Relating the Nigerian Reference Frame and AFREF

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Key words: Reference frame, ellipsoid, AFREF, Geoid, GPS

SUMMARY

A reference frame serves to define the position of an object in space. It is characterised by a reference ellipsoid and a set of datum parameters. Using a *handful* of reference ellipsoids, several reference frames can be obtained by seeking a best fit between the surfaces of the local geoid and the adopted ellipsoid. This fact, together with each country's colonial history and quest for national security and defence, has resulted in the emergence of several reference systems in Africa. This makes planning of regional and continental geospatial projects exceptionally difficult. It also presents difficulties in the utilization of regional and global geodetic information. As a result of these, there have been calls for the adoption of a uniform African coordinate system to promote *cross-border* cooperation and connectivity as a precondition for the success of the creation of regional and continental infrastructures. The World Geodetic System 1984 (WGS 84) is the most widely used global reference system because it is the system in which the very widely used GPS satellite coordinates are expressed in the Navigation *Message*. It can therefore be adopted as a uniform coordinate system for Africa. Its centre and origin are coincident with the earth's centre of mass.

In Nigeria the reference ellipsoid currently in use is Clark 1880. The centre and origin of the reference system are not coincident with the earth's centre of mass. Rather the origin is one of the triangulation stations located roughly at the centre of the associated triangulation network. Furthermore, the geoid, the reference surface for orthometric heights, has not been determined. There are, therefore, a number of difficulties to be surmounted before WGS 84 can be adopted by Nigeria *and before existing geodetic information can be correctly transformed to the WGS 84.* These difficulties are highlighted in this paper and solutions to them *proffered*.

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1. INTRODUCTION

1.1 Reference Systems and Reference Frames

A reference system serves to locate the position of an object in space. It is defined by the following:

i. a reference ellipsoid (also called spheroid), and
ii. a set of initial values and parameters on which measurements in the system are based.

The realization of a reference system is called a reference frame and involves the establishment of positions for several identifiable points on the earth and, in the case of modern reference systems, of the velocities of these points resulting from plate tectonics, together with the position of the earth's centre of mass.

Until recently, different regions of the world had adopted various reference ellipsoids to suit their local conditions. The adopted reference ellipsoid by many African nations was Clarke 1880 whose geometric constants are:

Semi-major axis, a	=	6,378,249.145
Flattering, f	=	1/293.465

Using a specific ellipsoid, an infinite number of fits can be obtained (see figure 1). This fact, together with each country's history and quest for national security and defence, has resulted in the emergence of several reference systems from only a handful of reference ellipsoids.

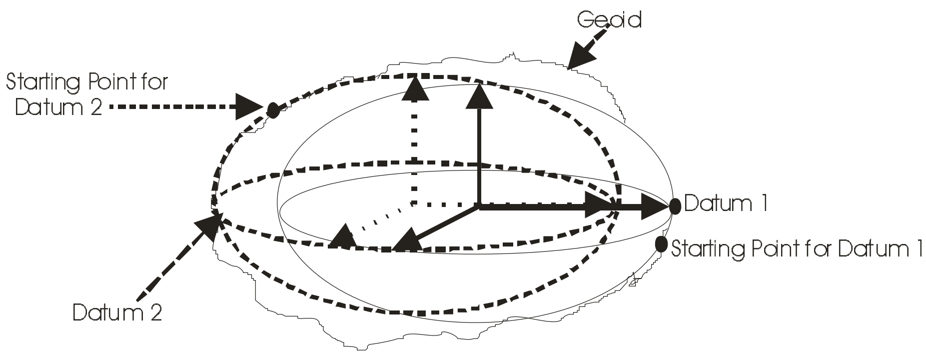

FIG. 1
Several Reference Systems from one Reference Ellipsoid
(Adapted from article on Hartebeestoek 94 – The New South African Datum)

Indeed, in some regions of the world, there are almost as many reference systems as there are countries. This proliferation of reference systems makes planning of regional and continental geospatial projects exceptionally difficult. For instance, the envisaged channelling of some waters of the Oubangui River at Palambo in Central Africa Republic through a navigable canal to Lake Chad (UNN IRIN 2002) cannot be realised if the different countries directly affected by the exercise, namely Central Africa Republic, Chad, Cameroon and Nigeria, remain in different geodetic reference systems. The proliferation also presents difficulties in the utilisation of regional and global geodetic information. As a result of these, there have been calls for the adoption of a uniform African coordinate system to promote cross-border cooperation and connectivity as a pre-condition for the success of the creation of regional and continental infrastructure.

1.2 The Nigerian Reference Frame

As in most African nations, the reference ellipsoid adopted for Nigeria is Clark 1880. The geodetic reference system is based on Minna Datum which is a local datum. The origin of the coordinate system is at station L40 (the Northern terminal of the Minna base of the Nigerian primary triangulation network) with the following adopted geodetic coordinates:

Latitude,	∅	=	09^{o} 38' 09" N
Longitude,	λ	=	06^{o} 30' 39" E
Height,	H	=	279.6 meters above the geoid.

Provisional values were used for the deviation of the vertical because data on them were not available (Uzodinma 2005).

1.3 Defects and Deficiencies in the Nigerian Reference Frame

Minna datum has a number of inherent deficiencies which introduce serious distortions in the Nigerian primary triangulation network. These distortions are actually traceable to the following sources (Uzodinma 2005).

i. Scale defects arising from use of wrong **conversion** factors in computing lengths
ii. Orientation defects arising from insufficient constraints
iii. Scale and orientation defects arising from poor definition of the network origin
iv. Scale defects arising from wrong reduction of observed data to the ellipsoid due to the absence of geoid height model.

1.3.1 <u>Scale Error</u>

A false compression of Clark 1880 ellipsoid by 1/138,000 occurred in the computation of the Invar Base distance measurements. This defect occurred because the measured distances were given in the "Clarke" foot (1 meter = 3.28086933ft) while the computations were done using tables prepared with the "British" foot (1 Meter = 3.28084558 ft).

1.3.2 Insufficient Laplace Stations

Only nine out of the 19 Laplace stations positioned at the junctions of the triangulation chains were observed. Furthermore, these observed stations are located on the western half of the geodetic network. As a result, there are insufficient azimuth checks and consequent distortions in the network.

1.3.3 Poor Definition of Network Origin

The Clark 1880 ellipsoid and the geoid should be coincident and coplanar at the origin of the network (L40). This implies that geoid height (N_o) and deviation of the vertical components in meridian and prime vertical *(ξ_o, η_o)* should have zero values at the origin, that is

$$N_o = \xi_o = \eta_o = 0$$

where $N_o = h_o - H_o$ (h_o is geodetic height of L 40).

The accuracy of the height of the origin (L 40) above the mean sea level (H_o) which is given as 279.6m is suspect because it is based on the inaccurate Lagos Vertical Datum (Uzodinma 2005). It is also noted that the geodetic coordinates $\varnothing_o$, λ_o of the datum origin are not accurately known. This introduces uncertainties in the *values* of ξ_o and η_o.

1.3.4 Absence of Geoidal Height Model

Because of the absence of values for geoidal undulations (geoidal heights), observations were reduced to the geoid rather than to the ellipsoid. Consequently, these geodetic reductions introduce distortions in the network. There were reports of scale distortions of between 1-3ppm in the north-eastern part of the network as a result of the absence of values for geoidal undulations (*Uzodinma* 2005).

2. MODERN REFERENCE FRAMES

As pointed out earlier, the proliferation of reference systems makes the implementation of regional and continental geospatial projects exceedingly difficult and presents difficulties in the utilization of regional and global geodetic information. This has necessitated efforts at finding reference systems that are of regional and global applications. These efforts have given rise to a number of modern reference systems. The major modern reference systems include the World Geodetic System (WGS), the International Terrestrial Reference System (ITRS) and the Parametri Zemli. While these systems differ only slightly in concept and definition, *some of them* differ significantly in their realizations. To date, there have been several realizations of these reference systems as institutions have systematically revised positions and velocities of earth points from time to time to keep pace with how evolving technology has improved positioning accuracy.

The differences between the realizations of the systems come from the manner in which their respective Cartesian axes have been located and oriented as well as from their respective concepts of distance. With respect to distance, the internationally adopted unit of linear measurement is the meter. Presently, scientists concerned with defining up-to-date terrestrial reference systems agree that the unit of measurement, the meter, corresponds to the length of path travelled by light in a vacuum during a time interval of exactly 1/299,792,458 seconds (Snay et al 1999). But the realization of each of the modern reference frames relies on a distinct set of measurements that were performed using one or more of several widely different types of instruments and techniques, among which are Global Positioning System (GPS), Electro-optical Distance Measuring instrumentation, Doppler Satellite Positioning, Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). While each measurement type had been calibrated to fit the definition of a metre as best as possible, the observations, nevertheless, contain uncertainties. Consequently, the "scale" of any particular reference frame is somewhat less than perfect.

2.1 The World Geodetic System (WGS)

The realization of the World Geodetic System (WGS) by the US Department of Defence is one result of efforts at finding reference systems with regional and global applications. Using available surface gravity observations, results from triangulation and trilateration networks and large amounts of Doppler and optical satellite data, and employing state-of-the-art techniques, WGS was realized. WGS is continually improved as better information about the earth becomes available. To date four such systems have been developed, namely WGS 60, WGS 66, WGS 72 and WGS 84, each successively more accurate. The current system, WGS 84, was realised with the coordinates of a catalogue of over 1,500 world-wide geodetic stations (Rizos 1999). The WGS 84 reference ellipsoid has a semi-major axis of 6,378,137.000m and a flattening of 1/298.257223563. Its centre and origin are coincident with the earth's centre of mass. The Z-axis is the direction of the IERS (International Earth Rotation Service) Reference Pole. The X-axis is the intersection of the IERS Reference Meridian and the plane passing through the origin and normal to the Z-axis. The Y-axis completes a right-handed, earth-centred, earth-fixed orthogonal co-ordinate system. Even the WGS 84 reference frame has undergone some refinements, one in 1994 and another in 1996, designated 'WGS 84 (G730)' and '*WGS 84 (G873)'* where the 'G' indicates that the refinements were obtained through Global Positioning System (GPS) techniques and the number following the 'G' indicates the GPS week number of implementation. In addition to the reference frame refinements, there has been an improvement in the global model of the earth's gravitational field now known as Earth Gravitational Model 1996 (EGM 96). This has been used to produce a refined WGS 84 geoid referred to as the WGS 84 EGM 96 Geoid (NIMA 1987). The WGS 84 system is the most widely used global reference system because it is the system in which the GPS satellite coordinates are expressed in the Navigation Message. This has further strengthened the need to adopt it by national geodetic systems.

2.2 The International Terrestrial Reference System (ITRS)

Another important reference system is the International Terrestrial Reference System (ITRS). The ITRS evolved from the initiative of the scientific community to define and maintain a datum at the highest level of accuracy. It started in 1991 when the International Association of

Geodesy (IAG) established the International GPS Service (IGS) to promote and support activities such as the maintenance of a permanent network of GPS tracking stations, and the continuous computation of the satellite orbits and ground station coordinates (Rizos 1999). These preceded the definition and maintenance of a new satellite datum that is independent of the network used to maintain the GPS datum. IERS is responsible for the definition of this reference system in which the coordinates of the tracking stations are expressed and periodically re-determined. This reference system is known as the International Terrestrial Reference System (ITRS) and its definition and maintenance is dependent on a suitable combination of the results of several space techniques, currently: Very Long Baseline Interferometry (VLBI), Lunar Laser Ranging (LLR), GPS, Satellite Laser Ranging (SLR), and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) (Boucher et al 2001). The ITRS is very much the same as WGS 84 in concept and definition but differs slightly in its realisation. The defining geometric constants are:

$\varnothing$ = 6,378,137.000m
f = 1/298.257222101

Almost every year a new combination of precise tracking results is performed and the resulting datum is referred to as ITRFxx (International Terrestrial Reference Frame xx) where “xx” denotes the year “epoch”. One characteristic that sets the ITRF series of datums apart from the WGS 84 is that the definition not only consists of the station coordinates but also their velocities due to plate tectonics. This makes it possible to determine station coordinates within the datum at some “epoch” by applying the velocity information. The IGS has adopted the ITRS as its reference frame. Consequently the IGS products are all referred to this system. Since 1997, the WGS 84 GPS broadcast ephemeris T-frame has been consistent with the ITRS at better than the 5cm level (Boucher et al 2001) and some users now refer to the two systems interchangeably.

2.3 Other Reference *Systems*

There are other reference systems. One such system is the Parametri Zemli 1990 (PZ 90). This is the reference system of the Global Navigation Satellite System (GLONASS) developed by the Russian Federation. It has been in use since November 1993 and its ellipsoid has a semi-major axis of 6,378,136m and a flattening of 1/298.257839303.

2.4 Reference System for Sustainable Geodetic Operations

Although the ITRS is the global terrestrial reference system officially adopted by the IAG, the WGS 84 reference system of the GPS is widely used by several communities and is now identical to the ITRS at the centimetre level. These facts, together with the explosive growth of GPS applications and the economics of GPS, make it the technique of choice for sustainable geodetic operations. Therefore, the use of WGS 84 is hereby stressed while ITRS is used in situations requiring the highest level of accuracy such as in scientific investigations and in the establishment of National Geodetic Datums where available space geodesy facilities permit. It is important to emphasize that the WGS 84 is fully integrated with the ITRS and its realization, the ITRF, for national, regional and continental applications.

2.5 Vertical Reference Frame

The vertical reference frame or datum forms the basis for all references in which heights are considered important. The vertical reference frame is traditionally tied to the geoid, which is closely approximated by mean sea level (Merry 2003). Therefore, the need to have a uniform height datum is a very important reason why a continental geoid should be adopted. Satellite-based observations also play a significant role in providing information on the geoidal undulation which is an important parameter in the determination of the geoid. A combination of the results of GPS observations and classical geodetic levelling remains the most accurate and straight forward approach to the determination of the geoid. Given the ellipsoidal height (h) of a point from GPS observations and the orthometric height (H) of the same point from classical geodetic levelling, the geoidal undulation (N) at a **point** is given by (see figure 2):

$$N \quad = \quad h - H$$

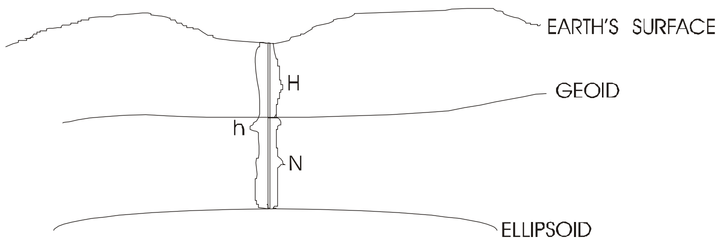

FIG. 2: Relationship between the ellipsoid, the geoid and the earth's surface

3. THE AFREF PROJECT

The African Reference Framework (AFREF) project is an African initiative with international support designed to unify the coordinate reference systems in Africa using Global Navigation Satellite Systems (GNSS) and, in particular, the GPS as the primary positioning tool. The outcome of this project will be a uniform and consistent coordinate system covering Africa to be used as the fundamental reference system for all regional and continental geospatial information, and planning and development projects across a wide spectrum of disciplines (Wonnacott 2005). It will be the fundamental basis for the national three-dimensional reference networks fully consistent and homogenous with the ITRF. When fully implemented, it will consist of a network of continuous, permanent GPS stations such that a user anywhere in Africa will have free access to and would be at most 1000km from such stations. The several objectives of the project (ICSU 2002), therefore, include:

- To define a continental geodetic reference frame
- To establish a precise and uniform African geoid
- To establish permanent GPS base stations throughout the continent which will become part of the world-wide International GPS Service

- To determine the transformation parameters between the local and the global reference systems.

The organisational structure of the project is such that every stakeholder has an avenue for making an input. The continent is split into five implementation regions based on the United Nations economic blocks. National Mapping Organisations (NMOs) are involved at the various levels of implementation of the project thus ensuring national expert representation at all levels as well as national project ownership. Although the realization of the AFREF project is a collective responsibility, certain aspects of the project require peculiar input from individual NMOs, based on results obtained from collective continental efforts. Such an input is required in the matter of relating the old and the modern systems.

4. THE CHALLENGES OF RELATING THE "ANCIENT" AND THE MODERN

4.1 Remedying Defects and Deficiencies in the old system

Before the Nigerian local reference system can be transformed to WGS 84, the system's defects and deficiencies highlighted in section 1.3 have to be addressed.

i. The scale check program mentioned in Uzodinma (2005) can be completed by carrying out additional measurements in parts of the country where they are sparse, and completing the re-adjustment.

ii. More Laplace stations can be observed to ensure their even spread throughout the country.

iii. From figure 3, the difference between the geoid and the Lagos Datum is given by the following relationship:

$$\boldsymbol{\delta_n} = h_{84} - H_s - \Delta h$$

where h_{84} is the height of L40 above WGS 84 ellipsoid and can be obtained from GPS observation

Δh may be obtained from Standard Molodensky transformation formula (NIMA 1987).

H_s is height above Lagos datum.

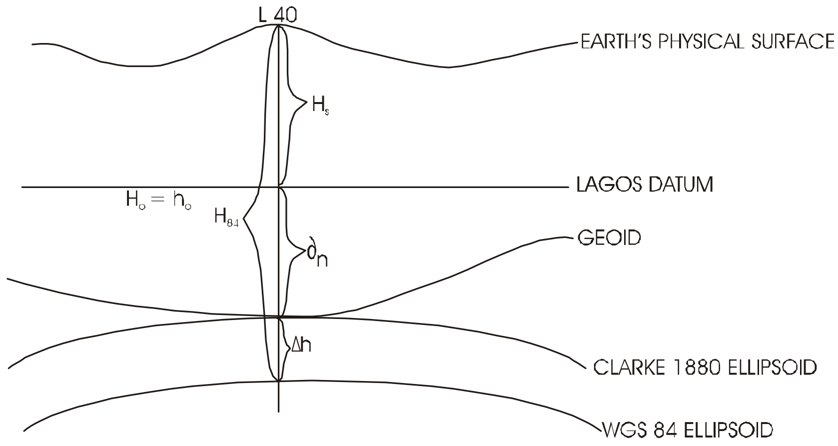

FIG. 3: Determination of δ_n
(Adapted from Uzodinma, 2005)

δ_n can, therefore, be calculated and applied as a correction to the Lagos Datum. Also, using accurate geodetic coordinates of L40 provided by GPS observations, components of the deviation of the vertical at the origin can be computed from Laplace Equations.

$$\xi_o = \Phi_o - \varnothing_o$$
$$\eta_o = \Lambda_o - \lambda_o$$

where Φ_o and Λ_o are the origin's astronomic latitude and longitude, respectively.

iv. *The question of the absence of values for geoidal undulations is already being addressed by the Federal Surveys of Nigeria through densification of GPS points whose orthometric heights could later be determined. The result would contribute to the determination of an African geoid and vertical reference frame.*

To date, there are only about 250 GPS stations distributed around the country which have been observed and coordinated. Three hundred others have been constructed but not yet coordinated and a proposal to construct an additional 120 is now being implemented (Federal Surveys of Nigeria 2004). It is important to point out that only about 16 primary triangulation stations with both orthometric and ellipsoidal heights have remained in situ.

4.2 Contributing to Continental and Global Efforts

Nigeria can contribute to continental and global geodetic efforts by providing GPS stations that would assist in the determination of the earth's centre of mass. The centre of the WGS 84 is coincident with the earth's centre of mass. The centre of mass of the earth is related to the size and shape of satellite orbits (Georgiadou 2004). According to Richards (1986),

$$v = r_e[\mu/(r_e+h)^3]^{0.5}$$

where v is effective velocity of the satellite over the ground (at its sub-nadir *point), ignoring earth rotation*
r_e is the earth's radius
μ is the earth's gravitational constant ($3.986 \times 10^{14} m^3/s^2$)
h is the altitude of the satellite above the earth.

WGS 84 enables satellite positions in their orbits to be expressed as a function of time (Snay et al 2004). Therefore the position of the GPS satellite at any instant (and thus its velocity) is known. Following from this, by observing GPS satellites (or indeed any satellite with precisely known characteristics), from various points *on* the globe, including Nigeria, the centre of mass of the earth and hence the origin *of* the WGS 84 can be pinpointed. *The density and spread of these points will influence the quality of the result. Any change in the location of the earth's center of mass will subsequently affect the location and orientation of the Cartesian axes.*

4.3 Determining Transformation Parameters between Existing and New Systems

Transformation from a local geodetic datum to WGS 84 datum can be performed using the following relationships (NIMA 1987):

$$\varnothing_{WGS84} = \varnothing_{Local} + \Delta\varnothing$$
$$\lambda_{WGS84} = \lambda_{Local} + \Delta\lambda$$
$$h_{WGS84} = h_{Local} + \Delta h$$

where $\Delta\varnothing$, $\Delta\lambda$, Δh are the corrections to transform local geodetic datum coordinates to WGS 84 values and are provided by the Standard Molodensky transformation formulas. Further details are given in NIMA (1987).

Three variables required in the transformation, namely ΔX, ΔY and ΔZ are given in the table as -92, -93 and +122 respectively, for Nigeria. There will be slight changes when these values are re-determined after the steps discussed in *Sections 4.1 and 4.2* are implemented. In order to re-determine the values of ΔX, ΔY and ΔZ, the absolute coordinates of ground based collocated points in both coordinate systems are compared. The points to be transformed must be bounded by these collocated points. The implementation of the steps discussed in 4.1 will also remedy the internal defects in the existing system and ensure that it is actually the correct positions of the points that are transformed.

5. SUMMARY

This paper stresses the importance of regional and continental geodetic reference systems. The available global reference frames are also discussed. Necessary steps in relating the local Nigerian reference framework to the proposed African reference framework are explained. It is emphasized *that, as a first step,* the defects and deficiencies in the local system should be taken care of so that the values to be transformed would be the correct values. Secondly, Nigeria should contribute to the realisation of a continental reference frame by participating actively in the AFREF project and by contributing geodetic information. This would ensure the realisation of an up-to-date reference frame which would be used to revise the transformation parameters provided in the Standard Molodensky transformation formulas. Thereafter, the values in the local geodetic framework can be transformed to the continental framework.

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BIOGRAPHY NOTES

Eugene Onyeka holds a BSc degree of the University of Nigeria in Surveying. He also holds a MSc degree in Land Surveying (Photogrammetry option) of Ahmadu Bello University. He taught Surveying for seven years at Kwara State College of Technology, Ilorin, before joining Home Construction and Dredging (Nig) Ltd, first as the Chief Surveyor and later as the Project Manager (Dredging). In 1985 he became a Member of American Society for Photogrammetry and Remote Sensing. On obtaining his Surveyor's License he commenced a professional surveying practice. In 1992 he joined the academic staff of Enugu State University of Science and Technology. He has just returned from a two-year leave at the Centre for Geodesy and Geodynamics, Toro, Nigeria.

Mr. Onyeka served as a member of Anaocha Town Planning Authority. He is a member of the Nigerian Environmental Society and a member of Geoinformation Society of Nigeria where he is currently the Treasurer. In August 2001 he was elevated to the status of Fellow of the Nigerian Institution of Surveyors. In October 2002 he was appointed a Consultant to the National Space Research and Development Agency. He serves on the National Technical Committee on Earthquake Phenomena and on a Sub-Committee on Census Mapping. He also serves on the Editorial Board of the Nigerian Journal of Surveying and Geoinformatics. In October 2005, he was appointed a Director of Anambra State Urban Development Board by the Anambra *State Gvernment*. The combination of academic and practice backgrounds has had a positive influence on his research efforts. His publications include:

- Onyeka, E. C. 1981. Precision of Field Survey Measurements. The Map Maker, Vol. 6 No. 2, January, pp 14 – 18.
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He also has a number of publications in Conference Proceedings.

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