335	57.3836	21.84553	53.77655		68.06731	65.52756
274	45.01187	49.14641		55.92495	37.15455	55.47376		66.83624	61.03523
275	45.97671	47.86305		57.48237	41.82523	54.14288		63.45362	62.69199
276	44.35889	47.94196		58.23212	41.82773	52.50266		62.54066	60.70506
277	42.82212	50.21765	42.25847	55.1779	44.33005	53.74038		63.13047	61.99079
278	49.05935	52.26466	51.16238	63.33449	35.44495	54.94634		66.38432	62.89481
279	51.13037	56.03693	51.22881	63.19658	42.09102	53.50622		67.84067	65.31731
280	50.8326	56.28413	45.33294	57.27993	36.63977	55.17549		67.95773	63.74595
281	48.93737	55.13215	46.83538	60.35167	27.00357	45.51388		66.96771	60.66656
282	48.21802	56.61667	45.34372	59.13274	26.53743	49.83609		64.55314	61.13078
283	49.92139	55.77769		57.41791	27.8838	50.1676		66.94957	62.43315
284	45.70665	45.16045		60.2076	24.21176	50.17545		65.64379	61.04867

285	49.09608	47.5086	49.67119	63.85631		51.42095		67.98715	64.9712
286	45.25574	50.97636	46.13138	56.67326		50.5973		66.27193	63.08506
287	39.28414	43.46562	43.23734	59.55619		47.72753		64.35673	62.17323
288	29.33865	32.13476	33.82572	48.71076		53.27016		54.71403	51.16455
289	37.79106	42.4921	38.04747	57.08829		46.22454		63.96696	58.2678
290	35.4329	41.3849	34.91216	56.01281		41.46652		63.6417	60.84645
291	35.44616	41.41044	34.92086	56.02898		47.58484		63.64094	60.84165
292	45.6663	42.17212	45.30613	54.74576		48.00096		58.47165	57.13541
293	35.50483	39.44547	37.79725	55.63568		37.04638		62.64226	58.99194
294	34.24426	36.3528	40.6336	61.38478		37.02674		62.959	60.3976
295	40.63229	37.60543	45.29458	59.60128	21.62421	44.59142		67.24591	63.53655
296	33.5652	41.36549		50.57955	28.38843	44.30483		62.70287	58.56411
297	25.71693	31.18939	27.68384	43.30953	27.87085	41.0288		63.25325	61.16597
298	29.25948	31.86636	33.44904	49.61668	23.26745	41.73201		63.50141	58.4425
299	31.13038	35.33276	32.52448	47.05558	18.00684	45.29548		64.5052	59.00644
300	22.43505	25.00629	21.66481	38.31088	18.46231	36.164		57.9863	50.15699
301	25.38015	31.59223	24.21542	42.74303	20.78468	35.79168		51.93974	48.97826
302	27.4986	31.10164	30.67979	52.4985	23.21625	38.59487		58.17347	55.05355
303	27.67074	27.27626	29.73628	43.73131	21.17441	36.78939		61.22764	58.75816
304	23.53966	24.67462	26.28393	34.28408	21.1459	41.91175		56.77844	53.025
305	22.80289	23.68651	25.25855	37.61215	24.73908	35.31093		58.69406	54.77528
306	22.03246	25.5648	26.21541	42.95044	26.95588	40.69219		63.95209	
307	18.99157	20.37473		40.30937	26.13662	34.21196		59.81282	54.6389
308	17.49731	21.17233	20.98266	34.87457	22.9765	35.31741		55.4137	49.22929
309	21.61989	26.93072	21.62592	33.31339	21.74741	36.23958		58.79289	52.28241
310	19.10855	25.15982	19.23434	34.15451	20.9095	37.57384		64.12404	57.00976
311	23.12907	22.21445	26.00209	37.1037	19.7182	28.73731		64.18105	
312	24.50418	24.44765	26.03961	41.00022	16.44045	28.46516		58.77095	50.44246
313	24.80532	26.92227	26.59301	39.71254	16.17644	27.50109		58.32241	52.47847

314	20.5711	22.83033	21.17833	28.17224	14.39819	30.92051		57.41381	53.17339
315	18.74172	21.10492	22.04288	26.5705	15.08086	31.70869		54.55989	49.2936
316	21.82295	18.69889	22.88671	30.27783	15.41436	30.12065		57.66657	46.34167
317	24.24683	21.20712		32.29014	13.45923	24.62902		59.31206	48.81792
318	21.01559	21.97405		29.689	15.21564	24.86683		52.79236	46.90612
319	20.58765	19.89921	21.90874	26.70155	14.27219	29.70149		49.822	46.75854
320	22.15605	18.29674	22.19539	30.21905	11.77552	28.74074		55.38217	48.62296
321	24.25925	22.88905	26.03141	30.89529	12.47059	23.88837		59.22034	45.35877
322	26.15048	27.05399	25.15339	30.75978	14.29717	19.65882		58.38421	46.02133
323	23.9271	26.95713	22.69876	28.92027	13.9318	21.07525		54.27341	45.85053
324	20.39808	24.6055	19.80362	27.41744	14.54655	22.04997		49.23268	42.8068
325	18.15241	23.06958	21.00237	24.37675	16.42878	17.55492		47.57147	44.10689
326	21.09929	18.84481	21.25308	25.10253	14.79773	15.85722		53.0613	44.78956
327	19.74078	20.6595	18.56341	21.81852	12.04153	15.12846		55.10223	42.61087
328	17.30324	22.05535	16.43135	20.28494	12.23137	13.94902		49.47834	41.83277
329	12.70968	15.24913	13.27332	18.39048		12.72977		46.43368	30.28864
330	13.52784	15.25571	14.35461	19.30565		13.31762		48.82649	30.98643
331	15.75075	16.42213	15.51291	19.71683		14.2936		46.60477	31.83935
332	12.46118	15.20572	13.1587	17.11479		16.8774		47.52149	26.06575
333	11.37725	12.72191	11.99348			20.18647		42.49442	25.83039
334	10.91974	12.6696	11.731			22.03668		33.15153	19.08481
335	10.89399	12.47486				15.52761		28.80706	19.49718
336	11.33334	13.27476	10.22725			13.67997		25.4642	17.77152
337	11.14334	12.74683	11.14866			16.19952		28.73079	18.96101
338	11.25361	12.24796	11.70001			18.93986		32.39921	20.61031
339	12.55498	14.72165	12.12358	17.17777		20.75705		36.43934	30.98283
340	15.42915	15.06204	15.61612	21.94564		21.703		38.04369	26.30172
341	17.81698	18.61672	17.89559	19.22907		19.4067		37.80493	27.42184
342	13.88203	18.20716	11.97588	15.43661		18.57337		39.8115	22.03687

343	10.45566	13.98736	9.785684	15.14203		16.65865		31.27973	18.28477
344	12.83	12.45089		20.61705		23.376		34.14777	20.8424
345	16.83122	13.95052	17.94334	22.30461		25.9373		29.88982	22.51543
346	16.79107	15.56022	18.1448	23.84529		26.98991		27.84912	26.73859
347	15.41254	13.70548	16.38132	21.30052		27.57732		29.3279	26.40779
348	14.66235	14.63051	14.94957	18.66645		27.38159		31.81182	23.06144
349	14.54896	14.92732	13.81263	17.57127		25.2052		29.28731	21.87916
350	12.99065	15.10903	13.8301	20.55951		24.18646		25.45482	21.43407
351	12.85268	14.3391	18.01299	24.97708		21.14769		36.69336	28.02127
352	15.57727	15.11878	21.35312	25.9617		24.45598		41.77082	30.87813
353	19.33544	18.85677	23.07442	26.74732		25.24741		46.09878	33.44997
354	21.0492	22.97129	21.55685	26.1231		26.62296		45.1373	35.98134
355	19.94343	21.0591	19.90836	21.20752		26.5694		45.99834	36.96935
356	18.59678	21.59963	16.78645	19.4406		30.448		43.12989	34.23871
357	17.01721	20.83267	16.74302	18.22894		26.4888		42.12193	25.3611
358	16.51096	19.3461	15.76986	19.05623		26.29536		43.12668	24.34552
359	18.89395	19.82246	19.23457	24.264				49.17648	28.17314
360	22.38565	23.71626	22.49191	26.37497				45.78968	25.95649
361	24.33968	25.45044	24.70632	27.83458				47.6263	30.93552
362	22.03658	23.25765	21.69259	22.47241				47.3762	33.69705
363	24.5383	22.33085	22.56364	20.86868				52.56353	45.29188
364	20.47616	19.88226	17.92884	18.56971				43.03115	43.30872
365	17.30121	20.40849	14.84639	16.97826				38.42552	39.99723

APPENDIX B:

Continuation of Table 4.3 on the validation of the estimated IWV.

MARCH		
STATIONS	MEAN DIFF.	RMSEs
MABUZ	-14.3847	2.583576
BKFP	1.486971	0.495664
CGGT	-22.3973	4.022679
FUTY	31.0179	5.570979
MDGR	-35.2684	6.334396
OSGF	9.943942	1.821054
RUST	37.17511	6.676847
ULAG	34.69962	6.232236
UNEC	26.78772	4.811217
APRIL		
ABUZ	-13.3751	2.417053
BKFP	1.185243	1.245107
CGGT	-22.0367	4.023332
FUTY	-4.29397	0.783969
MDGR	-26.5499	4.847321
OSGF	8.765077	1.661485
RUST	26.03149	4.752679
ULAG	30.82887	5.628555
UNEC	15.9566	2.913262
MAY		
ABUZ	-13.7393	2.467642
BKFP	0.231679	0.972645
CGGT	-16.1026	2.892111
FUTY	-9.79118	1.771926

MDGR	-20.8931	3.752504
OSGF	3.71145	0.865995
RUST	18.51464	3.110791
ULAG	30.0587	5.398701
UNEC	8.071755	1.44973
JUNE		
ABUZ	-9.81928	1.792748
BKFP	-0.2508	0.498804
CGGT	-12.5801	2.296802
FUTY	-5.63296	1.033157
MDGR	-12.1161	2.212091
OSGF	3.278401	0.746214
RUST	14.10589	2.575372
UNEC	5.793209	1.076218
JULY		
ABUZ	-6.76344	1.33861
BKFP	1.868359	0.730639
CGGT	-9.00636	1.646583
FUTY	-2.40223	0.739275
MDGR	-5.53346	1.240081
OSGF	8.22575	1.523098
RUST	12.53459	2.25128
ULAG		
UNEC	6.912283	1.242365
AUGUST		
ABUZ	-10.7486	1.930497
BKFP	-0.93426	0.707231
CGGT	-13.6475	2.451163

FUTY	-3.76686	1.119225
MDGR	-6.29381	1.438839
OSGF	0.57267	0.417009
RUST	4.733407	1.175297
ULAG	3.578798	1.021012
UNEC	0.632398	1.023653
SEPTEMBER		
ABUZ	-3.04088	0.833319
BKFP	8.079963	1.534355
CGGT	-6.35477	1.176031
FUTY	4.746248	1.137917
MDGR	-4.99002	1.112022
OSGF	12.93926	2.362375
RUST	16.08198	2.936154
ULAG	25.06686	4.576562
UNEC	13.38928	2.461375
OCTOBER		
ABUZ	-6.00041	1.539957
BKFP	9.665241	2.026472
CGGT	-9.45729	1.823718
FUTY	0.105679	1.059165
MDGR	-26.9266	4.836152
OSGF	10.90535	1.958659
ULAG	39.74212	7.137896
UNEC	20.09682	3.609495
DECEMBER		
ABUZ	-0.32773	0.589746

BKFP	5.923422	1.063878
CGGT	-2.10692	0.686426
FUTY	-12.2351	2.197492
OSGF	9.29841	1.670044
ULAG	28.15759	5.057252
UNEC	14.12545	2.537006