Geodetic parameters derived from gravity data across Nigeria

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Abstract

Physical geodetic survey of the Nigeria landmass was undertaken with the aim of furnishing engineers and scientists with vital geodetic information which have not been adequately available but required for the development of a standard national economic framework. The basic data used for the study were the absolute gravity field values, and the recorded coordinates and elevations at the Primary Gravity Network of Nigeria (PGNN) base stations. The absolute gravity data were processed using the appropriate mathematical and computational procedures to deduce geodetic information which include geoid undulation, height above the geoid, deflections of the vertical, distance from the earth's centre of mass to the reference ellipsoid and geoid, and the gravity potential value at the geoid. Comparison was also made between the WGS'84 and the geoid in the study area. Geoid undulations were found to range from 16.53 to 28.35 m and the deflections of the vertical ranged between 0.738685 to 10.28328 arc second. Height above the topography ranged from -16.38 m in Warri to +1257.13 in Jos. The distance from the earth's centre of mass to the WGS'84 reference ellipsoidal surface was maximum at Oron (6377988.04 m) and least at Illela (6376941.31 m). Similarly, the distance from the earth's centre of mass to the geoid was also maximum at Oron (6378008.39 m) and minimum in Illela (6376961.659 m). The interpolation of the distances from the earth's centre of mass to the spheroidal surface at each base station gave the definition of the WGS'84 ellipsoid over the continental Nigeria landmass while the interpolation of the distances from the earth's centre of mass to the geoidal surface gave the definition of the geoid over the continental Nigeria landmass. The average gravity potential at the geoid was evaluated as 62375050.41 m^2s^{-2}. The geoid over the continental Nigeria landmass was found to be comparably smooth as the WGS'84 ellipsoid over the region though they differ in terms of vertical separation. The quantitative difference in mGal corresponding to the vertical separation between the WGS'84 reference ellipsoid and the geoid was computed as 6.8042 mGal. The values of the deflections of the vertical at each station of the PGNN gave the angular correction to be applied when combining satellite-based ellipsoidal measurements and geoid-based physical geodetic measurement. Based on the significant range of the deflections of the vertical across the continental area of Nigeria, it was concluded that the physical structure of the lithosphere beneath the study area must be highly complex and heterogeneous.

Keywords: Physical geodetic survey, Primary Gravity Network of Nigeria (PGNN), geoid undulations, deflections of the vertical, gravity potential at the geoid.

1 Introduction

Physical geodesy, also called gravimetric geodesy, is a branch of geodesy that utilises measurements and characteristics of the earth's gravity field as well as theories regarding this field to deduce the shape of the geoid (earth's surface when all topographies are removed) and the size of the earth

(Burkard, 1959). Accurate determination of the shape and size of the earth has a lot of advantages and benefits. It enhances precision mapping and positioning, accurate definition of the reference height datum, and accurate determination of astronomic and geodetic angles which are very useful parameters in "Engineering surveying".

The primary data of use in physical geodesy is the gravity field data and invaluable information that can be realized through physical geodesy include the gravity field strength, the geoid undulation, height of topographies above the geoid, gravimetric deflections of the vertical and the earth's size (size of the earth's ellipsoid, especially as better approximated for a given region). (Burkard, 1959; Torge and Muller, 2012; Zhiping *et al*, 2014).

The best data for accurate determination of the earth's shape (or arc definition for the purpose of surveying) is gravity field data because the earth's gravity field is an inherent property of the earth whose response is directly influenced by the shape of the earth and the earth's response to forces acting on it. The use of gravity data thus eliminates the overdependence on highly subjective practices involving calibration, measurement of length and extrapolation of figures (arcs) generated from considering relative positions of stars and planets as the case is in geometric geodesy.

This study presents interested scientists with geodetic information which include geoid undulation, height above the geoid, deflections of the vertical, distance from the earth's centre of mass to the reference ellipsoid and geoid, potential at the geoid, and how well the geoid and WGS'84 ellipsoid compare across the Nigerian continental area using the more reliable gravity data and elevation measured with reference to the WGS'84 ellipsoid.

2 Methods

2.1 The Study Area

The area covered is the whole continental Nigeria landmass (Figure 1). This spans from Longitude 3^{o}E to 15^{o}E and Latitude 4^{o}N to 14^{o}N; and is bounded by Benin Republic to the West, Niger Republic to the North, Chad to the Northeast, Cameroon to the East and Gulf of Guinea to the

South. The zone falls within the West African sub-region and is close to the Equatorial African region. It covers an area of 923,768 km^2. The region comprises of thirteen (13) major geologic provinces, six of which constitute the basement complex terrains (that is, Southwestern basement complex, Younger metasediments, Older metasediments, Younger granites ring

complex, North-central basement and the Volcanic rock regions of northeastern Nigeria) and the remaining seven (i.e., the Benue trough, Bornu basin, Sokoto basin, Mid-Niger basin, Dahomey basin, the Niger delta and the Calabar flank) constitute the sedimentary terrains (McCurry, 1976; Ajibade, 1982; Dada, 1999; Obaje, 2009).

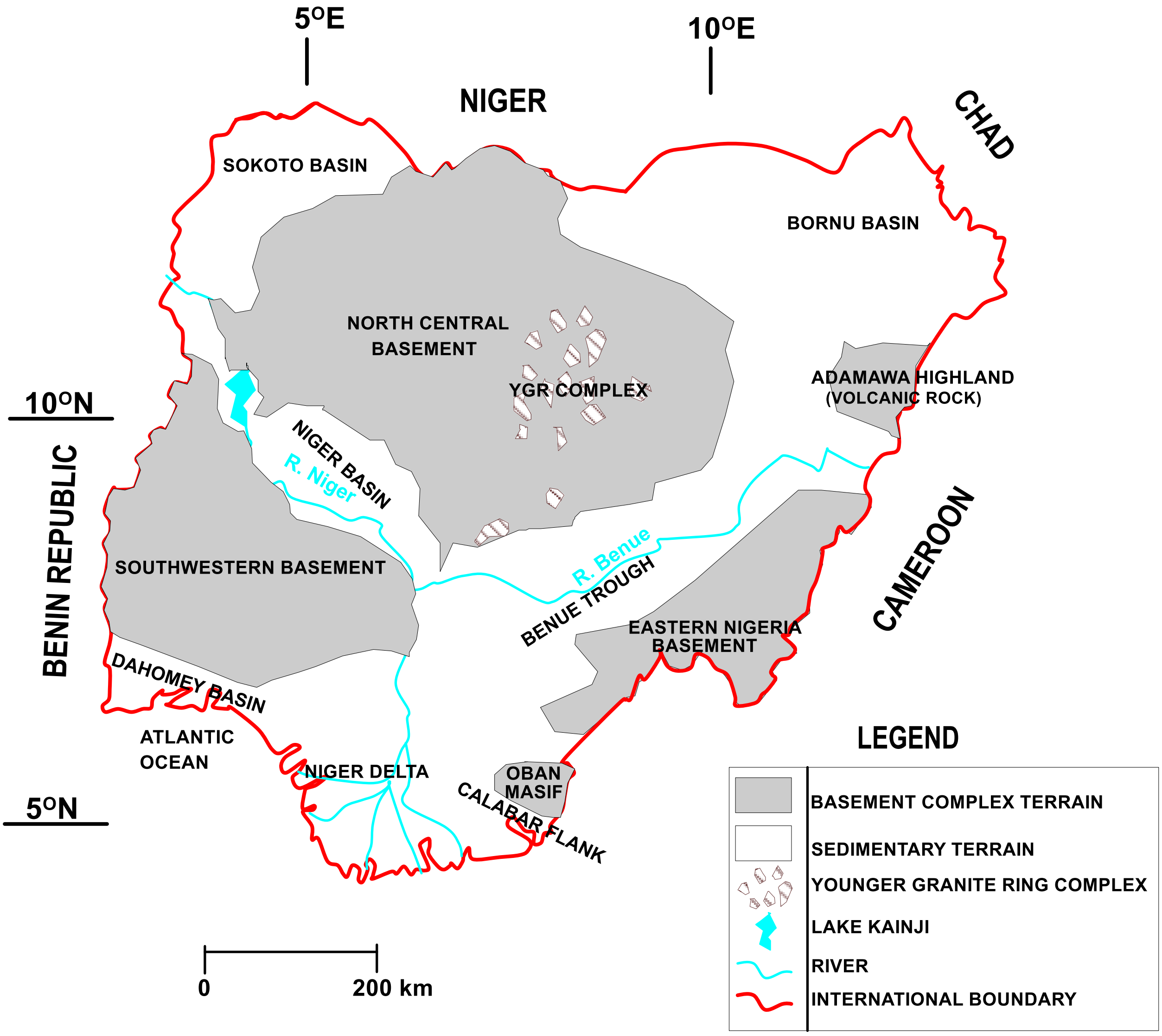

Figure 1: Geologic map of Nigeria showing the boundaries with neighbouring countries (Modified after Obaje (2009)).

The basement rocks of western and northcentral Nigeria are part of the West African Craton and have ages ranging from Precambrian to Cambrian (Avbovbo, 1980). However, they were reworked by the Pan-African thermotectonic orogenic event of about 600 Ma known as the Pan-African Orogeny. A region within the northcentral basement complex made up of predominantly polymetamorphic Migmatite-Gneiss complex was intruded by granites of Jurasic age known as the Younger Granites (Oyawoye, 1972). Volcanic and intrusive rocks of late Cretaceous to early Tertiary age occur also as part of the basement rocks in the eastern half of Nigeria (Avbovbo, 1980).

The sedimentary basins have been proposed to have developed from the inland extension of rifts upon which the Central Equatorial Atlantic Ocean opened during the separation of South America from Africa (Balogun *et al,* 2016). All the sedimentary basins are of Cretaceous age except the Niger delta basin which is of Tertiary age (Machens, 1973; Adeleye, 1974; Petters, 1978; Genik, 1993; Obaje *et al.*, 2004; Guiraud, *et al.*, 2005; Obaje, 2009).

2.2 The Data

The basic datasets used for this study were the evenly distributed absolute gravity data and their corresponding positions and elevations above the WGS'84 ellipsoid. The absolute gravity values adopted were from the comprehensive Primary Gravity Network of Nigeria (PGNN) established by Osazuwa (1985) with a total of fifty-nine (59) evenly distributed gravity stations spread across the continental Nigeria landmass (Figure 2). The coordinates and elevations at the fifty-nine (59) absolute gravity stations were recorded by Balogun (2020) using the Global Positioning System (GPS).

Figure 2: Map showing the distribution and location of the gravity base stations in Nigeria (Modified after Osazuwa, 1985)

2.3 Distance from the Earth's Centre of Mass to the WGS'84 Ellipsoidal Surface and Geoid

The distance from the earth's centre of mass to the WGS'84 ellipsoidal surface at a point can be considered as the radius from the earth's centre to such point since the spheroidal approximation will be more appropriate in such cases where it is a single point that is being considered per time. It is the extrapolation of many of such points that is expected to reflect the ellipsoidal nature of the earth's shape. According to Sandwell (2002), the radius, r(θ), from the earth's centre of mass to a point on the ellipsoidal surface is given as:

$$r(\theta) = \left(\frac{Cos^2\theta}{a^2} + \frac{Sin^2\theta}{c^2}\right)^{-\frac{1}{2}} \quad 1$$

where: r(θ) is the radius of spheroid, θ is the geocentric latitude, a is the equatorial radius (WGS'84), and c is the polar radius (WGS'84).

To convert from geocentric latitude θ to geographic latitude θ_g:

$$\tan\theta = \frac{c^2}{a^2}\tan\theta_g;\ \text{OR}\ \tan\theta = (1-f)^2\tan\theta_g \quad 2$$

where f is earth's flattening.

It should be noted that when the geoid undulation is added to (or subtracted as the case may be) the value of the radius from the earth's centre of mass to the reference ellipsoidal surface, the result gives the radius to the geoidal surface from the earth's centre of mass.

2.4 Geoid Undulation

Geoid undulation (N) means the departure of the geoid from the reference ellipsoid. To determine the geoid undulations from the free-air gravity (i.e. gravity on the reference ellipsoid), we should first bring to perspective that the free-air gravity (g_{fa}) differs from the free-air gravity anomaly (δg_{fa}) in that free-air gravity is given as:

$$g_{fa} = g_{obs} + \delta g_L \pm g_{FAc} \quad 3$$

while free-air gravity anomaly is given as:

$$\delta g_{fa} = (g_{obs} \pm g_{FAc}) - g_{Theoretical} \quad 4$$

Expressing δg_{fa} in terms of gravity potential, we have:

$$\frac{\partial \delta V}{\partial r} + \frac{2}{a'}\delta V = -\delta g_{fa} \quad 5$$

Solving for δV in equation 3, we have

$$\delta V = -\frac{\delta g_{fa} a'}{2} \quad 6$$

But Brun's formula (Li and Goetze, 2001) is given as:

$$\delta r\ (or\ N) = \frac{\delta V}{\gamma} \quad 7$$

Substituting equation 6 into equation 7 we have

$$N = -\frac{\delta g_{fa} a'}{2\gamma} \quad 8$$

where g_{fa} is free-air gravity, δg_{fa} is the free-air gravity anomaly, g_{obs} is the observed gravity, + δg_L is latitude correction, g_{FAc} is the free-air correction, a' is the radius of the ellipsoid from the centre of the earth to the position of gravity observation, r is the radius of the earth, γ is the theoretical gravity and N is geoid undulation.

Li and Goetze (2001) provided similar but non-simplified procedures for determining the Geoid undulation (N) from gravity data.

2.5 Heights above the Geoid (h)

Height above the reference ellipsoid is known as ellipsoidal height (H) while height of topography above the geoid is known as orthometric height (h) and departure of the ellipsoid from the geoid is known as geoid undulation (N). For regions where geoid is above the ellipsoid, the ellipsoidal height (H), orthometric height (h) and geoid undulation (N) is related by the equation below

$$Orthometric\ Height\ (h) = Ellipsoidal\ Height\ (H) - Geoid\ Undulation\ (N) \quad 9$$

2.6 Deflections of the Vertical at Topographic Surface

The deflection of the vertical is the angle between the normal to the geoid and the normal to the spheroid. In other words, the deflection of the vertical at a point on the earth is how far the direction of the local gravity field has been shifted by local anomalies. It can also be considered as the angular difference between the direction of the gravity vector (i.e. the plumbline) at a point and the corresponding ellipsoidal normal through the same point for a particular ellipsoid (Featherstone, 1999).

The deflection of the vertical at a point is oblique in nature and as such it is defined by both a north component (ξ) and an east component (η). The oblique nature may have resulted from the various motions of the earth that are neither uniform nor synchronous.

$$\xi = -\frac{1}{a}\frac{\partial N}{\partial \theta} \quad 10$$

$$\eta = \frac{1}{a\cos\theta}\frac{\partial N}{\partial \varphi} \quad 11$$

where ∂N is relative change in geoid undulations and θ is the geocentric latitude.

The knowledge of the deflection of the vertical is very important and have the following primary uses in surveying:

i. transformation of astronomical coordinates to geodetic (geographic) coordinates
ii. conversion of astronomic azimuth to geodetic (geographic) azimuth
iii. reduction of vertical and horizontal angle to the spheroid

2.7 Potential at the Geoid

This was computed by integrating the free-air gravity with respect to the geoid over the distance from the earth's centre of mass to the geoidal surface (Zhiping *et al.*, 2014). This on approximation yields the product of the free-air gravity with respect to the geoid and the distance from earth's centre of mass to the geoidal surface.

$$V_{geoid} = \int_0^r g_{fa}.\,dr \qquad 12$$

where V_{geoid} = Potential at the geoid, g_{fa} = free-air gravity and r = distance from the earth's centre of mass to the geoidal surface.

3 Results

Tables 1(a) and 1(b) present the computed free-air gravity, geoid undulation, height of topography above the geoid, deflections of the vertical, distances from the earth's centre of mass to the reference ellipsoid and geoid, and the potential at the geoid across the Nigerian continental area.

3.1 Geoid Undulation

The geoid undulation within a region gives the fluctuations of the true mean sea level away from the reference ellipsoid since most of the times the ellipsoid (especially the geocentric ellipsoid) do not coincide perfectly with the geoid which closely approximates the mean sea level.

Geoid undulation can be positive or negative. Positive geoid undulations mean that the geoid is above the reference ellipsoid while negative geoid undulations indicate that the geoid is below the reference ellipsoid. Determining the geoid undulations is crucial in the definition of a local (or regional) ellipsoid that will approximate the geoid in a particular region better than the geocentric ellipsoid. It is also crucial to determining the zero elevation (height reference) on the continent in a region such that having determined the geoid undulation and having also ascertained that the undulation is either positive or negative, we can easily compute the geoid level, hence determine the zero height reference surface. Most times, arcs are defined during geometric geodetic survey (datum establishment) from astro-geodetic methods but better arcs can be realised from fitting a best fitting surface over the geoid.

Figure 3 is a map showing the geoid undulations over the Nigeria continental landmass. The least geoid undulations were observed at Maiduguri (16.53 m), Mubi (17.25 m), Yola (17.58 m), Geidam (17.95 m) and Numan (18.29 m). These were the regions where the geoid appeared to be closest to the WGS'84 ellipsoid even though these undulations should still be considered as substantial. The maximum geoid undulations were observed at Minna (28.35 m), Iseyin (26.02 m), Ibadan (25.71 m), Osogbo (25.71 m; 25.70 m) and Ilorin (25.70 m). In general, relatively higher geoid undulations were observed at the southwestern and central western part of Nigeria while relatively lower undulations were observed at the eastern part of the country. The implication of this is that there are less crustal load or heterogeneity beneath the sub-surface in the eastern part of Nigeria compared to the western part. More than half (i.e. thirty-two (32)) of the fifty-nine 59 stations occupied have their geoid undulation values ranging between 20.00 and 24.00 m.

3.2 Height of Topography above the Geoid (h)

Following the determination of the amplitude (N) of geoid undulations, the height of topography above the geoid (also known as orthometric height), h, is computed by subtracting the geoid undulation (N) from ellipsoidal height (H). The orthometric height (h) is the height above the mean sea level. It is usually the standard reference datum for height. Figure 4 is the map showing the heights of topography above the geoid across the continental Nigeria landmass.

The least heights were gotten at Warri (-16.38 m), Port Harcourt (-4.39 m), Oron (11.65 m) and Lagos (17.26 m) base stations which were stations located within the coastal sedimentary lowland region. The maximum heights were gotten at Jos (1257.13 m), Saminaka (759.41 m), Biu (707.13 m), Funtua (694.00 m) and Zaria (667.43 m; 646.41 m) base stations which were stations within the Younger Granite Province, Adamawa Highland and Central Nigeria Basement Complex. Locations where maximum heights of topography above the geoid were obtained are known mountain ranges and elevated regions in Nigeria.

3.3 Deflections of the Vertical

Deflection of the vertical is the angular difference between the direction of the gravity field (or plumbline) at a point and the corresponding normal to the ellipsoid through the same point (Featherstone, 1999). The total deflection from the vertical at a point is given by the vector sum of the north-south (meridional) component (ξ) and the east-west (prime vertical) component (η). It should be noted that both the north-south and east-west components are always orthogonal to themselves.

Table 1(a): Gravity Field and Physical Geodetic Data Derived for the Continental Nigeria Landmass

Station Location	Station Code	Terrain	Region Classification	Long. (°)	Lat. (°)	Elev. above WGS' 84 ellips. (m)	Theoretical Gravity (mGal)	Drift Corrected Absolute Gravity (mGal)	Latitude Corrected Abs. Grav (mGal)	Value of Latitude Correction (mGal)	Free-air Gravity on the WGS'84 Ellips. (mGal)
Abeokuta	ABK – 100101	Basement	South-Western Nigeria Basement Complex	3.3141	7.1459	54	978112.5788	978119.8570	978039.9548	79.9022	978056.6192
Akure Excentre	AKR – 100502	Basement		5.1942	7.2537	356	978114.9937	978049.7390	977967.4279	82.3111	978077.2895
Akure (Main Base)	AKR – 100501	Basement		5.1846	7.2589	349	978115.1110	978050.2750	977967.8466	82.4284	978075.5480
Ibadan	IBD – 102301	Basement		3.9058	7.4303	231	978119.0279	978089.1900	978002.8419	86.3481	978074.1285
Osogbo (MKO)	SGB – 105001	Basement		4.4803	7.7712	309	978127.0852	978063.9080	977969.5061	94.4019	978064.8635
Osogbo (GPO)	SGB – 105002	Basement		4.5490	7.7801	316	978127.3006	978060.4980	977965.8810	94.6170	978063.3986
Iseyin	ISY – 102801	Basement		3.6154	7.9553	316	978131.5814	978076.5060	977977.6073	98.8987	978075.1249
Egbe	EGB – 101601	Basement		5.5039	8.2480	325	978138.9440	978061.7380	977955.4795	106.2585	978055.7745
Ilorin	ILR – 102701	Basement		4.4945	8.4332	344	978143.7359	978059.1380	977948.0888	111.0492	978054.2472
Kishi	KSH – 103701	Basement		3.8549	9.0749	393	978161.1344	978067.2780	977938.8330	128.4450	978060.1128
Keffi	KEF – 103601	Basement	Central Nigeria Basement Area	7.8763	8.8225	302	978154.1436	978061.1570	977939.7021	121.4549	978032.8993
Abuja (Suleja)	ABJ – 100202	Basement		7.1797	9.1778	416	978164.0382	978047.5040	977916.1586	131.3454	978044.5362

Station Location	Station Code	Terrain		Long. (°)	Lat. (°)	Elev. (m)	Theoretical Gravity (mGal)	Drift Corrected Absolute Gravity (mGal)	Latitude Corrected Abs. Grav (mGal)	Value of Latitude Correction (mGal)	Free-air Gravity on the WGS'84 Ellips. (mGal)
Minna	MNA – 104301	Basement	Central Nigeria Basement Area	6.4694	9.6664	293	978178.2654	978085.8900	977940.3155	145.5745	978030.7353
Saminaka	SMK – 105601	Basement		8.6937	10.4303	783.5	978201.9227	977987.6140	977818.4055	169.2085	978060.1936
Kaduna	KAD – 103202	Basement		7.4460	10.5930	641	978207.1828	978029.7370	977855.2630	174.4740	978053.0756
Birnin Gwari (Main Base)	BGW – 101101	Basement		6.5478	10.6690	431	978209.6689	978090.1060	977913.1359	176.9701	978046.1425
Birnin Gwari (GMSJ 24)	BGW – 101103	Basement		6.5494	10.6695	440	978209.6844	978089.4080	977912.4225	176.9855	978048.2065
Birnin Gwari (GMSJ 23)	BGW – 101102	Basement		6.5474	10.6700	432	978209.7008	978089.8120	977912.8100	177.0020	978046.1252
Kano	KAN -	Basement		8.5222	12.0486	476	978257.6911	978120.9500	977895.9675	224.9825	978042.8611
Katsina	KAT – 103501	Basement		7.6597	13.0069	506	978294.2769	978149.4190	977887.8580	261.5610	978044.0096
New Bussa	NBSA – 104602	Basement	North-Western Nigeria Basement Complex	4.4993	9.8874	185	978184.9316	978128.2270	977975.9814	152.2456	978033.0724
Kontagora	KON – 103801	Basement		5.4449	10.3964	346	978200.8366	978108.6360	977940.4924	168.1436	978047.2680
Rijau	RIJ – 105501	Basement		5.2630	11.1247	356	978224.9182	978115.2930	977923.0734	192.2196	978032.9350
Zaria	ZAR – 100001	Basement		7.6863	11.1380	669	978225.3736	978031.2250	977838.5668	192.6582	978045.0202

Station Location	Station Code	Terrain		Long. (°)	Lat. (°)	Elev. (m)	Theoretical Gravity (mGal)	Drift Corrected Absolute Gravity (mGal)	Latitude Corrected Abs. Grav (mGal)	Value of Latitude Correction (mGal)	Free-air Gravity on the WGS'84 Ellips. (mGal)
Zaria	ZAR/ABU - PH000	Basement	North-Western Nigeria Basement Complex	7.6530	11.1502	690	978225.7905	978030.5690	977837.4942	193.0748	978050.4282
Kafin Maiyaki	KAM – 103301	Basement		8.2020	11.4543	619	978236.3264	978056.3770	977852.7652	203.6118	978043.7886
Funtua	FUN – 101801	Basement		7.3160	11.5100	716	978238.2842	978048.3260	977842.7589	205.5671	978063.7165
Gusau	GSU – 102201	Basement		6.6939	12.1722	465	978262.2627	978100.6620	977871.1144	229.5476	978014.6134
Oron	ORN – 104901	Sedimentary	Southern Nigeria Sedimentary Terrain	8.2363	4.8076	32	978068.9441	978057.4790	978021.2125	36.2665	978031.0877
Port Harcourt	PHC – 105301	Sedimentary		7.0148	4.8419	15	978069.4619	978060.8090	978024.0246	36.7844	978028.6536
Calabar (Excentre)	CAL – 101402	Sedimentary		8.3220	4.9600	42	978071.2739	978071.1640	978032.5672	38.5968	978045.5284
Calabar (Main Bs.)	CAL – 101401	Sedimentary		8.3475	4.9691	66	978071.4150	978072.1870	978033.4491	38.7379	978053.8167
Warri	WAR – 106001	Sedimentary		5.7690	5.5417	2.5	978080.8293	978049.8220	978001.6714	48.1506	978002.4429
Ikom	IKM – 102401	Sedimentary		8.7236	5.9798	106	978088.7144	978084.6430	978028.6060	56.0370	978061.3176
Owerri	OWR – 105101	Sedimentary	South-Eastern Nigeria Sedimentary Terrain	7.0246	5.4983	73	978080.0805	978062.9040	978015.5015	47.4025	978038.0293
Benin	BEN – 100901	Sedimentary		5.6031	6.3167	78	978095.1800	978042.4090	977979.9095	62.4995	978003.9803
Enugu	ENU – 101701	Sedimentary		7.5668	6.4714	144	978098.2667	978082.2200	978016.6315	65.5885	978061.0699
Agbede	AGD -	Sedimentary		6.2633	6.8614	144	978106.3726	978071.3910	977997.6981	73.6929	978042.1365

Station Location	Station Code	Terrain	Region Classification	Long. (°)	Lat. (°)	Elev. (m)	Theoretical Gravity (mGal)	Drift Corrected Absolute Gravity (mGal)	Latitude Corrected Abs. Grav (mGal)	Value of Latitude Correction (mGal)	Free-air Gravity on the WGS'84 Ellips. (mGal)
Wukari	WUK – 106102	Sedimentary	Benue Valley and Gombe Sedimentary Area	9.7812	7.8709	179	978129.5078	978076.9520	977980.1265	96.8255	978035.3659
Wukari	WUK – 106101	Sedimentary		9.7858	7.8819	197	978129.7763	978074.3570	977977.2633	97.0937	978038.0575
Yola	YLA – 106201	Sedimentary		12.4304	9.2576	174	978166.3128	978100.6630	977967.0363	133.6267	978020.7327
Numan	NUM – 104801	Sedimentary		11.9090	9.5968	154	978176.1944	978105.5050	977961.9981	143.5069	978009.5225
Gombe	GMB – 102101	Sedimentary		11.1664	10.2868	441	978197.3467	978084.6670	977920.0164	164.6506	978056.1090
Gboko	GBK – 101901	Sedimentary	Benue Trough/Nupe Basin	9.0032	7.2533	203	978114.9843	978078.7370	977996.4329	82.3041	978059.0787
Lokoja	LOK – 104001	Sedimentary		6.4610	7.4611	188	978119.7414	978089.4200	978002.3585	87.0615	978060.3753
Makurdi	MKD – 104201	Sedimentary		8.6295	7.7056	94	978125.5079	978093.9760	978001.1483	92.8277	978030.1567
Bida	BDA – 101001	Sedimentary		6.0121	9.1021	147	978161.8983	978125.9790	977996.7626	129.2164	978042.1268
Mokwa	MKW – 104401	Sedimentary		5.0654	9.2974	171.5	978167.4562	978125.2450	977990.4717	134.7733	978043.3966
Baissa	BAI – 100701	Basement	Basal Slope of Adamawa Mountain	10.6167	7.2246	248	978114.3384	978022.6230	977940.9694	81.6536	978017.5022
Serti (Baruwah)	SER – 105701	Basement		11.3466	7.4989	338	978120.6229	977988.0820	977900.1482	87.9338	978004.4550
Shendam	SHD – 105801	Basement		9.5542	8.8911	231	978156.0252	978085.8660	977962.5268	123.3392	978033.8134

Station Location	Station Code	Terrain		Long. (°)	Lat. (°)	Elev. (m)	Theoretical Gravity (mGal)	Drift Corrected Absolute Gravity (mGal)	Latitude Corrected Abs. Grav (mGal)	Value of Latitude Correction (mGal)	Free-air Gravity on the WGS'84 Ellips. (mGal)
Jalingo	JAL – 102902	Basement	Basal Slope of Adamawa Mountain	11.3771	8.8929	207	978156.0733	978086.8660	977963.4785	123.3875	978027.3587
Jalingo	JAL – 102901	Basement		11.2867	8.8982	210	978156.2210	978087.3860	977963.8509	123.5351	978028.6569
Mubi	MUB – 104501	Basement		13.2670	10.2686	612	978196.7701	978017.8950	977853.8320	164.0630	978042.6952
Biu		Basement		12.1947	10.6128	726	978207.8286	978019.2640	977844.1463	175.1177	978068.1899
Jos	JOS - 103003/ 103001	Basement	Younger Granite Province and Environs	8.8913	9.8704	1282	978184.4119	977844.6040	977692.9220	151.6820	978088.5472
Bauchi (Main Base)	BAU – 100801	Basement		9.8306	10.2963	603	978197.6462	978029.9110	977864.9702	164.9408	978051.0560
Bauchi (Excentre)	BAU – 100802	Basement		9.8229	10.3204	621	978198.4123	978028.4340	977862.7276	165.7064	978054.3682
Daki Takwas		Sedimentary	Nigerian Section of the Iullemmeden Basin	5.2961	11.9882	206	978255.4729	978135.8600	977913.0915	222.7685	977976.6631
Birnin Kebbi	BKB – 101201	Sedimentary		4.1876	12.4505	231	978272.7147	978171.2610	977931.2484	240.0126	978002.5350
Sokoto	SKT – 105901	Sedimentary		5.2467	13.0090	297	978294.3593	978190.8250	977929.1705	261.6545	978020.8247
Illela	ILL – 102501	Sedimentary		5.3193	13.7331	276	978323.7317	978221.3240	977930.2999	291.0241	978015.4735
Azare		Sedimentary	Chad/Bornu Basin	10.2333	11.5875	444	978241.0258	978137.7510	977929.4243	208.3267	978066.4427
Potiskum		Sedimentary		11.0472	11.7111	422	978245.4331	978115.1130	977902.3854	212.7276	978032.6146

Station Location	**Station Code**	**Terrain**		**Long. (°)**	**Lat. (°)**	**Elev. (m)**	**Theoretical Gravity (mGal)**	**Drift Corrected Absolute Gravity (mGal)**	**Latitude Corrected Abs. Grav (mGal)**	**Value of Latitude Correction (mGal)**	**Free-air Gravity on the WGS'84 Ellips. (mGal)**
Maiduguri	MAI – 104101	Sedimentary	Chad/Bornu Basin	13.0819	11.8556	335	978250.6391	978155.9960	977938.0551	217.9409	978041.4361
Nguru	NGU – 104701	Sedimentary		10.5361	12.8292	348	978287.2923	978184.8740	977930.2854	254.5886	978037.6782
Geidam		Sedimentary		11.9214	12.8967	320	978289.9337	978184.5990	977927.3701	257.2289	978026.1221
Lagos	LAG – 103901	Sedimentary	Nigerian Section of Dahomey Basin	3.3322	6.5890	41	978100.6625	978114.3670	978046.3806	67.9864	978059.0332

Table 1(b): Gravity Field and Physical Geodetic Data Derived for the Continental Nigeria Landmass (Cont'd)

Station Location	Station Code	Free-air Gravity Anomaly on WGS'84 Ellipsoid (mGal)	Geoid Undula-tions (m)	ξ (arc sec)	η (arc sec)	θ (arc Sec)	Height of Topography above the Geoid (m)	Radius from the Centre of the Earth to the WGS '84 Spheroid (m)	Radius from the Centre of the Earth to the Geoid (m)	Potential over the Geoid (m^2s^{-2})	Free-air Gravity Value on the Geoid (mGal)	Difference between Free-air Grav. on WGS'84 Ellispoid and Geoid
Abeokuta	ABK – 100101	23.9426	25.40	-4.3935	0.6366	4.4394	28.60	6377808.81	6377834.21	62378329.70	978048.7810	7.8382
Akure Excentre	AKR – 100502	44.6069	24.72	-6.9712	1.7712	7.1927	331.28	6377798.89	6377823.61	62379557.72	978069.6611	7.6284
Akure (Main Base)	AKR – 100501	42.8654	24.75	-6.9319	1.7143	7.1408	324.25	6377798.40	6377823.15	62379441.66	978067.9108	7.6372
Ibadan	IBD – 102301	41.4487	25.71	-3.4095	2.1237	4.0168	205.29	6377782.31	6377808.03	62379184.18	978066.1929	7.9356
Osogbo (MKO)	SGB – 105001	32.1802	25.70	-1.3585	-0.0282	1.3588	283.30	6377749.22	6377774.92	62378269.68	978056.9314	7.9321
Osogbo (GPO)	SGB – 105002	30.7150	25.71	-1.1340	-0.2572	1.1628	290.29	6377748.33	6377774.05	62378167.47	978055.463	7.9356
Iseyin	ISY - 102801	42.4422	26.02	1.6128	0.8443	1.8204	289.98	6377730.75	6377756.76	62378740.39	978067.0964	8.0285
Egbe	EGB - 101601	23.0890	25.06	3.6209	-0.2725	3.6312	299.94	6377700.50	6377725.57	62377219.88	978048.0399	7.7346
Ilorin	ILR - 102701	21.5605	25.70	1.1399	1.8502	2.1732	318.30	6377680.82	6377706.52	62376923.64	978046.3161	7.9311
Kishi	KSH - 103701	27.4234	24.83	2.9271	1.1210	3.1344	368.17	6377609.35	6377634.17	62376607.35	978052.4512	7.6616
Keffi	KEF - 103601	0.2106	23.98	0.3000	5.9394	5.9470	278.02	6377638.06	6377662.05	62375160.99	978025.4981	7.4012

Station Location	Station Code	Free-air Gravity Anomaly on WGS'84 Ellipsoid (mGal)	Geoid Undula-tions (m)	ξ (arc sec)	η (arc sec)	θ (arc Sec)	Height of Topography above the Geoid (m)	Radius from the Centre of the Earth to the WGS '84 Spheroid (m)	Radius from the Centre of the Earth to the Geoid (m)	Potential over the Geoid (m^2s^{-2})	Free-air Gravity Value on the Geoid (mGal)	Difference between Free-air Grav. on WGS'84 Ellispoid and Geoid
Abuja (Suleja)	ABJ - 100202	11.8434	25.57	-3.2845	5.2961	6.2319	390.43	6377597.42	6377622.98	62375489.93	978036.646	7.8902
Minna	MNA - 104301	-1.9556	28.35	7.5750	-2.3648	7.9355	264.65	6377538.97	6377567.32	62374010.56	978021.9858	8.7495
Saminaka	SMK - 105601	27.4794	24.09	3.8300	0.6758	3.8892	759.41	6377441.78	6377465.87	62374980.89	978052.7585	7.4351
Kaduna	KAD - 103202	20.3668	23.78	2.7833	0.5873	2.8446	617.22	6377420.17	6377443.95	62374318.67	978045.7369	7.3387
Birnin Gwari (Main Base)	BGW – 101101	13.4437	22.94	0.6485	-1.1785	1.3451	408.06	6377409.96	6377432.90	62373784.92	978039.0621	7.0804
Birnin Gwari (GMSJ 24)	BGW – 101103	15.5076	22.94	0.6477	-1.1858	1.3511	417.06	6377409.89	6377432.84	62373915.91	978041.1258	7.0807
Birnin Gwari (GMSJ 23)	BGW – 101102	13.4264	22.94	0.6378	-1.1751	1.3370	409.06	6377409.83	6377432.77	62373782.54	978039.045	7.0802
Kano	KAN -	10.1525	22.27	-0.6813	0.9609	1.1779	453.73	6377212.66	6377234.93	62371652.67	978035.989	6.8721
Katsina	KAT – 103501	11.2937	21.15	2.5545	-1.5460	2.9860	484.85	6377062.33	6377083.48	62370266.78	978037.4828	6.5268
New Bussa	NBSA – 104602	0.3864	23.56	1.2849	0.4790	1.3713	161.44	6377511.58	6377535.14	62373939.23	978025.8023	7.2701
Kontagora	KON – 103801	14.5750	23.49	1.7659	0.5302	1.8438	322.51	6377446.24	6377469.74	62374206.14	978040.0179	7.2501
Rijau	RIJ – 105501	0.2364	21.99	4.1163	-3.1010	5.1536	334.01	6377347.31	6377369.29	62372339.35	978026.1498	6.7852
Zaria	ZAR - 100001	12.3048	22.59	3.6068	0.3766	3.6264	646.41	6377345.44	6377368.02	62373085.85	978038.0503	6.9699

Station Location	Station Code	Free-air Gravity Anomaly on WGS'84 Ellipsoid (mGal)	Geoid Undula-tions (m)	ξ (arc sec)	η (arc sec)	θ (arc Sec)	Height of Topography above the Geoid (m)	Radius from the Centre of the Earth to the WGS '84 Spheroid (m)	Radius from the Centre of the Earth to the Geoid (m)	Potential over the Geoid (m^2s^{-2})	Free-air Gravity Value on the Geoid (mGal)	Difference between Free-air Grav. on WGS'84 Ellispoid and Geoid
Zaria	ZAR/ABU - PH000	17.7125	22.57	3.6977	0.3429	3.7135	667.43	6377343.72	6377366.29	62373414.16	978043.4638	6.9644
Kafin Maiyaki	KAM - 103301	11.0740	22.22	1.1018	-0.1019	1.1065	596.78	6377300.44	6377322.66	62372570.77	978036.9301	6.8585
Funtua	FUN - 101801	30.9994	22.00	1.9210	0.2894	1.9427	694.00	6377292.39	6377314.39	62373765.21	978056.9279	6.7886
Gusau	GSU - 102201	-18.1017	21.18	3.3206	-0.9072	3.4423	443.82	6377193.87	6377215.05	62369678.36	978008.0783	6.5351
Oron	ORN - 104901	-1.5899	20.35	-8.0548	0.8873	8.1035	11.65	6377988.04	6378008.39	62378504.30	978024.8082	6.2795
Port Harcourt	PHC - 105301	-4.0239	19.39	0.7108	-1.3499	1.5256	-4.39	6377985.91	6378005.30	62378337.75	978022.6702	5.9834
Calabar (Excentre)	CAL - 101402	12.8513	21.08	-9.1846	-1.7681	9.3532	20.92	6377978.47	6377999.55	62379324.45	978039.0219	6.5065
Calabar (Main Base)	CAL - 101401	21.1396	21.15	-9.5157	-1.8882	9.7013	44.85	6377977.89	6377999.04	62379846.72	978047.2886	6.5281
Warri	WAR - 106001	-30.2358	18.88	2.4158	2.7625	3.6698	-16.38	6377939.22	6377958.10	62376214.46	977996.6174	5.8255
Ikom	IKM - 102401	28.6402	22.32	3.4087	-0.2547	3.4182	83.68	6377906.83	6377929.15	62379618.59	978054.4298	6.8878
Owerri	OWR - 105101	5.3513	19.75	-3.7622	-4.8991	6.1770	53.25	6377942.30	6377962.05	62378505.53	978031.933	6.0963
Benin	BEN - 100901	-28.7002	20.06	-7.8982	0.7786	7.9365	57.94	6377880.27	6377900.34	62375724.28	977997.7893	6.1910

Station Location	Station Code	Free-air Gravity Anomaly on WGS'84 Ellipsoid (mGal)	Geoid Undula-tions (m)	ξ (arc sec)	η (arc sec)	θ (arc Sec)	Height of Topography above the Geoid (m)	Radius from the Centre of the Earth to the WGS '84 Spheroid (m)	Radius from the Centre of the Earth to the Geoid (m)	Potential over the Geoid (m^2s^{-2})	Free-air Gravity Value on the Geoid (mGal)	Difference between Free-air Grav. on WGS'84 Ellispoid and Geoid
Enugu	ENU - 101701	28.3917	22.53	-2.0531	-0.5350	2.1216	121.47	6377867.60	6377890.12	62379216.97	978054.1175	6.9524
Agbede	AGD - 100401	9.4568	22.03	-6.7391	2.3528	7.1380	121.97	6377834.30	6377856.33	62377688.75	978035.3392	6.7973
Wukari	WUK - 106102	2.6836	20.90	-0.9087	3.1168	3.2465	158.10	6377739.27	6377760.17	62376338.60	978028.9155	6.4504
Wukari	WUK - 106101	5.3749	20.90	-0.9632	3.1057	3.2516	176.10	6377738.16	6377759.06	62376499.49	978031.6078	6.4497
Yola	YLA - 106201	-11.9534	17.58	4.1846	2.7091	4.9850	156.42	6377588.07	6377605.65	62373959.56	978015.3084	5.4243
Numan	NUM - 104801	-23.1650	18.29	-0.9261	4.7572	4.8466	135.71	6377547.48	6377565.76	62372840.58	978003.8797	5.6428
Gombe	GMB - 102101	23.4129	19.41	-0.0355	1.3376	1.3381	421.59	6377460.58	6377479.99	62374950.65	978050.1199	5.9891
Gboko	GBK - 101901	26.3985	21.96	-0.3071	1.7081	1.7354	181.04	6377798.92	6377820.89	62378423.93	978052.3007	6.7780
Lokoja	LOK - 104001	27.6954	23.45	-3.0820	2.4608	3.9439	164.55	6377779.38	6377802.83	62378300.80	978053.1392	7.2361
Makurdi	MKD - 104201	-2.5235	21.75	2.4348	0.3550	2.4605	72.25	6377755.70	6377777.45	62376158.64	978023.4437	6.7130
Bida	BDA - 101001	9.4449	25.43	-6.7559	-7.7534	10.2838	121.57	6377606.21	6377631.64	62375423.56	978034.2778	7.8490
Mokwa	MKW - 104401	10.7137	23.99	1.4394	1.4424	2.0378	147.51	6377583.37	6377607.37	62375295.49	978035.992	7.4046
Baissa	BAI - 100701	-15.1826	20.13	0.7030	0.2267	0.7387	227.87	6377801.58	6377821.71	62375816.35	978011.2898	6.2124

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Serti (Baruwah)	SER - 105701	-28.2341	19.29	3.1105	2.2856	3.8599	318.71	6377775.76	6377795.05	62374740.08	977998.5024	5.9526
Shendam	SHD - 105801	1.1274	21.69	-4.6404	3.5023	5.8137	209.31	6377630.33	6377652.02	62375166.43	978027.1206	6.6928
Jalingo	JAL - 102902	-5.3271	19.74	2.8689	-1.4357	3.2081	187.26	6377630.14	6377649.88	62374772.10	978021.2665	6.0922
Jalingo	JAL - 102901	-4.0290	19.67	2.1984	-1.1681	2.4895	190.33	6377629.53	6377649.20	62374849.67	978022.5868	6.0701
Mubi	MUB - 104501	9.9881	17.25	-1.6550	4.2678	4.5775	594.75	6377462.95	6377480.19	62374139.76	978037.3732	5.3221
Biu		35.4790	18.87	1.6176	1.8967	2.4928	707.13	6377417.52	6377436.39	62375305.26	978062.3669	5.8230
Jos	JOS - 10300/ 103001	55.8173	24.87	3.1992	1.5871	3.5712	1257.13	6377513.72	6377538.59	62377485.01	978080.8708	7.6764
Bauchi (Main Base)	BAU - 100801	18.3506	22.53	1.2228	3.8741	4.0625	580.47	6377459.35	6377481.88	62374585.46	978044.1036	6.9524
Bauchi (Excentre)	BAU - 100802	21.6623	22.53	1.3644	3.7974	4.0351	598.47	6377456.20	6377478.73	62374765.93	978047.4163	6.9519
Daki Takwas		-56.0413	20.75	2.9974	-2.2555	3.7512	185.25	6377221.77	6377242.52	62367535.21	977970.2587	6.4044
Birnin Kebbi	BKB - 101201	-30.1671	20.58	-0.3155	2.3474	2.3685	210.42	6377150.93	6377171.51	62368494.04	977996.1847	6.3503
Sokoto	SKT - 105901	-11.8801	20.08	-0.6329	1.3593	1.4994	276.92	6377062.00	6377082.08	62368795.50	978014.6266	6.1981
Illela	ILL - 102501	-17.2341	20.35	-0.8693	1.5597	1.7856	255.65	6376941.31	6376961.66	62367271.23	978009.1927	6.2808

Station Location	Station Code	Free-air Gravity Anomaly on WGS'84 Ellipsoid (mGal)	Geoid Undula-tions (m)	ξ (arc sec)	η (arc sec)	θ (arc Sec)	Height of Topography above the Geoid (m)	Radius from the Centre of the Earth to the WGS '84 Spheroid (m)	Radius from the Centre of the Earth to the Geoid (m)	Potential over the Geoid (m^2s^{-2})	Free-air Gravity Value on the Geoid (mGal)	Difference between Free-air Grav. on WGS'84 Ellispoid and Geoid
Azare		33.7436	21.12	1.1955	3.7235	3.9107	422.88	6377281.13	6377302.25	62373837.58	978059.9248	6.5179
Potiskum		-0.0909	19.54	1.4044	2.4037	2.7839	402.46	6377263.02	6377282.56	62371518.76	978026.5831	6.0315
Maiduguri	MAI - 104101	8.7379	16.53	1.6379	2.7340	3.1871	318.47	6377241.63	6377258.16	62371902.01	978036.3358	5.1002
Nguru	NGU - 104701	4.9745	19.66	0.8089	1.6660	1.8520	328.34	6377091.03	6377110.69	62370158.48	978031.6117	6.0665
Geidam		-6.5827	17.95	-1.5986	3.7722	4.0970	302.05	6377080.18	6377098.13	62369332.28	978020.5823	5.5397
Lagos	LAG - 103901	26.3571	23.74	-9.2615	0.9526	9.3104	17.26	6377857.75	6377881.50	62378978.80	978051.7063	7.3269

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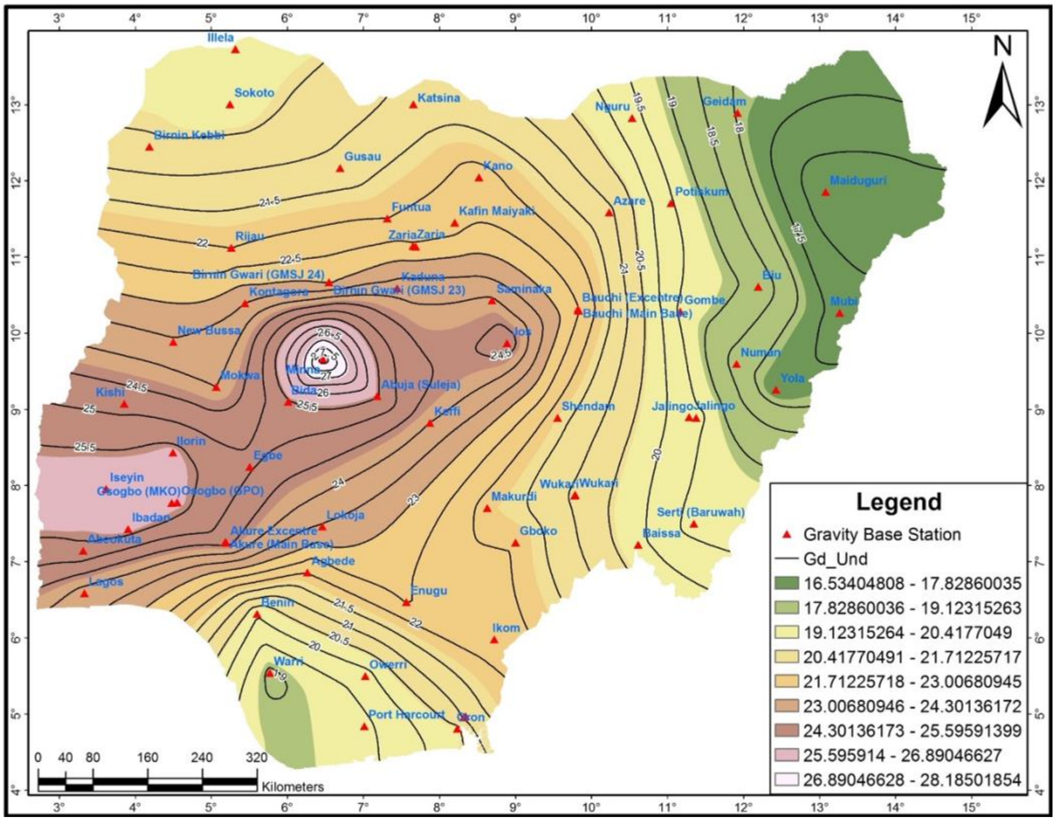

Figure 3: Map of geoid undulation over the continental Nigeria landmass

By convention, the north-south component is positive northward and the east-west component is positive eastward. To interpret the map of vertical deflections in general, when the direction of the gravity field points further south (in the case of north-south component) or further west (in the case of east-west component) than the corresponding ellipsoidal normal, then the deflection components are positive.

On the map of the total vertical deflections, areas of high values indicate larger deflection angles away from the vertical (plumbline) while areas of low values indicate less angles of deflection away from the vertical. It should be noted, however, that one will not be able to determine if deflections are positive or negative from the total vertical deflection map. Only the resultant magnitude of the deflection from the vertical can be established. The unit of measurement of the deflections from the vertical is the arc second (“)

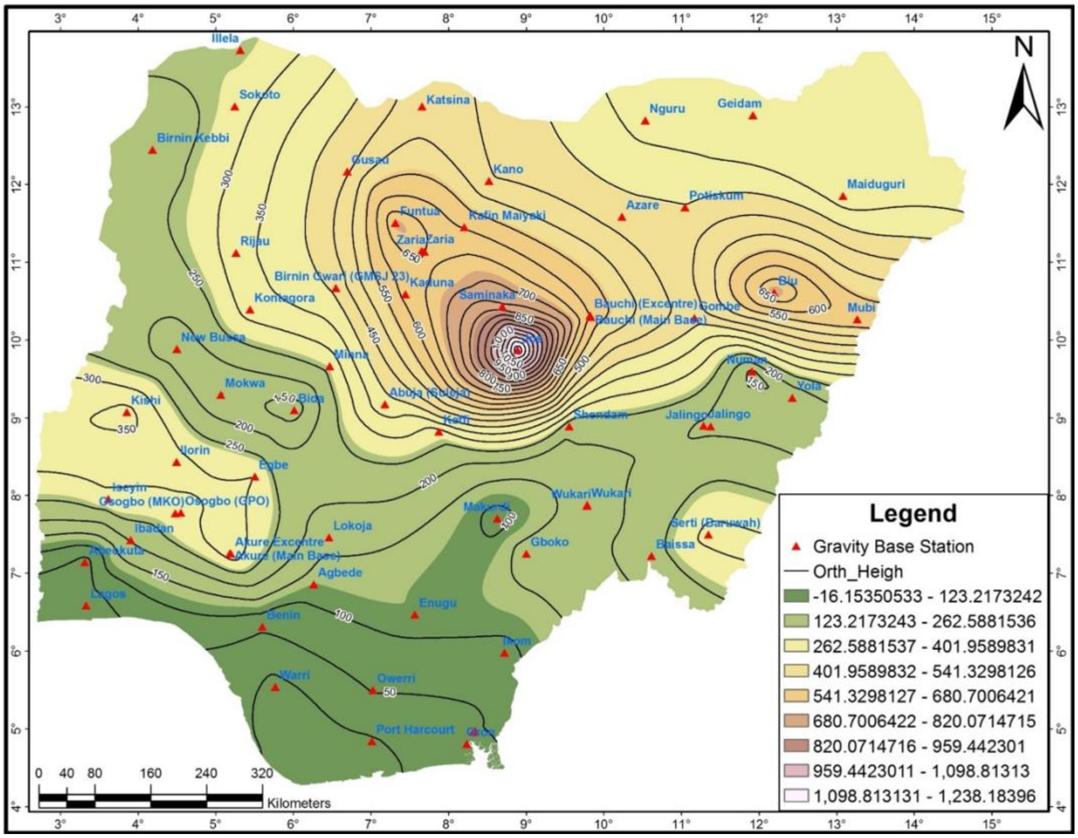

Figure 4: Raster Map of Orthometric Heights in Nigeria

Figures 5, 6 and 7 show how the vertical deflections vary across the continental Nigeria landmass. For the north-south component, deflections from the vertical range from -9.51574'' (at Calabar) to +7.574967" (at Minna). Its variation is steady in the northeastern part of the country and in the Sokoto section of the Iullemmeden basin (northwestern edge) compared to the other parts of the Nigerian landmass. Deflection magnitude is least at Gombe (-0.03553''), Keffi (0.299982"), Gboko (-0.30708") and Birnin Kebbi (-0.31552"). It was also observed that the values of the north-south component were relatively strongly positive in the central western Nigeria, over the North Central Nigeria Basement and on the Eastern Nigeria Basement while the values were negative or weakly positive over the sedimentary basins.

As for the east-west component, peak positive values (maximum deflection westwards) were found around the mountainous region of north central Nigeria (Figure 5.11). The peak negative values (maximum deflection eastwards) were observed over Bida (-7.753375"), Owerri (-4.899126"), Rijau (-3.100962") and Minna (-2.364821"). Total vertical deflections range from 0.738685'' (at

Baissa) to 10.28382” (at Bida). Maximum values were observed at Bida (10.28382’’), Calabar (9.701265”; 9.353203’’) and Lagos (9.310367”). Least values were observed at Baissa (0.738685”), Kafin Maiyaki (1.106532”) and Osogbo (1.162776”). The total vertical deflection exceeds 3.0000” in most parts of Nigeria (i.e. in the southern, central and extreme northeastern parts).

If a new local ellipsoid were to be defined from computed geoid undulations (Table 1(b), Figure 3) such that it approximates the geoid very closely, it will not be necessary to include the vertical deflections corrections (which are essential for the transformation of geodetic coordinates to astronomical coordinates and vice versa) into data realised from surveys done with reference to the newly defined local ellipsoid as the new ellipsoid approximates the geoid more accurately and the effect of the vertical deflections (plumbline curvature) will be negligible.

However, as long as the current WGS‘84 geocentric ellipsoid is being used, there will be need to include the deflections from the vertical into survey results for the transformation of astronomical coordinates to geodetic coordinates, conversion of astronomical azimuth to geodetic azimuths and the reduction of vertical and horizontal angle to the ellipsoid (WGS ’84 ellipsoid).

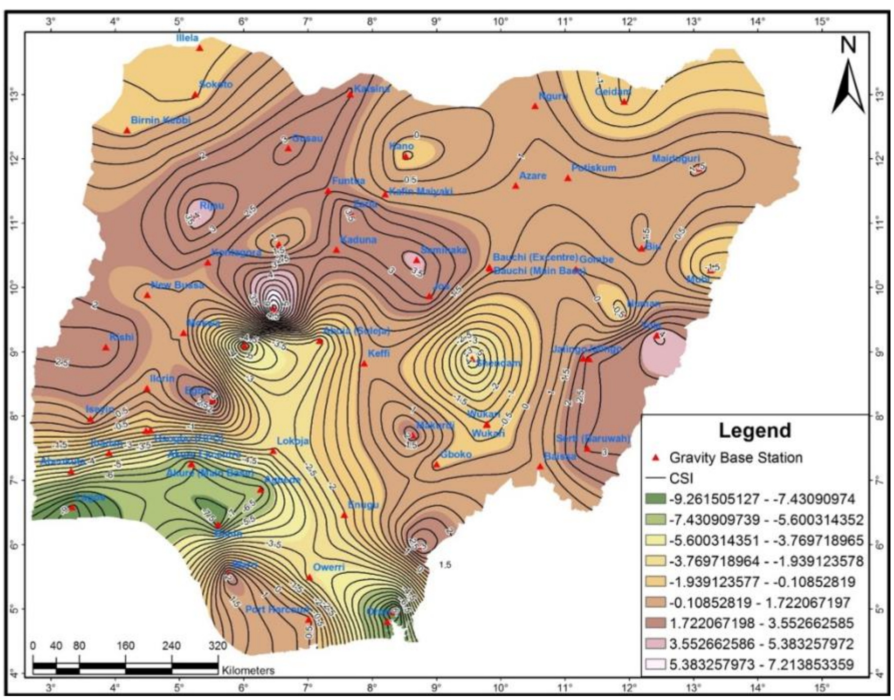

Figure 5: Map showing the North-South (Meridional) component of vertical deflection across continental Nigeria.

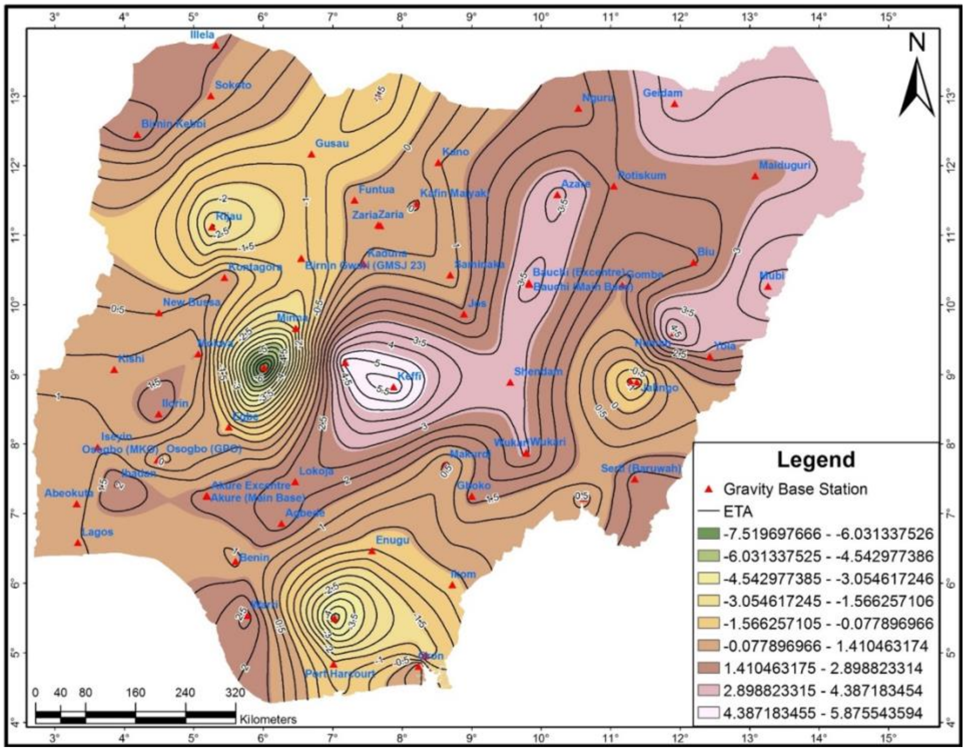

Figure 6: Map showing the East-West (Prime Vertical) component of vertical deflection across continental Nigeria.

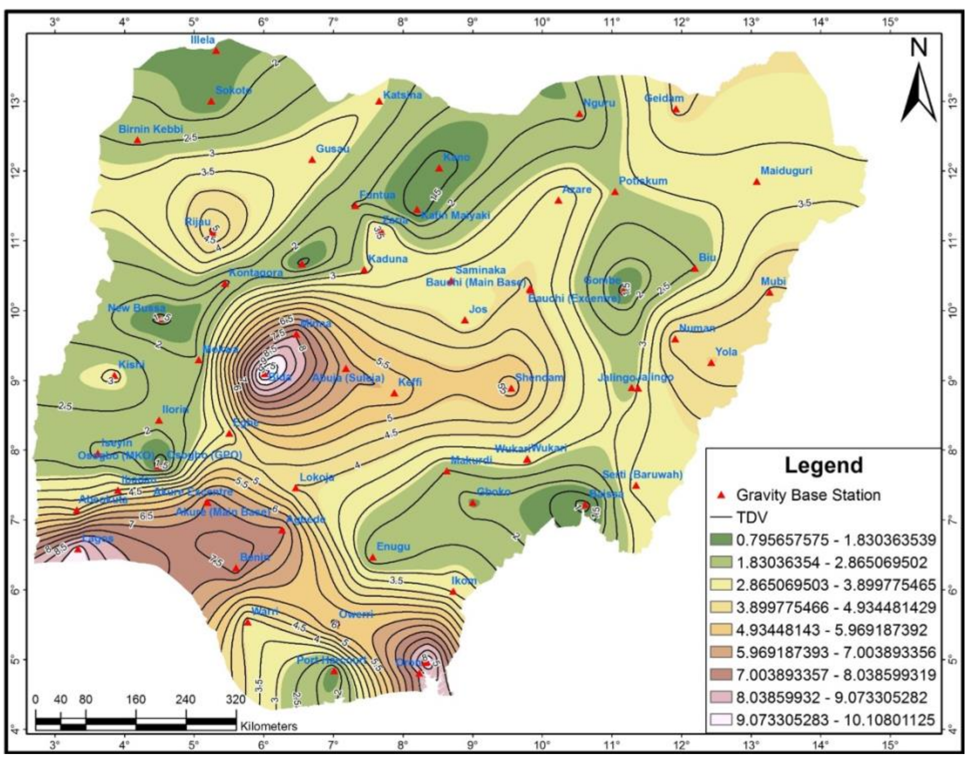

Figure 7: Map showing total vertical deflection across continental Nigeria

3.4 Distance from the Earth's Centre of Mass to the WGS'84 Reference Ellipsoidal Surface

Using equations 1 and 2 provided under "methods" section, the computed distances from the earth's centre of mass to the WGS '84 ellipsoidal surface below each of the gravity base stations were presented in Table 1(b) and Figure 8. The interpolation of these distances is expected to define the shape of the WGS '84 ellipsoid over the continental Nigeria landmass. As expected (because the earth is an ellipsoid), the distances obtained vary at different base stations.

The maximum distances were obtained in the most southerly base stations (Oron - 6377988.04 m; Port Harcourt - 6377985.91 m; Calabar - 6377978.47 m, 6377977.89 m) while the least distances were obtained at the most northerly base stations (Illela – 6376941.306 m; Sokoto – 6377061.996 m; Katsina – 6377062.335 m).

3.5 Distance from the Earth's Centre of Mass to the Geoid

With the knowledge that the geoid is above the ellipsoid, the amplitude of geoid undulations (N) were added to the distances from the earth's centre of mass to the reference ellipsoidal surface to give the distance from the earth's centre of mass to the geoidal surface Table 1(b) and Figure 9. The interpolation of the resultant distances defined the shape of the geoid over the continental Nigeria landmass. The variable distances obtained at different base stations is a proof that the earth is not a regular sphere (of constant radius) but an oblate spheroid (or ellipsoid).

It was observed that though the distances computed from the centre of the earth to the geoid exceeded the distances computed from the centre of the earth to the WGS '84 ellipsoid at each station (by some few tens of metres), the distances still decreased towards the pole with the largest radius observed at Oron (the most southerly base station) and the least observed at Illela (the most northerly station). The distance at Oron is 6378008.387 m while the distance at Illela is 6376961.659 m. The statistical range of the distances is 1046.728 m.

3.6 Gravity Potential at the Geoid

The gravity potential on the geoid at each of the gravity base stations was computed, interpolated and presented in Figure 10. The gravity potential values ranged from 62367271.23 m^2s^{-2} to 62379846.72 m^2s^{-2}. The least potential was observed at Illela while the highest potential was computed at Calabar, one of the most southerly stations.

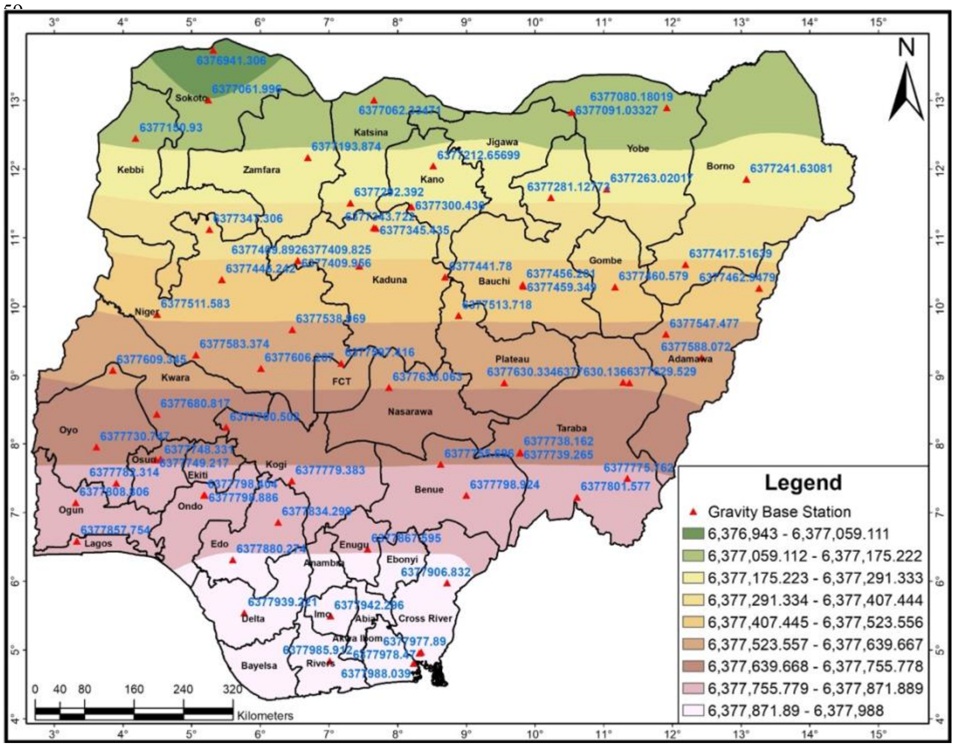

Figure 8: Map showing the distance from the earth's centre of mass to the WGS'84 Spheroid (Reference Ellipsoid) across continental Nigeria.

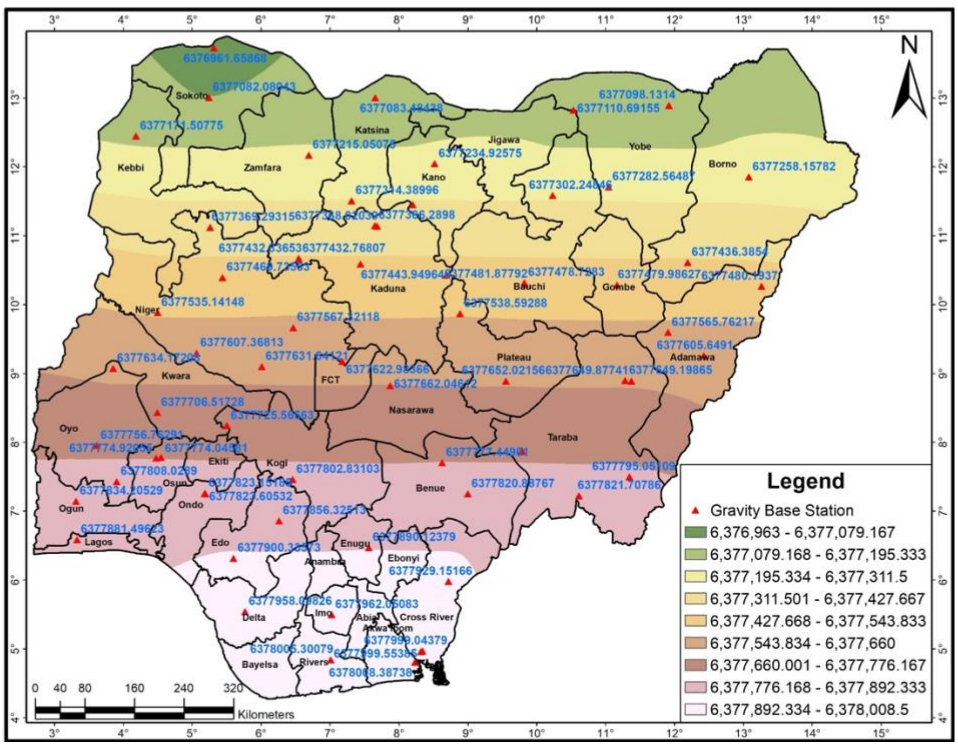

Figure 9: Map showing the distance from the earth's centre of mass to the Geoid across continental Nigeria.

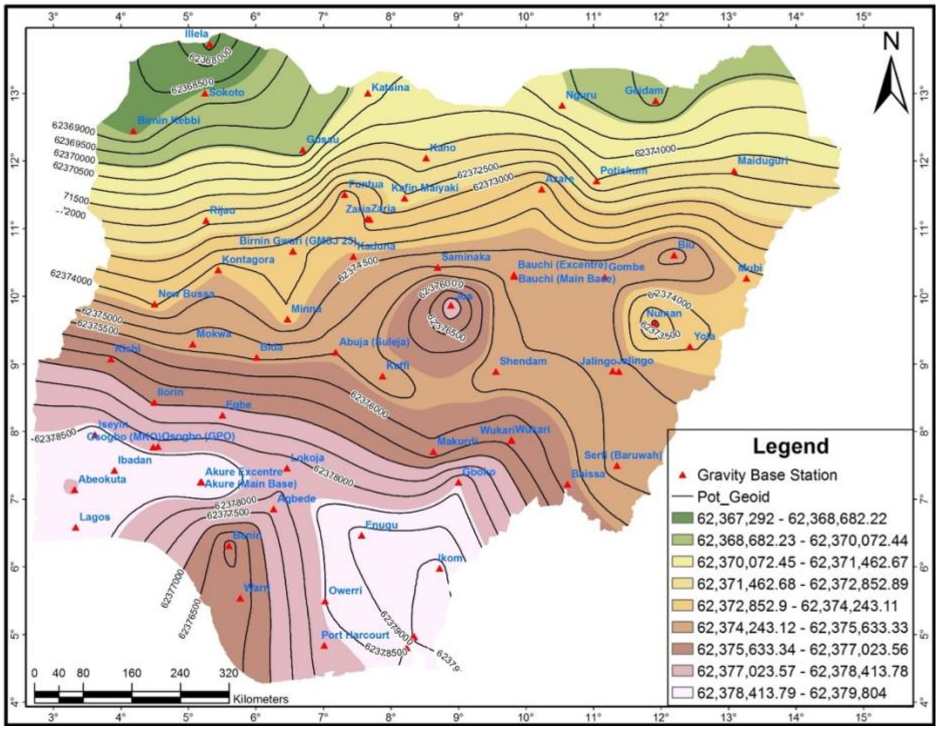

Figure 10: Map showing the gravity potential at the Geoid across continental Nigeria.

One would think that the gravity potential on the geoid at all of the base stations would be constant since the geoid is an equipotential surface but a difference of 12575.48 m^2s^{-2} was observed between the highest and the least potential. The reasons for this difference are the crustal heterogeneities within the subsurface bounded by the geoid, and the not perfectly spherical shape of the earth. However, if one were to compare the difference between the highest and least potential (evaluated as 12575.48 m^2s^{-2}) with the least potential observed (62367271.23 m^2s^{-2}), it will be discovered that the difference in potential (evaluated as 12575.48 m^2s^{-2}) is just 0.0202% of the least potential observed (i.e. 62367271.23 m^2s^{-2}). This can be considered as negligible.

To arrive at a generalised potential for the geoid over the continental area of Nigeria, the mean of all radiuses (computed at all the PGNN stations) to the geoid from the earth's centre of mass was adopted as "r", and the mean of the free-air gravity values (at all the PGNN stations) was adopted as g_{fa}. These values were plugged into "Equation 12" to obtain value of the geoid potential within the continental area of Nigeria as 62375050.41 m^2s^{-2}.

3.7 Comparison between the WGS'84 Spheroidal and the Geoidal Surfaces

Figures 11 (a) to (j) are profiles comparing the WGS'84 ellipsoid and the newly defined geoid. The highly positive correlation (in terms of shape) noticed between the WGS'84 ellipsoid and the geoid shows that the shape of the ellipsoid and the geoid are in great agreement only that they differ in potential (vertical separation).

To determine the quantitative difference between the WGS'84 ellipsoid and the geoid which have been presented to differ in terms of potential, the difference between the free-air gravity generated with heights above the WGS'84 ellipsoid (ellipsoidal heights) and the free-air gravity generated with the heights above the geoid (orthometric heights) were computed and the mean value was determined. The mean value of this difference was found to be 6.8042 mGal. This mean is the quantitative difference in mGal corresponding to the vertical separation (difference in potential) between the WGS'84 reference ellipsoid and the geoid.

Figure 11(a): Geoid and Ellipsoid at Latitude 5° (note that a base value of 6376940 m has been removed)

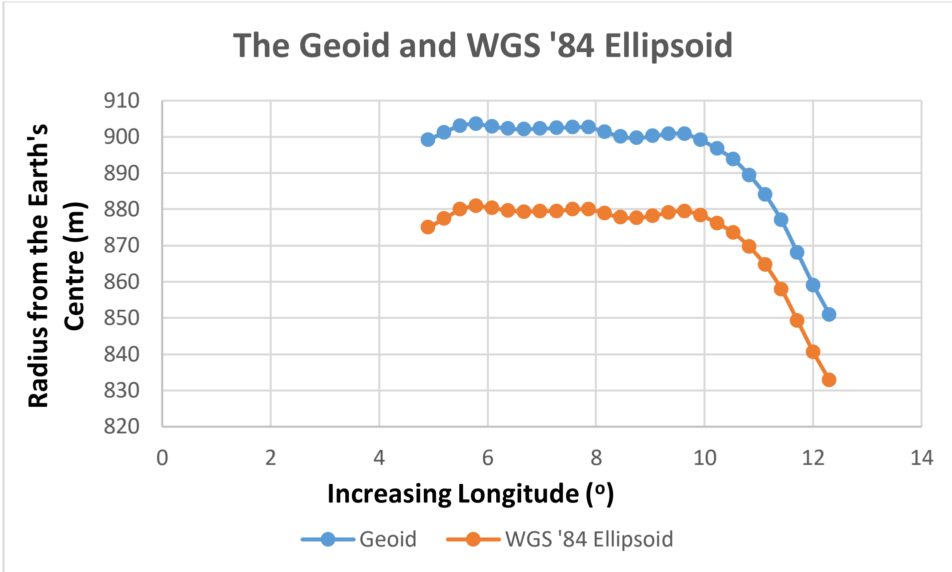

Figure 11(b): Geoid and Ellipsoid at Latitude 7° (note that a base value of 6376940 m has been removed)

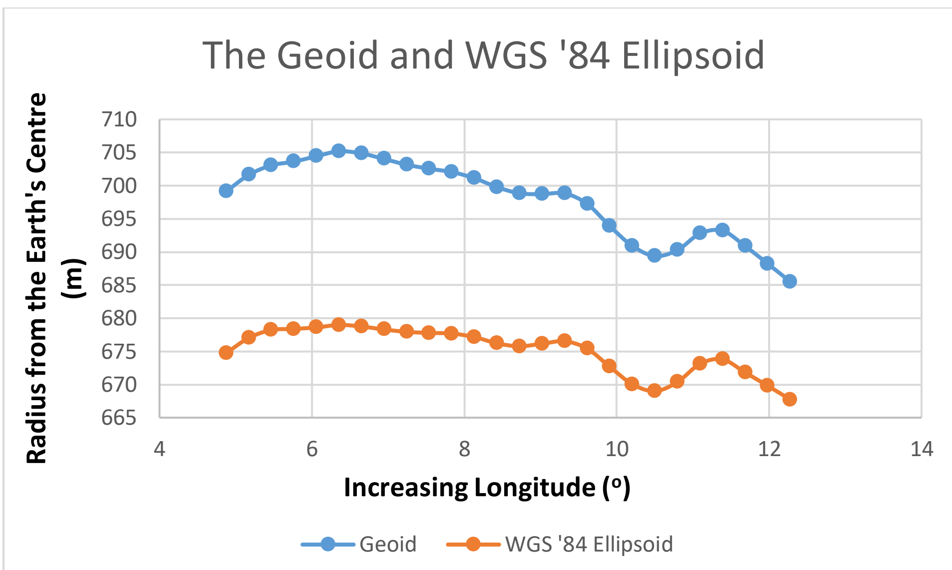

Figure 11(c): Geoid and Ellipsoid at Latitude 9° (note that a base value of 6376940 m has been removed)

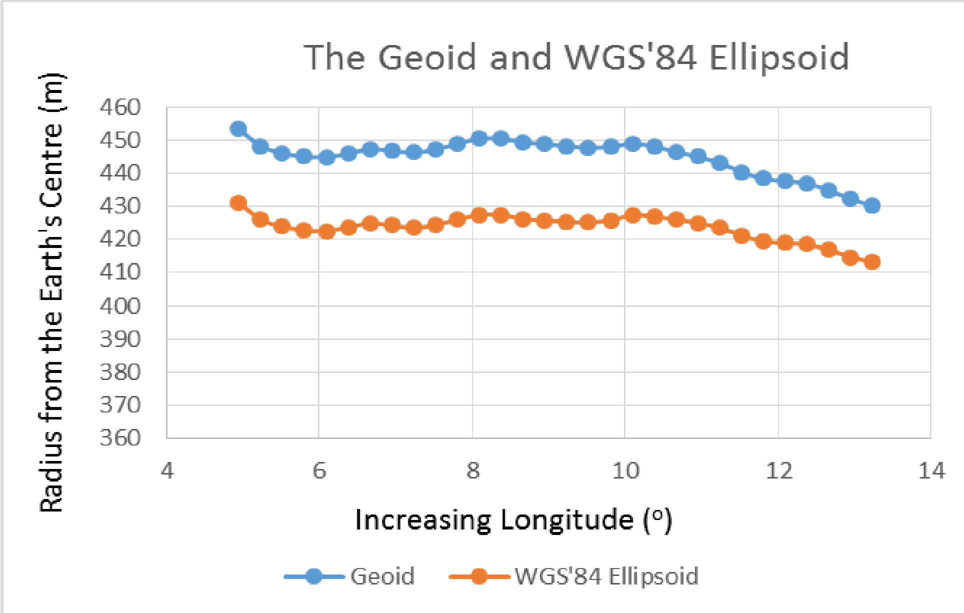

Figure 11(d): Geoid and Ellipsoid at Latitude 11° (note that a base value of 6376940 m has been removed)

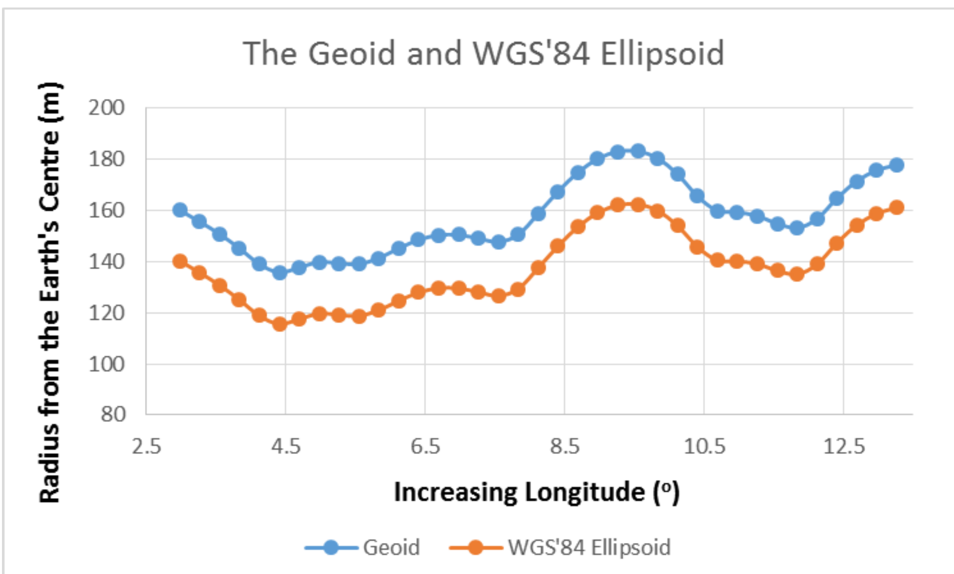

Figure 11(e): Geoid and Ellipsoid at Latitude 13° (note that a base value of 6376940 m has been removed)

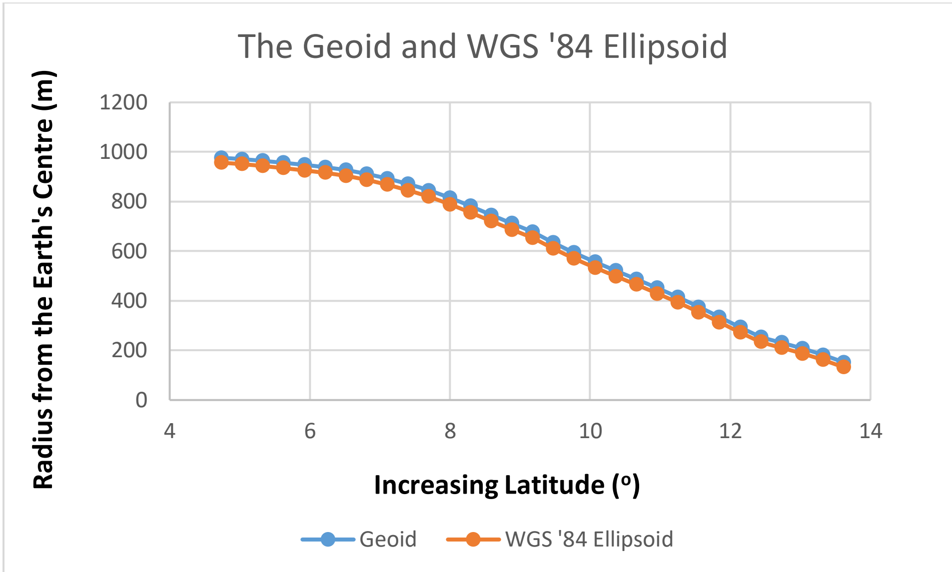

Figure 11(f): Geoid and Ellipsoid at Longitude 4° (note that a base value of 6376940 m has been removed)

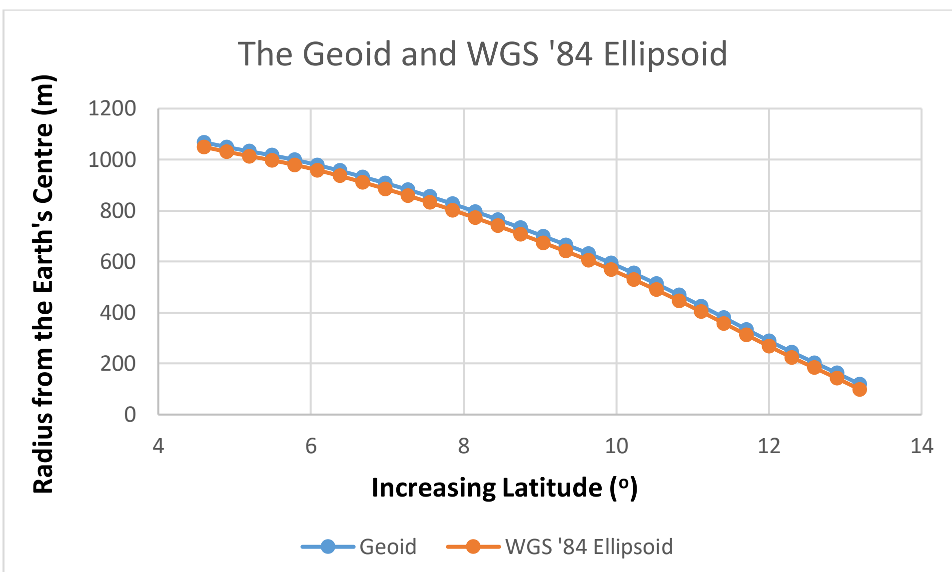

Figure 11(g): Geoid and Ellipsoid at Longitude 6° (note that a base value of 6376940 m has been removed)

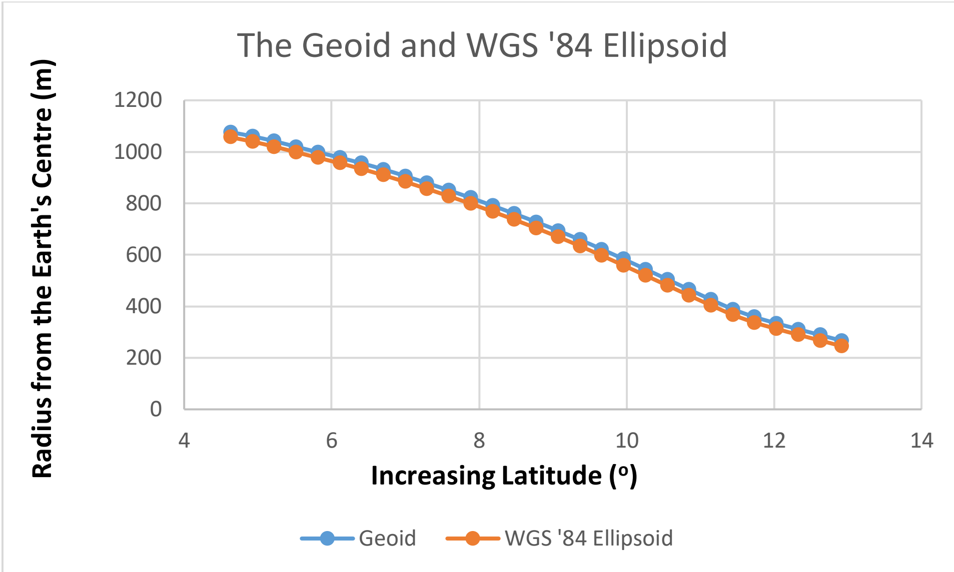

Figure 11(h): Geoid and Ellipsoid at Longitude 8° (note that a base value of 6376940 m has been removed)

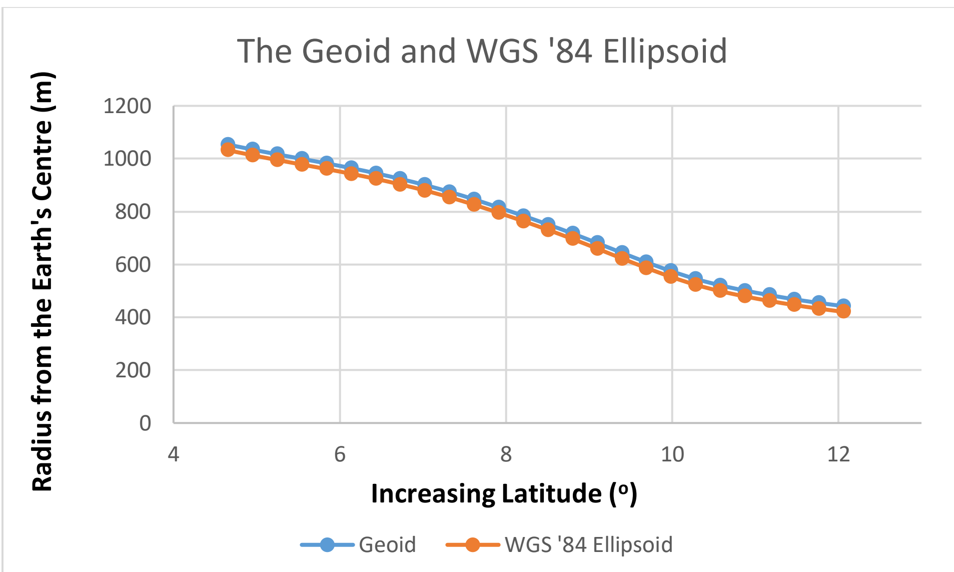

Figure 11(i): Geoid and Ellipsoid at Longitude 10° (note that a base value of 6376940 m has been removed)

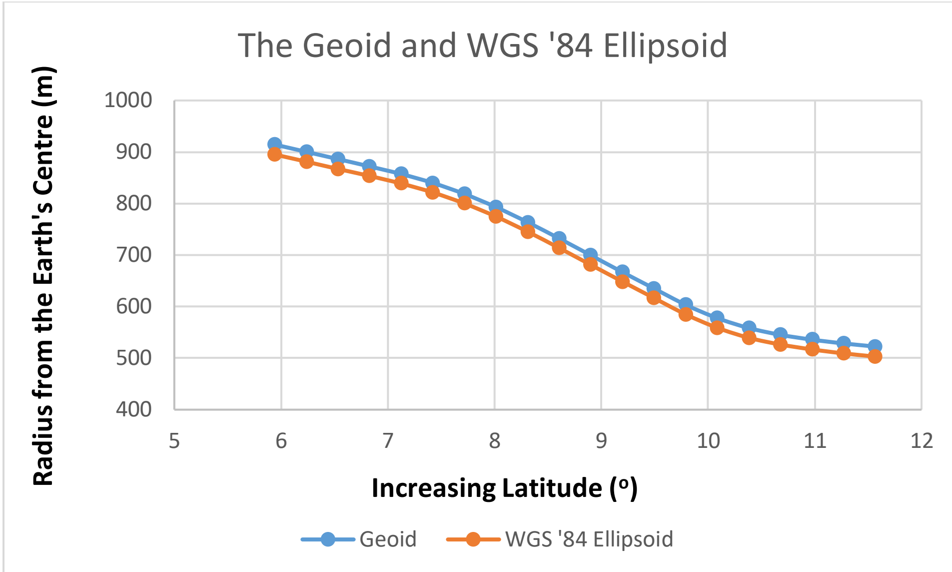

Figure 11(j): Geoid and Ellipsoid at Longitude 12° (note that a base value of 6376940 m has been removed)

4. Conclusion

Physical geodetic survey of the Nigeria landmass has been undertaken in order to make accurate geodetic information – which include geoid undulation, height above the geoid, deflections of the vertical, distance from the earth's centre of mass to the reference ellipsoid and geoid, and the gravity potential value at the geoid – which is of interest to geodesists, geoscientists, surveyors, engineers and aero-dynamists available across the Nigerian continental area using the more reliable gravity data and elevation measured with reference to the WGS'84 ellipsoid.

The basic data used were the absolute gravity field values and the coordinates and elevations at the Primary Gravity Network of Nigeria (PGNN) base stations. Appropriate mathematical and computational procedures were adopted to deduce geodetic inferences.

Geoid undulations were found to range from 16.53 to 28.35 m and the deflections from the vertical ranged between 0.738685 to 10.28328 arc second. Height above the topography ranged from -16.38 m in Warri to +1257.13 in Jos. The distance from the earth's centre of mass to the WGS'84 reference ellipsoid was maximum at Oron (6377988.04 m) and least at Illela (6376941.31 m). Similarly, the distance from the earth's centre of mass to the geoid was also maximum at Oron (6378008.39 m) and minimum in Illela (6376961.659 m). The interpolation of the distances from the earth's centre of mass to the spheroid at each base station gave the definition of the WGS'84 ellipsoid over the continental Nigeria landmass while the interpolation of the distances from the earth's centre of mass to the geoid gave the definition of the geoid over the continental Nigeria landmass. The gravity potential at the geoid was evaluated as 62375050.41 m^2s^{-2}.

The geoid over the continental Nigeria landmass was found to be comparably smooth as the WGS'84 ellipsoid over the region even though they differ in terms of vertical separation (potential). The quantitative difference in mGal corresponding to the vertical separation (difference in potential) between the WGS'84 reference ellipsoid and the geoid was computed as 6.8042 mGal.

Based on the significant range of the deflections of the vertical across the continental area of Nigeria, it was concluded that the physical structure of the lithosphere beneath the study area must be highly complex and heterogeneous.

Acknowledgement

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