UNIFICATION OF GEODETIC DATUMS IN INTERNATIONAL BOUNDARIES

A CASE STUDY OF MALAWI, MOZAMBIQUE AND ZAMBIAN BOUNDARIES

BY

ANDREW MWALIMU SILWEMBE

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DECLARATION

I, the undersigned, declare that this dissertation represents my own work and has not previously been submitted for a degree, diploma or other qualification at this or any other University.

Signature: ……………………..
Name: Andrew Mwalimu Silwembe
Date: ……………………..

APPROVAL

This dissertation of Andrew Mwalimu Silwembe has been approved as fulfilling the partial requirements for the award of Master of Engineering in Geodesy and Geo-Information by the University of Zambia.

Examiner 1: ………… Signature: …………....... Date: ……………..

Examiner 2: ………… Signature: …………....... Date: ……………..

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ABSTRACT

The diversity of datums in use today and the technological advancements that have made possible global positioning measurements with sub-meter accuracies, require careful datum selection and careful conversion between coordinates in different datums. This is due to different positional accuracies attributed to different datums. Zambia and Malawi's coordinate system are based on Arc 1950 datum whereas Mozambique is based on 1960 Tete datum. Land Surveyors, Engineers and Planners require a unified datum or a known relationship to execute cross border projects between countries with different datums.

The research was aimed at reviewing relevant literature, tying local coordinates of Zambia-Malawi and Zambia-Mozambique international boundaries to the World Geodetic System 1984 (WGS 84) positioned on the International Terrestrial Reference Frame 2008 (ITRF2008) and to establish the relationships between geodetic datums thereby unifying them. However, the unification of the vertical datum was beyond the scope of the research.

Reviewed literature confirmed a lack of known relationship between Zambia and Mozambique datums under study and this posed a challenge to Land Surveyors in the execution of joint international boundary surveys. The Global Navigation Satellite System (GNSS) static observations were employed to collect primary data and secondary data was collected via internet, relevant organisations and archived books. The Online Positioning User Service was used to determine the WGS 84 coordinates of NYS 82 and ZP15. The raw data was analysed using Leica Geomatic Office software and the GNSS network was adjusted using three-dimensional minimally constrained network adjustment. The international boundary coordinates were tied to the WGS 84 datum which is homogeneous with ITRF2008. The transformation parameters from WGS84 to Arc 1950 datums were determined for Zambia-Malawi and Zambia-Mozambique boundaries based on twelve and seven well distributed common points respectively. The quality of fit of the Seven-Parameter transformation for the former boundary had been determined to be 0.3560m while for the latter it was 0.2724m.

Keywords: *geodetic datum, transformation parameters, adjustment, reference frame*

DEDICATION

This dissertation is dedicated to my late revered mother, Laidess Musukuma Silwembe, for the encouragement and inspiration.

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ACRONYMS AND ABBREVIATIONS

AFREF	African Geodetic Reference Frame
APREF	Asian Pacific Reference Frame
CTP	Conventional Terrestrial Pole
CTRS	Conventional Terrestrial Reference System
DMA	Defence Mapping Agency
DoD	Department of Defense
DORIS	Doppler Obitography and Radio positioning Integrated by Satellite
ECEF	Earth Centered Earth Fixed
EGM	Earth Gravitational Model
EUREF	European Union Reference Frame
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRS 80	Geodetic Reference System 1980
GTRF	Galileo Terrestrial Reference Frame
HGO	Hi-target Geomatic Office
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IGS	International GNSS System
IERS	International Earth Rotation Service
IHO	International Hydrographic Organisation
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IUGG	International Union of Geodesy and Geophysics
LGO	Leica Geomatic Office
LU	Local Uncertainty
MGM	Geographic Mission of Mozambique

MLNREP	Ministry of Lands, Natural Resources and Environmental Protection
NAD	North American Datum
NEPAD	New Partnership for Africa's Development
NGA	National Geospatial-Intelligence Agency
NZGD	New Zealand Geodetic Datum
NIMA	National Imagery and Mapping Agency
NNR	No Net Rotation
OPUS	Online Positioning User Service
PU	Positional Uncertainty
SLRF	Satellite Laser Ranging Frame
SKI	Static Kinematic
UNCTAD	United Nations Conference on Trade and Development
VLBI	Very Long Baseline Interferometry
WGS 84	World Geodetic System 1984
WMM	World Magnetic Model
ZSD	Zambia Survey Department

CHAPTER ONE: INTRODUCTION

This chapter introduces and defines a geodetic datum in general. In addition, it briefly highlights the limitations associated with different datums and the importance of having a unified and homogeneous datum across national borders and the world at large. Further, it brings to light the ideals of New Partnership for Africa's Development (NEPAD) which require that the coordinate reference frame be uniform and of an appropriate standard in order to coordinate planning and development efforts within countries and across national borders (Wonnacott, 2005).

In view of the mapping limitations associated with Zambia-Mozambique international boundary in particular, the primary objective of this research was to unify and tie the geodetic datums of the two international boundaries including Malawi, to the global geocentric World Geodetic System 1984 (WGS 84) datum. This would provide the basis for the establishment of a three-dimensional dynamic reference frame for Zambia and the regional African Reference Frame (AFREF) which was born in 2000 (Wonnacott, 2005). According to Moritz (1978), a non-geocentric datum is a thing of the past and that modern datums should be geocentric.

The author realizes the higher economic value which is attached to geodetic reference frame by the government through the Ministry of Lands and the high risks associated with wrong decision making on land related matters based on un-reliable geodetic frame. The risks would be avoided by the unification of the geodetic datums. Until a global geodetic datum is accepted, used and implemented worldwide, a means to convert (transformation relationship) between geodetic datums would be required (NIMA, 2008).

1.1 Background

A geodetic datum defines the size and shape of the earth and the origin and orientation of the coordinate systems used to map the earth (Dana, 2014). According to McWilliam (2005), it is a reference model of the earth. It is defined by the dimensions of the reference ellipsoid (semi-major axis, a, and flattening f) and its initial position (φ_o, λ_o) at the origin with respect to the earth or geoid (Hofmann, 2005). The diversity of datums in use today and the technological advancements that have made possible global positioning measurements with sub-meter accuracies, require careful datum selection and careful conversion between coordinates in different datums, (Dana, 2014). According to King et al. (1985), a geodetic datum has no specific predefined relationship with the geocentre or the earth's rotation pole. The definition is quite arbitrary and its selection is subject only to convenience, as such, local geodetic datums have little relevance outside the local region for which they are defined. The need to coordinate planning and development efforts within countries and across national borders in line with the ideals of New Partnership for Africa's Development (NEPAD) has become paramount and cannot be achieved successfully if the fundamental point of departure for these planning projects, i.e. the co-ordinate reference frame, is not uniform and of an appropriate modern standard (Wonnacott, 2005). Different nations and agencies use different datums as the basis for coordinate system used to identify positions in Geographic Information System (GIS), precise positioning and navigation. Referencing coordinates to the wrong datum can result in positional errors of hundreds of meters (Dana, 2014). Local reference frames (classically known as geodetic datums) are the basis for most topographic maps, navigation, GIS, planning, asset management, environmental and cadastral surveys (Stanaway et. al, 2012). According to Moritz (1978) a non-geocentric datum is a thing of the past and that modern datums should be geocentric. Until a global geodetic datum is accepted, used and implemented worldwide, a means to convert between geodetic datums is required (NIMA, 2008). A geocentric system provides a basic reference for the mathematical figure of the Earth. It also provides a means for establishing various geodetic datums to an Earth Centered, Earth-Fixed (ECEF) coordinate system termed the World Geodetic System (WGS). According to National Geospatial-Intelligence Agency (NGA) (2014), the World Geodetic System 1984 (WGS 84), represents the best global geodetic reference system for the Earth available at this time for practical applications of mapping, charting, geo-positioning, and navigation. This standard includes the definition of the coordinate system, fundamental and derived constants, the Earth Gravitational Model 2008 (EGM2008), the ellipsoidal (normal) gravity model, a description of the associated World Magnetic Model (WMM), and a current list of local datum transformations (NGA, 2014).

As already mentioned, a geodetic datum is a reference model of the earth defined by the dimensions of the reference ellipsoid, as such, each datum has a reference ellipsoid which is a mathematical figure of the earth. Zambia and Mozambique's coordinate systems are based on different datums namely, Arc 1950 (Clifford et. al, 2004) with the reference ellipsoid modified Clarke 1880 and Tete datum of 1960 (Clifford et. al, 2011) with the reference ellipsoid Clarke 1866 respectively. This has contributed to challenges faced by land surveyors in the execution of joint international boundary surveys particularly between Zambia and Mozambique due to different positional accuracies attributed to different datums. Unlike Mozambique, Malawi uses the same Arc 1950 datum (Clifford et. al, 2011) as Zambia, as such, there are no challenges within and across national borders except the need to tie the datum to the modern and appropriate datum (WGS 84) in line with the ideals of NEPAD. The anticipated improvement in precision and proliferation of Global Navigation Satellite System (GNSS) and GIS is dependent upon consistency between the International Terrestrial Reference Frame (ITRF) and a local reference frame which defines fixed land boundaries, services and physical infrastructure. This is only achievable through use of a suitable transformation to relate the ITRF to a local reference frame at any epoch (Stanaway et. al, 2012). ITRF is the fundamental reference datum used in geodesy defined by large networks of GNSS, Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) coordinates defined at reference epoch and site velocities (Stanaway, 2007)

1.2 Problem Statement

1. Zambia’s Arc 1950 datum is referenced to Clarke 1880 reference ellipsoid (Clifford et. al, 2004) whereas Mozambique’s Tete datum of 1960 is referenced to Clarke 1866 reference ellipsoid (Clifford et. al, 2011). According to King et al (1985), local geodetic datums have little relevance outside the local region for which they are defined. Hence there is no relationship between the stated datums. To that effect, there is need to tie local coordinates to global coordinates and establish the relationships between datums.

2. Like most local geodetic datums, Arc 1950 is basically a horizontal datum rather than three dimensional (Al Marzooqi et. al, 2005). One of the principal purposes of a world geodetic system is to eliminate the use of local horizontal geodetic datums by providing a globally consistent reference system (NGA, 2014). However, the unification of vertical datums was beyond the scope of the research.

The study endeavoured to tie local coordinates of Zambia's international boundaries to the global geocentric WGS 84 coordinates aligned with the current realization of the International Terrestrial Reference Frame 2008 (ITRF2008) at the time of research and the determination of the seven-parameter Helmet transformation relationships between the datums. This would enable the unification of the regional datums under study.

1.3 Problem

There is no known relationship between the regional datums, as such, they are rendered irrelevant outside the local region for which they are defined.

1.4 Research Questions

1. How could we unify the regional datums?
2. Can GNSS play a role in the unification of these datums?

1.5 Objectives

1. To unify the datums for Zambia's international boundaries (Malawi and Mozambique) by employing GNSS and its datum -WGS 84.
2. To establish the datum-relationships between Zambia-Mozambique and Zambia-Malawi boundaries with respect to the WGS 84 Datum.

1.6 Study Area

The study area (Figure 1.) is the stretch connecting three tri-union points. The first tri-union point connects the international boundaries of the trio countries namely; Zambia, Tanzania and Malawi whereas the second (tri-union) point connects Zambia, Malawi and Mozambique and is commonly referred to as *Coumba* with the third point connecting Zambia, Mozambique and Zimbabwe.

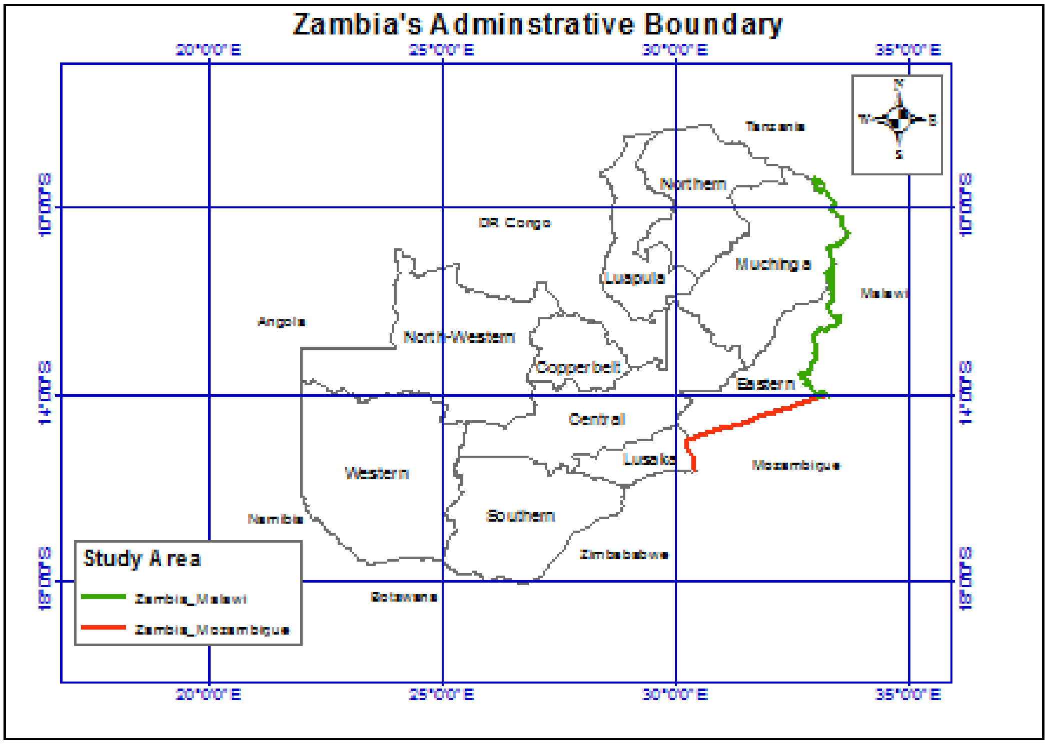


Figure 1. Study Area

1.7 Scope of Works

- To review literature on geodetic datums, datum transformations and Global Navigation Satellite System (GNSS) observations and processing.
- To collect data (local coordinates and GNSS observations) on the international boundary beacons of the study area.
- To tie international boundaries to the GNSS datum and establish the relationship (datum transformation parameters) between the various datums under study.

1.8 Significance of the Study

The main contribution of the study included establishing the datum relationship (seven transformation parameters) between local geodetic datums and the geocentric GNSS datum and tying the local datums to the world geocentric datum which provided a homogenous framework for cross border mapping activities with minimized or no miss-matched edges at the borders. In addition, this promoted information sharing for regional economic and political activities and further minimized misunderstandings and conflicts on boundary disputes.

1.9 Structure of the Dissertation

This dissertation is divided into six chapters and the contents of each chapter are briefly explained below.

Chapter One outlines the background, problem statement, problem, research questions, objectives, study area, scope of the study, significance of the study and structure of the dissertation.

Chapter Two reviews previous related literature on geodetic datums, the background and limitations of Zambia and Mozambique’s datums and datum transformation models.

Chapter Three highlights the methodology used to carry out this research.

Chapter Four presents data collection and analysis

Chapter Five presents and discusses the results obtained in chapter four.

Chapter Six presents the conclusion and recommendations

CHAPTER TWO: LITERATURE REVIEW

This chapter presents an overview of the three widely used reference frames or datums namely; Global, Regional and Local reference frames. It further highlights the background and limitations of Zambia and Mozambique's geodetic datums.

A number of the former British colonies in Southern and East Africa, including Zambia, adopted the Cape Datum co-ordinate system based on the Modified Clarke 1880 spheroid, but even these countries have different realizations of what, in name, is the same thing (Wonnacott, 2005). The adjustment carried out on the Modified Clarke 1880 ellipsoid established the datum known as the Arc 1950 Datum whose adjustment in turn established the Arc 1960 Datum. The Arc 1950 Datum and its reference ellipsoid, the Modified Clarke 1880 ellipsoid, was regarded as the first step to a common geodetic datum for Africa. It was the extension of the Cape Datum along the 30th Arc Meridian up to the Equator, thus resulting in the spread of the Modified Clarke 1880 over the African continent.

Mozambique has three classical geodetic Datums namely Madzansua, Observatorio Campo Rodrigues and Tete Datums which are all referenced to Clarke 1866 ellipsoid. According to Clifford et. al (2011), the Cape Datum was connected to Campo Rodrigues Datum of 1907 through Transvaal Triangulation. The largest of the classical horizontal geodetic datum in Mozambique is the Tete Datum commonly referred to as the Tete datum of 1960. In South Africa, the geodetic network based on the Cape Datum, served well for a century and was superseded on 1st January, 1999 by the Hartebeesthoek94 Datum based on the World Geodetic System 1984 (WGS 84) ellipsoid (Zakiewicz, 2005). Similarly, in January 1998, the Tete Datum of 1960 in Mozambique was superseded by the MOZNET98 (ITRF94) which is compatible with the WGS 84 datum (Clifford et. al., 1999). However, the official datum for Mozambique is the Tete Datum (Santos et. al, 2006). Literature review confirmed that Zambia and Malawi's geodetic datums were still referenced to Arc 1950 datum which is non-geocentric. A serious challenge was observed in the Joint Survey of the Zambia-Mozambique boundary in which the two countries are based on two different non-geocentric official datums. The challenge was avoided by unifying the two datums to the geocentric WGS 84 coordinate system.

2.1 Background

There are over 50 countries in Africa all of which are considered as developing nations and each with its own difficulties and challenges. Most of these countries have their own coordinate reference system and frame. Additionally, there are some countries that have more than one system each based on a different datum (Wonnacott, 2005). However, satellite geodesy led to the development of the global geodetic reference systems and its latest version, the well-known WGS84 which is a unifying datum worldwide.

In the introduction to the New Partnership for Africa's Development (NEPAD) dated October 2001, African leaders recognized that they have a pressing duty to eradicate poverty and to place their countries, both individually and collectively, on a path of sustainable development and thus halt the marginalization of Africa in the globalization process (UNCTAD, 2012). As a result of the importance of geographic information, the science and technology platform of NEPAD includes an objective to promote cross-border co-operation and connectivity and an action to establish regional cooperation on product standards development and dissemination (NEPAD, 2001). The fundamental point of departure for any project, application, service or product which is reliant on some form of geo-referencing, must be a uniform and reliable co-ordinate reference system (Wonnacott, 2005).

2.2 Global Reference Frames

Global reference frames define the fundamental basis for geodetic coordinates and their rates of change for any location with respect to the earth. Conventionally, the centre of mass of the earth (the geocentre) is used as the fundamental origin for a global reference system (Petit and Luzum, 2010). The earth's shape is actually determined by forces of attraction and centrifugal acceleration, these physical geodesy elements, along with others are employed to define a global geodetic datum. The following are the defining parameters of a global geodetic datum (Brinker and Minnick, 2013).

a) The datum origin is located at the earth's centre of mass
b) The Z-axis is the direction of the Conventional International Origin (CIO) defining a mean North Pole.

c) The X-axis is parallel to the zero meridian adopted by the Bureau International De L’Heure (BIH) and known as the Greenwhich mean astronomical meridian.

d) The Y-axis completes the right handed, Earth-Centred Earth-Fixed (ECEF), orthogonal reference frame.

e) A reference ellipsoid defined by;
    i. a = semi-major axis
    ii. GM = the geometric gravitational constant (the Newtonian constant, G, times the mass, M, of the earth, including the atmosphere)
    iii. J_2 = zonal spherical harmonic coefficient of second degree
    iv. ω = earth’s angular velocity

The World Geodetic System 1984 (WGS 84) Coordinate System is a Conventional Terrestrial Reference System (CTRS) defined as a right-handed, orthogonal and Earth-Centred Earth-Fixed (ECEF) coordinate system which is intended to be as closely coincident as possible with the CTRS defined by the International Earth Rotation Service (IERS). It is important to understand the definition of a coordinate system and the practical realization of a reference frame. To achieve a practical realization of a global geodetic reference frame, a set of station coordinates must be established. A consistent set of station coordinates infers the location of an origin, the orientation of an orthogonal set of Cartesian axes, and a scale. In modern terms, a globally distributed set of consistent station coordinates on the surface of the earth represents an ECEF Terrestrial Reference Frame (TRF) (NGA, 2014). Figure 2. on the next page depicts the WGS 84 Coordinate System.

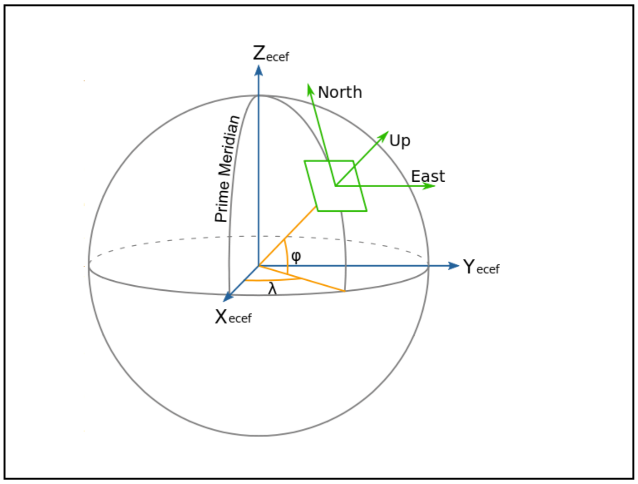


Figure 2. WGS 84 Coordinate System

Locations on the Earth’s surface are moving due to the effect of plate tectonics, so a No-Net-Rotation (NNR) condition is defined in which the angular momenta of all tectonic plates and deforming zones sum to zero. The NNR condition implicitly defines the motion of features on the Earth’s surface with respect to the underlying mantle, which is considered to be coupled with the Earth’s rotation on geological time scales. Coordinates in this system are often considered to be “absolute” (Altamimi et al., 2011). In order to maintain centimeter-level stability in a CTRS, a given set of station positions represented at a particular epoch must be updated for the effects of plate tectonic motion (NIMA, 2004). In practice, any terrestrial frame is defined by a set of points with assigned coordinates and velocities. These parameters (coordinates and velocities) materialize the reference frame. The velocities are important to change positional coordinates from one epoch to another (Soler, 2014). Given sets of globally distributed station coordinates represented at a particular epoch, slowly degrade as the stations ride along on the tectonic plates. This motion has been observed to be as much as 7cm/year at some Department of Defence (DoD) GPS tracking stations. If the accuracy requirements of a DoD application warrant it, the DoD practitioners decide which tectonic plate a given station is on and apply a plate motion model to account for these horizontal effects. The current recommended plate motion model is known as NNR-NUVEL1A (NIMA, 2004). ITRF is considered to be the fundamental realisation of a NNR terrestrial reference system and is defined by the coordinates of a combination of space geodetic sensor monuments and their site velocities around the Earth. ITRF forms the basis for many modern regional and local reference frames. Individual space geodetic techniques define specific reference frames (e.g. IGS08 for GPS, WGS84 (G1150) for GPS, SLRF2008 for SLR, and GTRF for Galileo), however these are all constrained by ITRF (Altamimi et. al., 2011). The six sets of self-consistent Global Navigation Satellite Service (GNSS) realized coordinates (Terrestrial Reference Frames) derived to date have been designated WGS 84, WGS 84 (G730), WGS 84 (G873), WGS 84 (G1150), WGS 84 (G1674) and WGS 84 (G1762) (NGA, 2014). The "G" indicates these coordinates were obtained through GNSS measurements and the number following the "G" indicates the GPS week number when these coordinates were implemented in the NIMA precise ephemeris estimation process (Soler, 2014). Table 1. shows GNSS WGS 84 reference frames derived to date and their accuracy.

Table 1. GNSS WGS 84 Reference Frames Realized to Date

Name	**Implementation Date**		**Epoch**	**Accuracy**
	GPS Broadcast Orbits	**NGA Precise Ephemeris**		
WGS 84	1987	1st January 1987		1-2 meters
WGS 84 (G730)	29th June 1994	2nd January 1994	1994.0	10cm
WGS 84 (G873)	29th January 1997	29th September 1996	1997.0	5cm
WGS 84 (G1150)	20th January 2002	20th January 2002	2001.0	1cm
WGS 84 (G1674)	8th February 2012	7th May 2012	2005.0	<1cm
WGS 84 (G1762)	16th October 2013	16th October 2013	2005.0	<1cm

Source: NGA, 2014

The latest realisation of ITRF at the time of the study was ITRF2008 (Altamimi et. al., 2011). According to the National Geospatial-Intelligence Agency (2014) formerly NIMA, the current realization of the WGS 84 reference frame is designated WGS84 (G1762) is aligned to ITRF2008 with the same epoch of 2005.0 in order to ensure scientific integrity and follow best practices. The latest WGS 84 realization marked the first time the WGS 84 reference frame was tied to the site's Antenna Reference Point (ARP) located at the base of the ground plane which supports the antenna's electronics. All previous realizations of the WGS 84 reference frames were tied to the antenna's electrical phase center so as to conform to the GPS Control Segment’s expectations. However, modern standards for reporting reference frame anchor points are for the ARP.

The principal characteristic of a kinematic reference frame such as ITRF is that the coordinates of earth-fixed features change by up to several centimetres a year due to the effects of plate tectonic. In addition, major earthquakes can result in almost instantaneous coordinate changes of up to several metres. The GNSS analysis techniques intrinsically use IGS orbit products, as such, the coordinates of GNSS reference stations should be realised by the most recent epoch of ITRF in order to prevent errors in analysis, particularly within tectonically active regions and for long baseline processing. Constantly changing coordinates, however, are impractical for most end users. For example, it is very difficult to integrate or combine spatial data collected at different epochs of measurement (e.g. laser scanned point clouds and cadastral data) (Stanaway and Roberts, 2011).

2.3 Regional Reference Frames

A regional geodetic datum (frame) has an initial point on the ellipsoidal surface and is chosen for its’ approximation to the earth’s shape for a particular area or continental land mass, but a global geodetic datum or frame has its datum point at the earth’s centre of mass and the reference ellipsoid is chosen on the basis of global “best fit” (Brinker and Minnick, 2013). Regional reference frames are realised by a denser network of geodetic tracking stations under the aegis of regional collaboration between national geodetic agencies (Stanaway et. al, 2012). A regional geodetic datum is defined by (Brinker and Minnick, 2013);

i. a = semi-major axis of the reference ellipsoid
ii. f = flattening of the reference ellipsoid
iii. ξ_o = deflection of the vertical in the meridian at the datum origin, $\xi_o = \Phi_o - \phi_o$
iv. η_o = deflection of the vertical in the prime vertical at the datum origin, $\eta_o = (\Lambda_o - \lambda_o)\cos\Phi$
v. α_o = geodetic azimuth from the origin along an initial line of network, $\alpha_o = A_o - \eta_o \tan\Phi$
vi. N_o = geoidal height at the datum origin (the distance between the reference ellipsoid and the geoid).

vii. The condition that the ellipsoid's minor axis be parallel to the earth's spin axis

Where Λ_o and Φ are astronomical longitude and latitude respectively while λ_o and ϕ_o are geodetic longitude and latitude respectively.

The regional frames include the European Union Reference Frame (EUREF), North American Datum 1983 (NAD83), Asia Pacific Reference Frame (APREF) and African Reference Frame (AFREF) among others. The Africa Reference Framework project (AFREF) is an African initiative with international support designed to unify the co-ordinate reference systems in Africa using Global Navigation Satellite Systems (GNSS) and, in particular, the Global Positioning System (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 geo-spatial information and planning and development projects across a wide spectrum of disciplines (Wonnacott, 2005). The AFREF project has been already initiated in order to unify all the geodetic datums in Africa and to create a uniform co-ordinate system positioned on ITRF (Zakiewicz, 2005). In regions which are dominated by a single and stable tectonic plate, a plate fixed condition is often used in preference to the NNR condition in order to minimise site velocities of the network stations. The relationship between plate-fixed regional reference frames, for example, the European Union Reference Frame (EUREF) and North American Datum 1983 (NAD83) and ITRF is defined by a 14 parameter conformal transformation (7 parameters at the reference epoch and their rates of change). Regional frames which encompass a variety of tectonic plates adopt a NNR approach and are fully consistent with ITRF e.g. Asia Pacific Reference Frame (APREF). Regional reference frames form the basis for national and local reference frames (Stanaway et. al, 2012).

2.4 Local Reference Frames

Local reference frames (classically known as geodetic datums) are typically defined by static coordinates of a network of fiducial or zero order geodetic monuments e.g. Ordinance Survey Great Britain 1936 (OSGB36), New Zealand Geodetic Datum 2000 (NZGD2000) (Stanaway et. al, 2012). Brinker and Minnick (2013) defines a geodetic datum using geometric geodesy concepts as follows:

i. a = semi-major axis of the reference ellipsoid
ii. b = semi-minor axis of the reference ellipsoid
iii. ϕ_o = latitude of the initial point
iv. λ_o = longitude of the initial point
v. α = azimuth from an initial point to another point

Local reference frames are the basis for most topographic maps, navigation, GIS, planning, asset management, environmental and cadastral surveys. Over the last twenty years, many developed nations have adopted different realisations of ITRF or regional reference frames as the basis for their national datums, however many jurisdictions still use non-geocentric (e.g. astro-geodetic) and assumed datums (Stanaway et. al, 2012). Until now, there are several African countries which have their co-ordinate system based on the Arc 1950 Datum and its Modified Clarke 1880 ellipsoid viz.; Botswana, Burundi, Democratic Republic of Congo, Lesotho, Malawi, Swaziland, Zambia and Zimbabwe. The Sudan portion of the Arc, while being on the Adindan Datum, was also computed on the Modified Clarke 1880 ellipsoid while Kenya and Tanzania are based on the Arc 1960 Datum (Zakiewicz, 2005). The need to coordinate planning and development efforts within countries and across national borders in line with the ideals of NEPAD has become paramount and cannot be achieved successfully if the fundamental point of departure for these planning projects, i.e. the co-ordinate reference frame, is not uniform and of an appropriate modern standard (Wonnacott, 2005). Any changes of coordinates in a static local frame are usually due to improved observations and subsequent network re-adjustments. The coordinate changes reflect better positional uncertainty (PU) and convergence towards their true values rather than any physical movement of the monument. Dimensional or Local Uncertainty (LU) can be described as the dimensional uncertainty between any adjoining points (e.g. two points on a bridge span, or two adjacent corners of a cadastral boundary), whereas PU is the uncertainty of a group of related points (e.g. a cadastral parcel, or structure) with respect to another group of points not directly connected by a cadastral boundary, engineering structure and or a geodetic datum monument (Stanaway et. al, 2012).

2.5 Background on Zambia's Geodetic Datum

Zambia is bordered by Angola (1,110Km), Democratic Republic of the Congo (1,930Km), Malawi (837Km), Mozambique (419Km), Namibia (233Km), Tanzania (338Km), Zimbabwe (813Km) and Botswana (0.15Km). The climate is tropical, modified by the altitude of the mostly high plateau with some hills and mountains (Zackiewicz, 2005). The Arc of the 30th Meridian is referenced to the Cape Datum of 1950 where the astronomic coordinates of the initial point, Buffelsfontein, near Port Elizabeth are; Φ_o = 33º 59' 32.000" S and Λ_o = 25º 30' 44.622" E. The reference ellipsoid is the Clarke 1880, with the semi-major axis, a, given as 6,378,249.145m and the inverse flattening, f^{-1}, given as 293.4663077 (Clifford, 2004).

According to Dare and Mutale (1997) the Directorate of Colonial Surveys, Federal Surveys, and the Directorate of Overseas Surveys, established 12 triangulation nets and three traverse loops between 1949 and 1964. The triangulation net (Shreeve, 1986) was initially along the Arc of the 30th Meridian which triangulation net formed part of the arc measurement for the definition of the Arc 1960 reference ellipsoid. Later surveys within Zambia were then tied to this 30th Arc measurements using triangulation or traversing techniques. The traverse stations are often designated: TP, TS, and TT for primary, secondary and tertiary traverse stations respectively. In the western part of Zambia where no classical geodetic framework existed up to the early 1980s, Satellite Doppler surveys were undertaken in order to map this part of Zambia. Doppler points were designated by the degree square of its latitude and longitude and have DP suffixes.

The Zambian geodetic framework comprises triangulation stations of primary, (ZP), secondary, (ZS), tertiary, (ZT) and quaternary (ZQ) orders. The main areas of primary control (Dare, 1997) may be grouped as follows: Part of Arc of the 30th Meridian; Fort Jameson (Chipata)/Malawi Network; Isoka Network; Zambia Main Network; Copperbelt Network; Solwezi/ Kasama/Mumbwa Loop; Fort Rosebery (Mansa) – Congo (Zaire) link; Livingstone Memorial Area – Mansa Loop; Mwinilunga Loop Traverse; Luwingu series and Mansa loop; Mankoya loop Traverse; Kalomo Livingstone loop Traverse. The side lengths in primary traverse are approximately 30 km; in other cases the lengths of sides are approximately 60 km.

The old transformation parameters (Clifford, 2004) expressed in the standard American convention sign for rotations from Arc Datum 1950 to WGS84 Datum for all of Zambia are shown in Table 2. This solution was based on eleven observed points and the accuracy represented to the nearest metre.

Table 2. Old Transformation Parameters for Zambia

Number of Common Points 11			
Parameter	Value	r.m.s	units
ΔX	-152	±0.4	m
ΔY	-60	±0.4	m
ΔZ	-297	±0.4	m
R_x	-12	±0.4	"
R_y	1	±0.8	"
R_z	8	±1	"
S.F.	-8.328	±1.773	[ppm]

A pilot project was undertaken in an area of Lusaka that developed three - transformation parameters that were different from the above parameters in excess of 10 meters per translation component. As a basis of comparison, NGA lists the 3 parameter transformation from Arc 1950 to WGS 84 as: ΔX = –147m ±21m, ΔY = –74m ±21m, ΔZ = –283m ±21m, and this solution was based on 5 points. According to Nsombo (2012), the seven (7) datum transformation (Helmert) parameters (see Table 4.0) for the whole Zambia were computed using Molodensky-Badekas model based on 36 common points. Further, a zone-by-zone transformation parameter determination was carried out in the three Universal Transverse Mercator (UTM) zones 34^o, 35^o and 36^o that cover the country. Owing to the large size of the country (753,000 sq. km) and due to inconsistencies in the local geodetic network arising from the non-adjustment of the triangulation network, it is imperative that these parameters are estimated. The following Tables 3. and 4. show the seven - datum transformation parameters from WGS84 to Clarke 1880 datums for Eastern Zambia (UTM 33^o or Zone 36L) and Zambia respectively.

Table 3. 7-Parameters for Eastern Zambia (UTM 33, Zone 36L)

Number of Common Points 11			
Rotation Origin		$\Delta X_o = 5314850.235\text{m}$	
		$\Delta Y_o = 3277181.995\text{m}$	
		$\Delta Z_o = -1277073.349\text{m}$	
Parameter	Value	r.m.s	units
ΔX	162.143	0.304	m
ΔY	62.672	0.304	m
ΔZ	299.263	0.304	m
R_x	-12.0760	0.2489	"
R_y	-0.2366	0.2938	"
R_z	6.1130	0.5587	"
S.F.	-6.1045	1.1566	[ppm]
σ_o, sigma a posteriori: 1.006m			
Statistics of the residuals			
	Lat. (φ)	Long. (λ)	Height (m)
Max.	1.991	0.998	2.330
Min.	-0.734	-1.263	-2.179
Av.	0.000	-0.002	0.000
Std. dv.	0.782	0.592	1.293
r.m.s.	0.746	0.564	1.233

Source: Nsombo, 2012

Table 4. 7-Parameters for Zambia

Number of Common 36			
Rotation Origin		$\Delta X_o = 5465694.030$m	
		$\Delta Y_o = 2905373.693$m	
		$\Delta Z_o = -1477565.885$m	
Parameter	Value	r.m.s	units
ΔX	147.870	0.315	m
ΔY	71.532	0.315	m
ΔZ	282.536	0.315	m
R_x	-10.0537	0.1731	“
R_y	-1.06305	0.2714	“
R_z	6.167565	0.2295	“
S.F.	-10.2058	0.7341	[ppm]
σ_o, sigma a posteriori: 1.889m			
Statistics of the residuals			
	Lat. (φ)	Long. (λ)	Height (m)
Max.	4.061	2.680	5.872
Min.	-3.108	-4.072	-3.317
Av.	-0.003	0.001	0.000
Std. dv.	1.593	1.722	2.189
r.m.s.	1.571	1.698	2.159

Source: Nsombo, 2012

2.6 Limitations of Zambia's Geodetic Datum

The local geodetic network is inconsistent due to a non-adjustment of the triangulation network, only partial network adjustment has been carried out (Nsombo, 2012). In addition, different ITRF realizations in various countries surrounding Zambia with the exception of a few, has contributed in the non-homogeneity of the geodetic framework across Zambia's international boundaries. This has resulted into mapping inconsistencies in cross border mapping activities. Therefore, the unification of geodetic datum in international boundaries by employing GNSS receivers which use a global datum (WGS 84) would help eliminate or reduce to a large extent the survey and mapping inconsistencies in the three countries especially between Zambia and Mozambique which are based on different geodetic datums namely Arc 1950 and Tete Datum of 1960 respectively. Unlike Mozambique, Zambia and Malawi are referenced to same Arc 1950 datum which renders no problem in the execution of cross border mapping projects. The challenge is observed in the planning and execution of cross border projects e.g. the survey of Zambia/Mozambique international boundary.

According to Nsombo (2012), the current seven transformation parameters for Zambia are aligned to ITRF2000 which in turn (NGA, 2014) is aligned to WGS84 reference frame of epoch 2001.0, while the latest realization of WGS84 reference frame of epoch 2005.0 is aligned to ITRF2008. The comparison (NGA, 2014) between latest WGS 84 Reference Frame to ITRF2008 shows a Root Mean Square (RMS) difference of less than one centimeter overall whereas a comparison (NIMA, 2002) of the WGS 84 of epoch 2001.0 to ITRF2000 showed a RMS difference of one centimeter per component. The principal characteristic of a kinematic reference frame (Stanaway and Roberts, 2011) such as ITRF is that the coordinates of earth-fixed features change by up to several centimetres a year due to the effects of plate tectonics. The GNSS analysis techniques intrinsically use IGS orbit products, as such, the coordinates of GNSS reference stations should be realised by the most recent epoch of ITRF in order to prevent errors in analysis. Therefore, such ad hoc realisations of ITRF fixed at different reference epochs are inconsistent and subsequently require time dependent transformation and deformation models to relate these ITRF coordinates to a specified fixed epoch of realisation of a local reference frame.

2.7 Background on Mozambique's Geodetic Datum

Mozambique comprise ten (10) provinces, some of which are the namesakes of local datums: Cabo Delgado, Gaza, Inhambane, Manica, Maputo, Nampula, Niassa, Sofala, Tete, and Zambézia (Clifford et. al., 1999). Mozambique is bordered by Zambia through a distance of about 419 km (Clifford et. al, 2004). According to Clifford et. al. (1999), the Mozambique – Zambia international boundary commences in the Northwest at the tripoint (with Malawi) where the Lake Nyasa – Zambezi River drainage divide meets at the 14th parallel in accordance with the agreement of June 11, 1891 between the United Kingdom and the Kingdom of Portugal. The tripoint was determined to be located at φ = 14° 00' 00"S, λ = 33° 14' 32"E by a joint boundary commission in 1904. The commission was led by Captain (later Admiral) Carlos Viegas Gago Coutinho of the Portuguese Navy and by Major O'Shee of the United Kingdom. The boundary proceeds to the southwest along the Zambezi River drainage divide until it meets the Luangwa River. Thence, the boundary follows along that river until it meets the Zambezi River to tripoint (with Zimbabwe) Beacon Number 1 where: φ = 15° 37' 27"S, λ = 30° 25' 20.3"E. Coutinho and O'Shee later spent 1904-1905 correcting and re-marking the border north of the "14°S" Malawi tripoint.

Land and boundary surveys in Mozambique were authorized by the Portuguese crown in 1857. Topographic mapping for Mozambique was designed by the Portuguese Junta das Investigações do Ultramar (Board of Overseas Research) in Lisbon, Portugal. The Junta coordinated the activities of the geographic mission that established horizontal and vertical control for photogrammetric mapping accomplished by Serviços Geográficos e Cadastrais (SGC) in Maputo. Control surveys for systematic mapping was initiated in 1931 by the SGC with the assistance of the Junta, and all 61 sheets at 1:250,000 scale were completed by 1955 (Clifford et. al., 1999). The first organization devoted to do geodetic work in Mozambique, Geodetic Mission of Eastern Africa, was created in 1907. Its activity was carried out until 1910 with plenty of difficulties arising from the terrain formation of the areas to be covered at the time. A total number of 75 first order geodetic points were established, with two bases measured. To restart the suspended work, on the 13th of July 1932, the Geographic Mission of Mozambique (MGM) was created and re-organised in 1934. It maintained intense activity until 1973 when the last campaign took place, executing successive annual campaigns of field work in Mozambique within the duration of six months on average, with office work in Lisbon. In 1983 the MGM was integrated into the Geodesy Centre referred to as Tropical Research Institute of Portugal (IICT). The triangulation network of Mozambique involves a linear development of 9000 Km covering the whole territory with a wide net appropriated for 1:250 000 cartography.

It is supported by 644 first order points, 77 second order points and 209 of lower order points (Santos et. al., 2006).

There are three classical geodetic Datums in Mozambique, and all are referenced to the Clarke 1866 ellipsoid where a = 6,378,206.4 meters and 1/f = 294.9786982. This ellipsoid was a favorite of the Portuguese in Africa which they also used in Angola. The oldest is the Madzansua Datum of 1904 with its origin at point MGM 2 (near the village of Zumbo), where: Φ_o = 15° 35' 20.7"S, Λ_o = 30° 28' 09.3"E and H_o = 1010.9 meters. The most often quoted classical datum for Mozambique in Western literature is the Observatorio Campo Rodrigues Datum of 1907. Its origin is near Maputo at (MGM 650) station where: Φ_o = 25° 58' 06.99"S, Λ_o = 32° 35' 37.75"E. The defining azimuth is unknown. The Cape Datum was connected to the Observatorio Datum of 1907 by the M'Ponduine and Ypoy (MGM 675) stations through the Transvaal triangulation. Both of these old datums were established by Captain Coutinho (Clifford et. al., 1999). The largest classical horizontal geodetic datum (Clifford et. al., 2011) is the Tete Datum of 1960. Its' origin is at the North-West (NW) Tete Baseline (MGM 799) station where: Φ_o = 16° 09' 03.058"S, Λ_o = 33° 33' 51.300"E. The reference azimuth to station Caroeira (MGM 40), α_o = 355° 50' 21.07" from south, and H_o = 132.63 meters. The Tete Datum of 1960 coordinates of MGM 2 and MGN 650 stations before adjustment were: φ = 15° 35' 15.349"S, λ = 30° 28' 15.057"E and φ = 25° 58' 10.359"S, λ = 32° 35' 40.056"E respectively. In 1995, a comprehensive re-adjustment of the entire geodetic network of Mozambique was initiated by Norway Mapping in collaboration with the government (Clifford et. al, 1999) and in 1996 (Santos et. al., 2006), it was constituted by a fundamental network with 8 absolute stations which were used to make the connection to the ITRF94 and 237 relative stations forming a first order network with 96 stations and various second order chains (Gaza and Sofala with 29 stations, Maputo, 31, Beira,19, Quelimane, 18, Nampula, 24 and Pemba 20). The project was concluded in January of 1998, and the result was a 32-point constrained adjustment of 759 two-dimensional triangulation points throughout the country which led to the designation of a new datum called MOZNET/ITRF94 (MOZNET 98), compatible with the WGS84 Datum, The government of Mozambique adopted the use of the UTM Grid in 1954 with the exception of the M'Ponduine Polyhedric Grid, no other Grids are used (Clifford et. al., 1999). The MOZNET 98 adjusted coordinates of the four stations referred to above, are shown in Table 5. below.

Table 5. MOZNET 98 Adjusted Coordinates for Four Geodetic Stations

Station	**Station Code**	**Latitude (φ)**	**Longitude (λ)**
Madzansua	MGM 2	15° 35’ 18.7529”S	30° 28’ 12.3667”E
Campo Rodrigues	MGM 650	25° 58’ 12.7520”S	32° 35’ 38.4687”E
M’Ponduine	MGM 675	25° 56’ 52.6154”S	31° 58’ 39.6248”E.
NW Tete Base	MGM 799	16° 09’ 07.0480”S	33° 33’ 49.7778”E

2.8 Limitations on Mozambique’s Geodetic Datum

The origin of the Tete Datum of 1960 (Clifford et. al. 1999) is at the North-West (NW) Tete Baseline (MGM 799) station where: Φ_o = 16° 09’ 03.058”S, Λ_o = 33° 33’ 51.300”E. The reference azimuth to station Caroeira (MGM 40), α_o = 355° 50’ 21.07” from south, and H_o = 132.63 meters. A French memo from Maputo observed that the astronomic coordinates were equal to geodetic coordinates, however it was suspected (according to the results of the computations) that the deviation of the vertical were at the point chosen for the ‘datum.’ In effect for each zone north and to the north-west, there were concentrated deflection forces due to iron mineral deposits, whereas to the south and south-east, coal and less dense minerals were found. Most likely, this hypothesis could have led to a comprehensive readjustment of the entire geodetic network of Mozambique in 1995 which led to a designation of a new datum MOZNET98 (ITRF94) based on WGS 84 datum referenced to epoch 1997.0. A seven parameter Bursa-Wolf transformation was developed, but the national model yielded residual errors as high as 30 meters. Four “regional” models were developed, but there accuracies varied between one to ten meters, depending on the “region.” To that effect, Mozambique seemed to be an ideal country for the development of a multiple regression equation model for a single national datum shift model.

2.9 Principles of Least Squares Method

Making adjustments of measured values by the method of least squares is not new. It was done by the German mathematician Karl Gauss as early as the latter part of the 18th Century. Some assumptions underlying least squares theory are that, (i) mistakes and systematic errors have been eliminated (2) the number of observation equations being adjusted is large and (3) the frequency distribution of the errors is normal. Although these basic assumptions are not always met, least squares adjustment still provides the most rigorous error treatment available (Brinker and Minnick, 2013).

There are two basic methods of employing least squares in survey adjustments (1) the observation-equation and (2) the condition-equation. The conditional equation or model enforces geometric conditions on the measurements and their residuals. However, parametric models are more commonly used because it can be difficult to express all of the conditions in a complicated measurement network. The parametric model expresses equations in terms of unknowns that were not directly measured, but relate to the measurements (e.g. a distance expressed by coordinate inverse). Observation equations are written for the parametric model with one equation written for each observation and generally expressed as a function of unknown variables equals a measurement plus a residual. For a unique solution, the number of equations must equal the number of unknowns. If redundant observations are made, then more observation equations can be written than they are needed for a unique solution and most probable values of the unknowns can be determined by the method of least squares (Brinker and Minnick, 2013) by minimizing the sum of squares of the residuals. Partial derivatives are taken with respect to each of the variables and set equal to zero after which the resulting reduced number of equations, are solved. The minimum number of observations required to solve for the seven parameters is seven (Hofmann and Moritz, 2005). However, one point yields three observation equations, as such, a minimum of three points is required to solve for the seven unknowns. The three points yield two redundant observations. The following equation (2-1) shows the matrix form of the linear observation equations in three-dimensional (3D) coordinate transformation.

$$AX = L + V \tag{2-1}$$

Where,

A is the design or coefficient matrix, X is parameter vector (vector of unknowns), L is the observation matrix and V is the vector of residuals. For three points, the design matrix will have nine rows and seven columns, where the number of rows represents the number of observation equations and the number of columns represent the number of unknown parameters. The number of rows minus the number of columns in an over-determined system, gives the redundant observation equations. According to Al Marzooqi et. al (2005), the general form of the least squares solution for the unknown parameters, X, together with their statistics, could be computed from;

$$X = (A^T PA)^{-1} A^T PL \tag{2-2}$$

$$C_{T=\sigma_O^2(A^T PA)^{-1}}$$

$$\sigma_O^2 = \frac{V^T PV}{\ddot{n} - u}$$

Where,

C_T : covariance matrix

σ_o^2 : a posteriori variance of unit weight

P : weight matrix of the observation equations

$\ddot{n}$: number of observations

u : number of unknowns

2.10 Coordinate Transformations

Three-dimensional co-ordinates could be transformed from Cartesian to curvilinear through the knowledge of the parameters of an adopted reference ellipsoid. The following sections show the basic transformation formulae between the ellipsoidal coordinates φ, λ, h and the rectangular coordinates X, Y, Z of a point outside the ellipsoid.

2.10.1 The Cartesian Co-ordinates Transformation

The forward transformation from geodetic co-ordinates (φ, λ, h) to Cartesian co-ordinates (X, Y, Z,) (Hofmann and Moritz, 2005) is given as;

$$\begin{aligned} X &= (V + h)\cos\varphi\cos\lambda \\ Y &= (V + h)\cos\varphi\sin\lambda \\ Z &= [V(1 - e^2) + h]\sin\varphi \end{aligned} \tag{2-3}$$

With:

$V = a\,(1 - e^2\sin^2\varphi)^{-½}$,

$e^2 = \frac{a^2 - b^2}{a^2}$

Where,

V, the prime vertical radius of curvature:

a, the semi-major axis of the reference ellipsoid and

e, the first eccentricity of the reference ellipsoid

2.10.2 The Curvilinear Co-ordinates Transformation

The reverse transformation from Cartesian co-ordinates (X, Y, Z) to geodetic co-ordinates (φ, λ, h) without iteration but with inherent approximation is given as:

$$\begin{aligned} \varphi &= \arctan\left[\frac{Z + e'^2 b\sin^3\theta}{P - e^2 a\cos^3\theta}\right] \\ \lambda &= \left[\frac{Y}{X}\right] \\ h &= P\cos\varphi + Z\sin\varphi - a\sqrt{1 - e^2\sin^2\varphi} \end{aligned} \tag{2-4}$$

$$\text{With: } \theta = \arctan\left[\frac{aZ}{bP}\right],\ P = \sqrt{X^2 + Y^2},\ e'^2 = \frac{a^2 - b^2}{b^2}$$

Where,

θ : the parametric latitude

b : the semi-minor axis of the reference ellipsoid

e' : the second eccentricity of the reference ellipsoid

2.10.3 Three-Dimensional Transformation in General Form

According to Hofmann and Moritz (2005), the seven parameter transformation, also denoted as Helmert transformation or similarity transformation in space between two sets of Cartesian coordinates can be formulated by the relation;

$$X_T = X_o + \mu R X \qquad (2\text{-}5)$$

Where X_o is the translation (or shift) vector, μ is a scale factor and R is a rotation matrix, X_T is the Cartesian coordinate set of one system and X is the Cartesian coordinate set of another system. The components of the shift vector are given by;

$$X_o = \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}$$

The $X_{o,}$ account for the coordinates of the origin of the X system in the X_T coordinate system. If X_T denotes WGS84 Coordinate system, the translation vector represent the coordinates of the centre of the ellipsoid with respect to the geocentre. More generally (but with GPS not necessary), three scale factors, one for each axis, could be used, however only one scale factor is considered. The rotation matrix is an orthogonal matrix which is composed of three successive rotations.

2.11 Datum Transformation Models

A (geodetic) datum transformation (Hofmann, 2005) defines the relationship between a global (geocentric) and a local (non-geocentric) three dimensional (3D) Cartesian coordinate system, as such, a datum transformation transforms one coordinate system of a certain type to another coordinate system of the same type. This is one of the primary tasks when combining GNSS data with terrestrial data i.e. transformation of geocentric WGS 84 coordinates to local terrestrial coordinates e.g. the Clarke ellipsoid or the GRS 80 ellipsoid in the United States of America and the Bessel ellipsoid in many parts of Europe. The terrestrial system is usually based on a locally best-fitting ellipsoid. The local ellipsoid is linked to a non-geocentric Cartesian coordinate system where the origin coincides with the center of the ellipsoid. The well-known datum transformation models include the Abridged Molodensky, Bursa-Wolf and Molodensky-Badekas models.

2.11.1 The Abridged - Molodensky Transformation Model

According to Al Marzooqi et. al., (2005), the Abridged - Molodensky transformation model is a five parameter datum transformation model, which transforms three dimensional curvilinear co-ordinates between two datums as used by the National Imagery and Mapping Agency (NIMA), the former Defence Mapping Agency (DMA). It simply applies the three dimensional geocentric datum shift parameters (ΔY, ΔZ, ΔX,) in conjunction with the differences between the semi-major axis (Δa) and flattening (Δf) of the local geodetic system ellipsoid and the WGS84 ellipsoid (WGS84 minus local) respectively. According to NIMA (2004), the Abridged Molodensky transformations in curvilinear form are given as;

$$\Delta\varphi'' = \frac{[-\Delta X \sin\varphi \cos\lambda - \Delta Y \sin\varphi \sin\lambda + \Delta Z \cos\varphi + (a\Delta f + f\Delta a)\sin 2\varphi]}{\rho \sin 1''}$$

$$\Delta\lambda'' = \frac{[-\Delta X \sin\lambda + \Delta Y \cos\varphi]}{v \cos\varphi \sin 1''} \qquad (2\text{-}6)$$

$$\Delta h_m = \Delta X \cos\varphi \cos\lambda + \Delta Y \cos\varphi \sin\lambda + \Delta Z \sin\varphi + (a\Delta f + f\Delta a)\sin^2\varphi - \Delta a$$

With: $\rho = \frac{a(1 - e^2)}{(1 - e^2 \sin^2\varphi)^{\frac{3}{2}}}$

Where;

φ, λ, h : geodetic coordinates of the local geodetic system ellipsoid

Δφ, Δλ, Δh : corrections to transform local datum coordinates to WGS84 φ, λ, h

ΔX, ΔY, ΔZ : corrections to transform local datum co-ordinates to WGS84 X, Y, Z

Δa, Δf : (WGS84 minus local) semi-major axis and flattening respectively

a : semi-major axis of the local geodetic system ellipsoid

f : flattening of the local geodetic system ellipsoid;

ρ : radius of curvature in the meridian.

2.11.2 The Bursa-Wolf Transformation Model

The Bursa-Wolf Transformation Model (Al Marzooqi et. al, 2005) is a seven-parameter model for transforming three-dimensional Cartesian co-ordinates between two datums. This transformation model is more suitable for satellite datums on a global scale. The transformation involves three geocentric datum shift parameters (Δ_Y , Δ_Z , Δ_X), three rotation elements (R_y, R_z, R_x,) and scale factor (1 +ΔL). The Bursa-Wolf model uses the centre of mass as the origin for rotations. The model in its matrix-vector form could be written as;

$$\begin{bmatrix} X_{WGS84} \\ Y_{WGS84} \\ Z_{WGS84} \end{bmatrix} = \begin{bmatrix} \Delta_X \\ \Delta_Y \\ \Delta_Z \end{bmatrix} + \begin{bmatrix} 1+\ \Delta L & R_z & -R_y \\ -R_z & 1+\ \Delta L & R_x \\ R_y & -R_x & 1+\ \Delta L \end{bmatrix} \begin{bmatrix} X_{CLK} \\ Y_{CLK} \\ Z_{CLK} \end{bmatrix} \tag{2-7}$$

Where;

X_{WGS84}, Y_{WGS84} and Z_{WGS84} are the global datum (WGS84) Cartesian co-ordinates;
X_{CLK}, Y_{CLK} and Z_{CLK} are the local datum (e.g. CLARK1880) Cartesian co-ordinates.

2.11.3 The Molodensky-Badekas Transformation Model

Like Bursa-Wolf, the Molodensky-Badekas is also a seven-parameter model for transforming three-dimensional Cartesian co-ordinates between two datums. This transformation model is more suitable for transformations between terrestrial and satellite datums. The transformation also involves three barycentric datum shift parameters (d_Y, d_Z, d_X), three rotation elements (R_y, R_z, R_x,) and scale factor (1 +ΔL) (Al Marzooqi et. al, 2005). In this model, the rotations and scale change take place in the region of interest, not the geocenter, hence the additional three parameters and the model is also known as the 7 + 3 model. This was done to alleviate high correlations that may exist among the usual seven parameters when computed at the geocentre (NGA, 2014). The model is theoretically identical to the Bursa-Wolf model. The Molodensky-Badekas model uses the centroid of the network as the origin for rotations whereas the Bursa-Wolf model uses the centre of mass as the origin for rotations. The model in its matrix-vector form (Al Marzooqi et. al, 2005) could be written as;

$$\begin{bmatrix} X_{WGS84} \\ Y_{WGS84} \\ Z_{WGS84} \end{bmatrix} = \begin{bmatrix} d_X \\ d_Y \\ d_Z \end{bmatrix} + \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} + \begin{bmatrix} 1+\ \Delta L & R_z & -R_y \\ -R_z & 1+\ \Delta L & R_x \\ R_y & -R_x & 1+\ \Delta L \end{bmatrix} \begin{bmatrix} X_{CLK}-X_m \\ Y_{CLK}-Y_m \\ Z_{CLK}-Z_m \end{bmatrix} \tag{2-8}$$

With: $X_m = 1/n\sum_{i=1}^{n} X_i$ $\quad Y_m = 1/n\sum_{i=1}^{n} Y_i$ $\quad Z_m = 1/n\sum_{i=1}^{n} Z_i$

Where;

X_i, Y_i, Z_i : are the Cartesian co-ordinates of one coordinate system (the local Clarke 1880) to be transformed to another system (the WGS 84) in the case of equation (2-8)

X_m, Y_m, Z_m : are the Cartesian coordinates of the centroid of the network or rotation origin.

n : is the number of common points

2.11.4 Least Squares Estimation of Transformation Parameters

Helmert transformation seven parameters are based on least squares estimation. Equation (2-8) involves multidimensional point data, hence its representation in a linearized matrix system. Linearization can be described by general form of linear equations as;

$$y = a_1x_1 + \dots + a_nx_n \qquad (2\text{-}9)$$

where $a_1 \dots a_n \in R^n$, y and x denote dependent and independent variables respectively. To simplify, the second order terms in equation (2-9) are neglected and the equation becomes;

$$y = Ax \qquad (2\text{-}10)$$

where $A \in R^n$, denotes a design matrix. Equation (2-5) and (2-10) are comparable and both have similar properties (Islam, 2014). The variables y and x could be replaced by L and X respectively and thus equation (2-10) simply becomes;

$$L = AX \qquad (2\text{-}11)$$

where L is the vector of observation equations and X is the vector of unknowns. Assuming n observations and u unkown parameters, leads to a design matrix, A, comprising n rows and u columns. According to Hofmann et. al. (1994), for n > u, the system (2-11) is over-determined and, in general, non-consistent because of observational errors or noise. To assure consistency, the noise vector, V is added to the vector of observations and equation (2-11) converts to equation (2-1) as;

$$V = AX - L$$

The Bursa-Wolf model given by equation (2-7) could be re-written in a linear form using equation (2-1) as;

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & X_{CLK} & 0 & -Z_{CLK} & Y_{CLK} \\ 0 & 1 & 0 & Y_{CLK} & Z_{CLK} & 0 - X_{CLKx} & \\ 0 & 0 & 1 & Z_{CLK} & -Y_{CLK} & X_{CLK} & 0 \end{bmatrix} \begin{bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \\ R_z \\ s \end{bmatrix} - \begin{bmatrix} X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \end{bmatrix} \qquad (2\text{-}12)$$

where;

$$V = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix},\ A = \begin{bmatrix} 1 & 0 & 0 & X_{CLK} & 0 & -Z_{CLK} & Y_{CLK} \\ 0 & 1 & 0 & Y_{CLK} & Z_{CLK} & 0 - X_{CLKx} & \\ 0 & 0 & 1 & Z_{CLK} & -Y_{CLK} & X_{CLK} & 0 \end{bmatrix},\ X = \begin{bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \\ R_z \\ s \end{bmatrix} \text{ and } L = \begin{bmatrix} X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \end{bmatrix}$$

For the detailed linearization of the Bursa-Wolf mathematical model, the reader is referred to (Islam, 2014). In a similar manner, the linearized form of Molodensky-Badekas mathematical model given by equation (2-8) could be re-written as;

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \mu_x & 0 & -\mu_z & \mu_y \\ 0 & 1 & 0 & \mu_y & \mu_z & 0 - \mu_x & \\ 0 & 0 & 1 & \mu_z & -\mu_y & \mu_x & 0 \end{bmatrix} \begin{bmatrix} T_x \\ T_y \\ T_z \\ R_x \\ R_y \\ R_z \\ s \end{bmatrix} - \begin{bmatrix} X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \end{bmatrix} \qquad (2\text{-}13)$$

With, $\begin{bmatrix} \mu_x \\ \mu_y \\ \mu_z \end{bmatrix} = \begin{bmatrix} X_{CLK} - X_m \\ Y_{CLK} - Y_m \\ Z_{CLK} - Z_m \end{bmatrix}$, $X_m = 1/n\sum_{i=1}^{n} X_i$, $Y_m = 1/n\sum_{i=1}^{n} Y_i$, $Z_m = 1/n\sum_{i=1}^{n} Z_i$,

Where,

X_m, Y_m and Z_m is the centroid of the network

X_i, Y_i and Z_i are coordinates in the local Clarke 1880 Coordinate system

X_{WGS}, Y_{WGS} and Z_{WGS} are coordinates in the geocentric WGS 84 1984 Coordinate System

T_x, T_y and T_z are shift parameters in X, Y and Z respectively between the two systems

R_x, R_y and R_z are rotation parameters in X, Y and Z respectively between the two systems

S is the scale difference between the two systems n is the number of common points between the two systems.

The Least-Squares solution of the unknown seven parameters, X, of the linearized Molodensky-Badekas model, using three minimum number of points could be computed from equation (2-13) as follows;

$$X = (A^T A)^{-1} A^T L$$

Where;

$$A = \begin{bmatrix} 1 & 0 & 0 & \mu_x & 0 & -\mu_z & \mu_y \\ 0 & 1 & 0 & \mu_y & \mu_z & 0 & -\mu_x \\ 0 & 0 & 1 & \mu_z & -\mu_y & \mu_x & 0 \\ 1 & 0 & 0 & \mu_x & 0 & -\mu_z & \mu_y \\ 0 & 1 & 0 & \mu_y & \mu_z & 0 & -\mu_x \\ 0 & 0 & 1 & \mu_z & -\mu_y & \mu_x & 0 \\ 1 & 0 & 0 & \mu_x & 0 & -\mu_z & \mu_y \\ 0 & 1 & 0 & \mu_y & \mu_z & 0 & -\mu_x \\ 0 & 0 & 1 & \mu_z & -\mu_y & \mu_x & 0 \end{bmatrix}, \quad A^T = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ \mu_x & \mu_y & \mu_z & \mu_x & \mu_y & 0 & \mu_x & \mu_y & \mu_z \\ 0 & \mu_z & -\mu_y & 0 & \mu_z & -\mu_y & 0 & \mu_z & -\mu_y \\ -\mu_z & 0 & \mu_x & -\mu_z & 0 & \mu_x & -\mu_z & 0 & \mu_x \\ \mu_y & -\mu_x & 0 & \mu_y & -\mu_x & 0 & \mu_y & -\mu_x & 0 \end{bmatrix}$$

$$X = \begin{bmatrix} T_x \\ T_y \\ T_Z \\ R_x \\ R_y \\ R_z \\ s \end{bmatrix}, \text{ and } L = \begin{bmatrix} X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \\ X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \\ X_{WGS} - X_{CLK} \\ Y_{WGS} - Y_{CLK} \\ Z_{WGS} - Z_{CLK} \end{bmatrix}$$

The design matrix, A, is a 9 by 7, row by column matrix, with two redundant observation equations. The adjustment itself (i.e the solution of the system of linear equations) is purely a mathematical task that needs to be solved by a computer or computer program. The adjustment principle $A^T PA$ = minimum necessitates for the solution the implementation of the weight matrix P. In the above case, P is assumed to be a unit matrix. Extensive details on this subject can be found in Leick and Tartanikov (2015).

CHAPTER THREE: METHODOLOGY

This chapter highlights the methodology employed in carrying out the research.

Geodesy is study of the gravity field and figure of the earth including size and shape. The scientifically relevant “figure of the earth” is the geoid. The geoid is defined as the equipotential surface of the earth’s gravity potential, of which the (mean) surface of the oceans forms part. Heights above sea level are heights above the geoid, and are thus both physically and geometrically defined (Hofmann, 2005). For an optimal understanding and use of local (or rather regional) geodetic datums, we must know their relation to the global geodetic system as used in GNSS.

To fix a position of a point in space, we need three coordinates. We could use a rectangular Cartesian coordinate system which is a basic geometric coordinate system. It may be converted computationally to ellipsoidal coordinates, φ, λ, h referred to any given reference ellipsoid or be projected on a map. Similarly, geocentric positions can be determined by GNSS to an accuracy of better than one decimeter in a purely geometric way.

3.1 Background

The quantities X_o, Y_o, and Z_o in equation (2-8) represent the coordinates of the centre of the ellipsoid with respect to the geocentre, they are called shift parameters (Moritz, 1978). Since the geocentre was not accessible to classical geodetic measurements (i.e. gravimetric methods and dynamic satellite techniques) before the satellite era, it could not be determined, as such, a fundamental or initial point such as Meades Ranch for North America and Postdam for Central Europe was chosen on the Earth’s surface. It turns out that a convenient but conventional choice of the ellipsoidal coordinates φ_1, λ_1, and h_1 of the fundamental point is equivalent to X_o, Y_o, and Z_o of the geocentre (Hofmann et. al, 2005). The advancement in technology and the birth of satellite geodesy, have led to the determination of the geocentre by physical methods i.e. gravimetric methods and dynamic satellite techniques.

The most accurate approach for obtaining the WGS 84 data or coordinates is to acquire satellite positions and the related data at the site of interest. To accomplish the conversion (transformation), local geodetic datum coordinates and WGS 84 coordinates are both required at one or more sites within the local datum area so that a local geodetic datum to WGS 84 datum shift can be computed (NIMA, 2008).

3.2 Research Design

The applied and fundamental research types with a bias towards a quantitative research approach were employed under this study. The methodology involved the following:

- Literature review of relevant material from journal articles, text books and internet.
- Design of a GNSS network for static observations
- Primary data collection by mapping using GNSS static and Real Time Kinematic observations.
- Secondary data collection from reviewed literature and relevant organisations.
- Data Analysis using Geomatic Softwares.

3.3 Research Techniques

The research instruments included the following;

- Leica Global Navigation and Satellite System (GNSS) equipment, Viva and 1200 Leica Systems.
- Leica Geomatic Office (LGO) software,
- Hi-target Geomatic Office (HGO) software
- Online Positioning User Service (OPUS)
- Static Kinematic (SKI) software
- Transformation of Coordinates software
- ZAMBAS scientific calculater

3.4 Relevant Literature Review

Literature was reviewed regarding various geodetic reference frames and the background on Zambia and Mozambique’s geodetic datum as well as estimation of datum transformation parameters for Dubai Emirate. The reviewed literature showed that Zambia (Nsombo, 2012) and Mozambique’s (Santos, 2005) datum are not homogeneous within and across national borders. According to King et. al. (1985), a local geodetic datum has no specific predefined relationship with the geocentre or the earth's rotation pole. The definition is quite arbitrary and its selection is subject only to convenience, as such, local geodetic datums have little relevance outside the local region for which they are defined.

3.5 Design of a GNSS Network for Static Observations

The GNSS Primary networks were designed for Zambia-Mozambique and Zambia Malawi. The networks included the control points in the National Grid for Zambia, Mozambique and Malawi. The minimum number, m, of sessions (Hofmann et. al, 1994) was computed by the following equation;

$$m = \frac{s-k}{r-k} \qquad (3\text{-}1)$$

where;

k : denotes the number of overlapping sites between the sessions

s : the number of sites

r : the number of receivers

The above equation (3-1) is only true if $k \geq 1$ and $r > 1$. In case of a real number, m must be rounded to the next higher integer. The planned number of sessions, m, for Zambia-Mozambique GNSS network with 14 sites, six receivers and two overlapping sites between sessions was three. The computation is as shown below;

$$m = \frac{14-2}{6-2} = 3$$

Similarly, the planned number of sessions for the first part of Zambia-Malawi GNSS network with 39 sites, six receivers, and two overlapping sites between sessions was ten computed as follows;

$$m = \frac{39-2}{6-2} = 9.25 = 10$$

Figures 3. and 4. below show the GNSS Primary Networks for Zambia-Mozambique and part of Zambia-Malawi respectively.

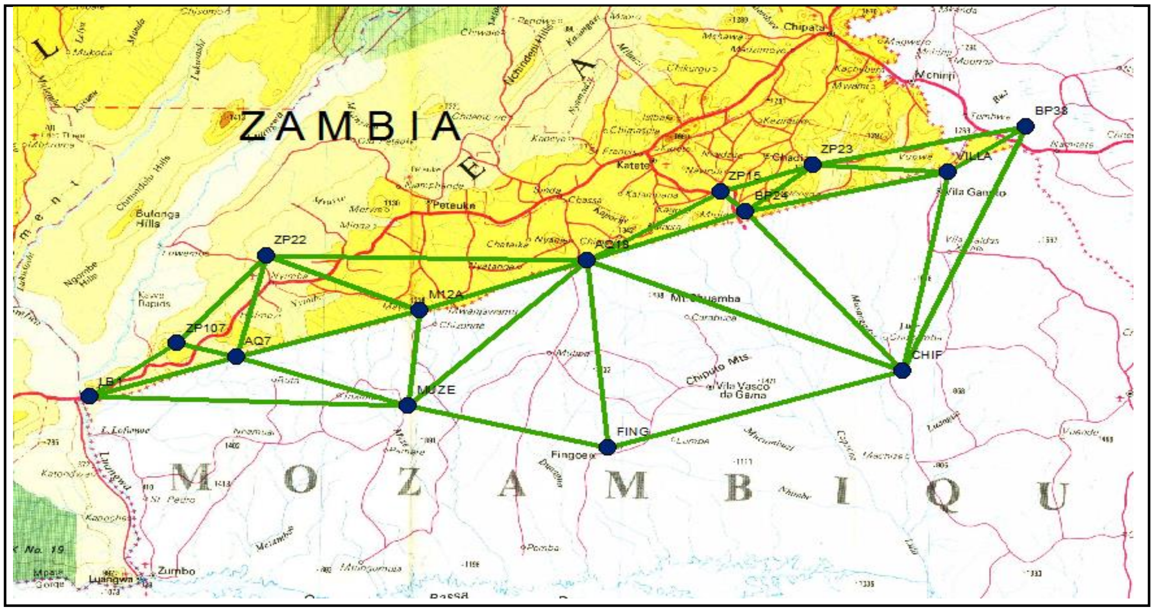


Figure 3. Zambia-Mozambique Primary Control Network

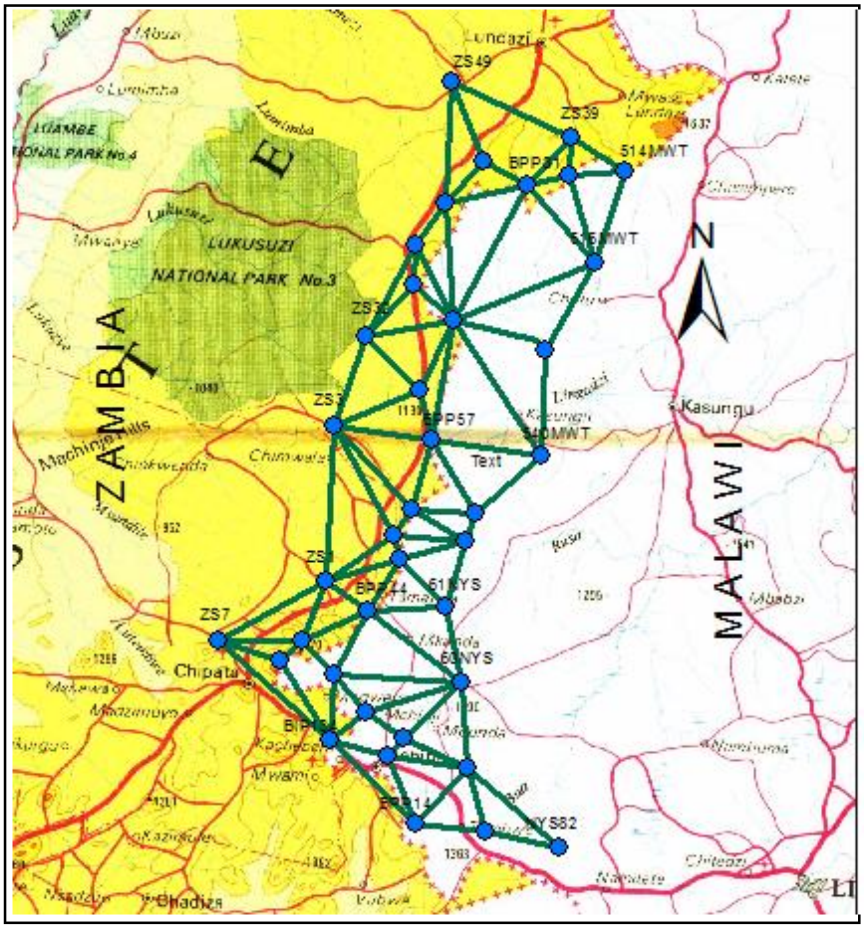


Figure 4. Part of Zambia-Malawi Primary Control Network

3.6 Primary and Secondary Data Collection

The primary data for both Zambia-Malawi and Zambia-Mozambique sites was collected using six GNSS receivers per project site. The six GNSS receivers were set on the six control stations and two operators per station were given field sheets. A two hour observation session was employed for the moving receivers. The other primary data of the boundary beacons were collected by taking RTK measurements referenced from the primary network in the case of Zambia-Malawi and only static observations were used to collect primary data in Zambia-Mozambique case.

The secondary data (i.e. archived local control point coordinates) for Zambia were obtained from the Ministry of Lands National Control database under Survey Department, the local coordinates for Malawi were collected from the national control database for Malawi. However, the local coordinates for Malawi are based on the same coordinate system and thus survey of the international boundary renders no challenge. Unlike Malawi, Mozambique is based on a different datum, MOZNET98 which is geocentric and based on WGS 84 datum with reference epoch of 1997.0. The MOZNET98 datum is consistent with ITRF 1994 (ITRF94). Owing to that, the collection of local coordinates based on Tete datum of 1960 proved futile because the country has since 1998 shifted from the use of the non-geocentric datum to the use of the geocentric datum.

3.7 Data Analysis Using Geomatic Softwares

The post processing of static observations which included baseline processing, network adjustment as well as conversion of GPS observations to Receiver Independent Exchange (RINEX) format which could be used in other GPS processing softwares, were done using Leica Geomatic Office (LGO) software. The Hi-target Geomatic Office (HGO) post processing software was used as alternative software in order to check and compare the results. The Online Positioning User Service (OPUS) was particularly used in the computation of WGS 84 coordinates of trigonometric points ZP15 and NYS82 of Zambia and Malawi respectively. The logic applied in OPUS in the computation of three dimensional geocentric (WGS 84) coordinates of an arbitrary point(s) in this case, ZP 15 and NYS 82, was such that, using IGS ephemeris and the RINEX data at three nearby IGS (HARB, RBAY and ZAMB) stations whose coordinates on the ITRF2008 are known at epoch of observation (2015), the coordinates of ZP15 and NYS82 at time 2015 on the frame ITRF2008 were determined. The two points ZP15 and NYS82 were used as control points in network adjustments for Zambia-Mozambique and Zambia-Malawi networks respectively. The SKI software was used in the determination of datum transformation parameters by employing the linearised least squares mathematical models of Molodensky-Badekas.

CHAPTER FOUR: DATA COLLECTION AND ANALYSIS

This chapter highlights the data collection and analysis procedure that was employed in the unification (tying) of the local coordinates of the international boundary beacons to the global geocentric WGS 84 coordinate system and the determination of the seven datum transformation relationship.

The GNSS receiver uses the WGS 84 datum and hence the coordinates obtained upon taking measurements, are WGS 84 coordinates. However, the initial WGS 84 coordinates obtained from the observations are autonomous and cannot be taken as ‘absolute’ WGS 84 coordinates nor be used as control points in network adjustment. To that effect, WGS 84 coordinates of one of the points was computed online by sending the GNSS observation files with long observation duration in Receiver Independent Exchange (RINEX) Format to Online Positioning User Service (OPUS). The online software used the IGS ephemeris and the RINEX data at three nearby IGS stations to compute the WGS 84 coordinates of the point and gave the solution report with computed WGS 84 coordinates via email.

There are basically two different ways to define the transformation parameters between WGS84 and the local datum (in this case Arc 1950 datum its reference ellipsoid the modified Clarke 1880). The two ways are to set a condition that:

- The axes of the two ellipsoids are parallel. In this case, the transformation would be expressed with only three translations.
- The axes are not parallel and scale varies, the Seven-parameter similarity transformation would be made up of three translations, three rotations and scale factor.

In this study a full seven-parameter datum transformation approach was adopted.

4.1 Background

The primary data (static observations) were downloaded in LGO software and the baselines were processed. The absolute (fixed) WGS84 coordinates were obtained online by sending the GNSS observation files of the control point(s) in RINEX format to Online Positioning User Service (OPUS) which computed the coordinates and sent the solution report via email. The Zambia-Mozambique boundary was completed whereas the Zambia-Malawi was half-way completed, as such, the seven-transformation parameters for the Malawi network are only applicable in the southern part of the boundary covering the areas of Sindamisale and Muzuzu areas of Zambia and Malawi respectively in the south to the areas mid-way towards the north in Mpingozi area and Kasungu National Park in Zambia and Malawi respectively.

4.2 Data Collection

The primary data for Zambia-Malawi and Zambia-Mozambique sites was collected using twelve GNSS receivers. The GPS primary networks (with closed polygons) were designed for both Zambia-Malawi and Zambia-Mozambique sites (see Figures 3. and 4.) by taking into consideration the inclusion of local control geodetic points in the network. Six GNSS receivers were employed per project site and these were set on the six control stations. Due to limited receivers, the GNSS observations of the primary network were done in parts of overlapping sessions. Two operators were left at each station (geodetic marker) with a field sheet. The following information was recorded on a field sheet (See Appendix 4) at every session prior to the observations; the name of the geodetic marker and where it was located, the type and serial number of receiver used on the geodetic marker, the antenna height and date of the session among others. The observation rate of the GNSS receivers was set at 5 seconds and was sometimes changed to 15 seconds in repeated observation sessions or baselines where ambiguities were not resolved. A two hour observation session was employed for the moving receivers after which they were moved and set on other stations. The next observation session, included two points of the previous session which created a session overlap. This implied transferring control from one session to another, as such, consistency was upheld. The processed data was checked for ambiguity resolution in LGO software after which it was backed up for further analysis. For the detailed procedure, the reader is referred to Rear et. al. (1989).

The secondary data (i.e. archived local control point coordinates) for Zambia were obtained from the Ministry of Lands National Control database under Survey Department whereas the local coordinates for Malawi were collected from National Control database for Malawi. As earlier alluded to, the international boundary between the two countries gives no challenge in surveying owing to the fact that Zambia and Malawi's coordinate system, are referenced to the same Arc 1950 datum. Unlike Malawi, Mozambique is based on a different datum, MOZNET98 which is geocentric and based on WGS 84 datum with reference epoch of 1997.0. The MOZNET98 datum is consistent with ITRF 1994 (ITRF94). To that effect, the collection of local coordinates based on Tete datum of 1960 proved futile because the country has since 1998 shifted from the use of the non-geocentric datum to the use of the WGS 84 geocentric datum.

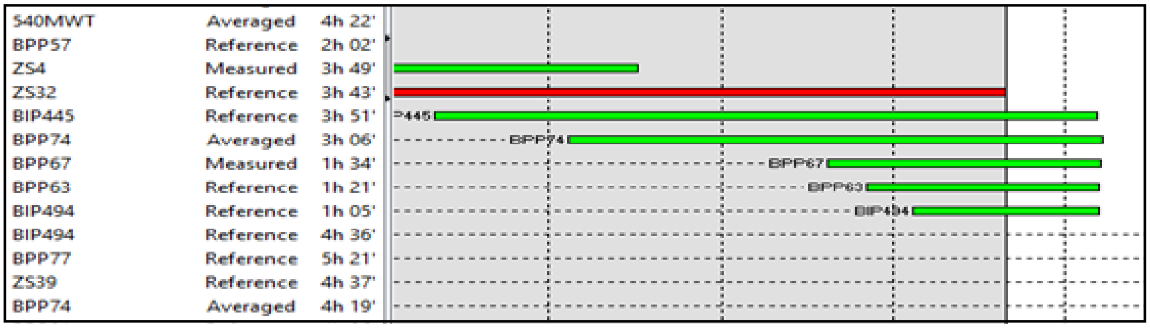
4.3 Data Analysis

The primary data (static observations) were downloaded in LGO software from which baselines were processed. In the case of the Zambia-Malawi primary network, the Trigonometric Station NYS82 of Malawi was selected to be used as a control point in network adjustment. The WGS 84 coordinates of the point were processed online by sending the GNSS observation files of the control point in RINEX format to OPUS which computed the coordinates of NYS82 using the components of the vectors radiating from the three closest International GNSS Service (IGS) stations which included; HARB, RBAY and ZAMB and gave a solution report via email, as such, the principle of 'Whole to Part' was adhered to as per surveying tradition. Like the case with Zambia-Malawi GNSS network, the Trigonometric Station, ZP15 was selected as a control point in the Zambia-Mozambique primary network and the online procedure was repeated and the OPUS computed the coordinates online and a solution report was emailed back. The computed points NYS82 and ZP15 were then used as control points with known WGS 84 coordinates in the computation of baselines and adjustment of the GNSS primary networks in LGO.

The seven-transformation parameters of the Similarity (Helmert) Transformation were computed using Molodensky Badekas mathematical models in SKI software. In the case of Zambia-Malawi boundary, a set of 12 well distributed common points (see Figure 11) with known coordinates both in WGS 84 and Clarke 1880 datums were selected on either side of the countries. Two coordinates sets, A and B, were created in SKI software, set A had WGS 84 coordinates and set B had Clarke 1880 coordinates, both coordinate sets had the same number of points and point identities. The two sets of coordinates were then automatically matched in the software after which the seven-parameter mathematical model, the Molodensky-Badekas in particular, was chosen to compute the seven-transformation parameters. The computed parameters were stored in the software as forward and inverse parameters. In this dissertation, the forward transformation parameters or transformation parameters mean the parameters to transform coordinates from WGS 84 to Clarke 1880 and not vice versa. The common points for Zambia-Malawi primary network included; ZS1, ZS3, ZS7, ZS32, ZS39 and ZS49 on the Zambian side as well as 76BMWS, 514MWT, 516MWT, 540MWT, 60NYS and 61NYS on the Malawian side. Similarly, the procedure was repeated for Zambia-Mozambique boundary and the seven-transformation parameters were computed. However, Mozambique and Zambia use different datums, as such, the common points were limited to the confines of either side of a network up to the international boundary joining the two countries and particularly within the Zambia side because Mozambique is currently using the WGS 84 geocentric system of epoch 1997.0 and no longer uses the local datum. The transformation parameters on Zambia-Mozambique boundary were based on a set of seven well distributed common points (see Figure 10) and included; ZP15, ZP22, ZP23, ZP107, AQ1, AQ18 and AQW38 (BP38). The seven-transformation parameters were used to transform 11 points with known Clarke 1880 coordinates from WGS 84 to Clarke 1880 datum in the case of Zambia-Malawi GNSS network in order to test the accuracy of the parameters. In a similar manner, the transformation parameters for Zambia-Mozambique network were used to transform 16 points with known Clarke 1880 coordinates from WGS 84 to Clarke 1880 datum in order to test the accuracy of the parameters.

4.3.1 LGO Baseline Processing

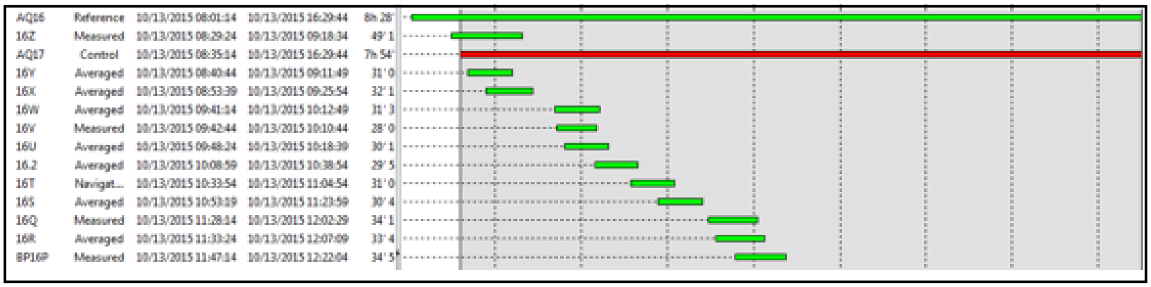
The GNSS raw data for both international boundaries, was downloaded in LGO software. The baselines with common observation time were processed simultaneously. One baseline with the longest observation duration, was set as control baseline to process other baselines. The processed baselines were checked for ambiguity resolution. If the ambiguities were resolved, the baselines were stored and backed-up for further analysis. In certain instances where ambiguities failed to resolve, the observations were repeated and observation duration increased among other factors. Figures 5 and 6 show part of the Zambia-Malawi and Zambia-Mozambique baseline processing respectively.



540MWT	Averaged	4h 22'
BPP57	Reference	2h 02'
ZS4	Measured	3h 49'
ZS32	Reference	3h 43'
BIP445	Reference	3h 51'
BPP74	Averaged	3h 06'
BPP67	Measured	1h 34'
BPP63	Reference	1h 21'
BIP494	Reference	1h 05'
BIP494	Reference	4h 36'
BPP77	Reference	5h 21'
ZS39	Reference	4h 37'
BPP74	Averaged	4h 19'

Figure 5 Part of Zambia-Malawi LGO Baseline Processing

The red bar represents the reference or control point which was used to process the baselines for the roving receivers represented by the green bars in order to ascertain ambiguity resolution.



AQ16	Reference	10/13/2015 08:01:14	10/13/2015 16:29:44	8h 28'
16Z	Measured	10/13/2015 08:29:24	10/13/2015 09:18:34	49' 1
AQ17	Control	10/13/2015 08:35:14	10/13/2015 16:29:44	7h 54'
16Y	Averaged	10/13/2015 08:40:44	10/13/2015 09:11:49	31' 0
16X	Averaged	10/13/2015 08:53:39	10/13/2015 09:25:54	32' 1
16W	Averaged	10/13/2015 09:41:14	10/13/2015 10:12:49	31' 3
16V	Measured	10/13/2015 09:42:44	10/13/2015 10:10:44	28' 0
16U	Averaged	10/13/2015 09:48:24	10/13/2015 10:18:39	30' 1
16.2	Averaged	10/13/2015 10:08:59	10/13/2015 10:38:54	29' 5
16T	Navigat...	10/13/2015 10:33:54	10/13/2015 11:04:54	31' 0
16S	Averaged	10/13/2015 10:53:19	10/13/2015 11:23:59	30' 4
16Q	Measured	10/13/2015 11:28:14	10/13/2015 12:02:29	34' 1
16R	Averaged	10/13/2015 11:33:24	10/13/2015 12:07:09	33' 4
BP16P	Measured	10/13/2015 11:47:14	10/13/2015 12:22:04	34' 5

Figure 6. Part of Zambia-Mozambique LGO Baseline Processing

4.3.2 LGO Network Adjustment

In the Zambia-Malawi and Zambia-Mozambique GNSS networks, the NYS82 and ZP15 stations with WGS 84 coordinates computed online via OPUS, were respectively held fixed in the networks and the three-dimensional (3D) minimally constrained adjustment was used to adjust the respective networks. The detailed procedure of network adjustment is given in Leick et. al. (2015). The LGO adjusted WGS 84 coordinates for the Zambia-Mozambique and Zambia-Malawi boundaries are attached under appendix A. Figure 7 shows part of the Zambia-Mozambique adjusted network.

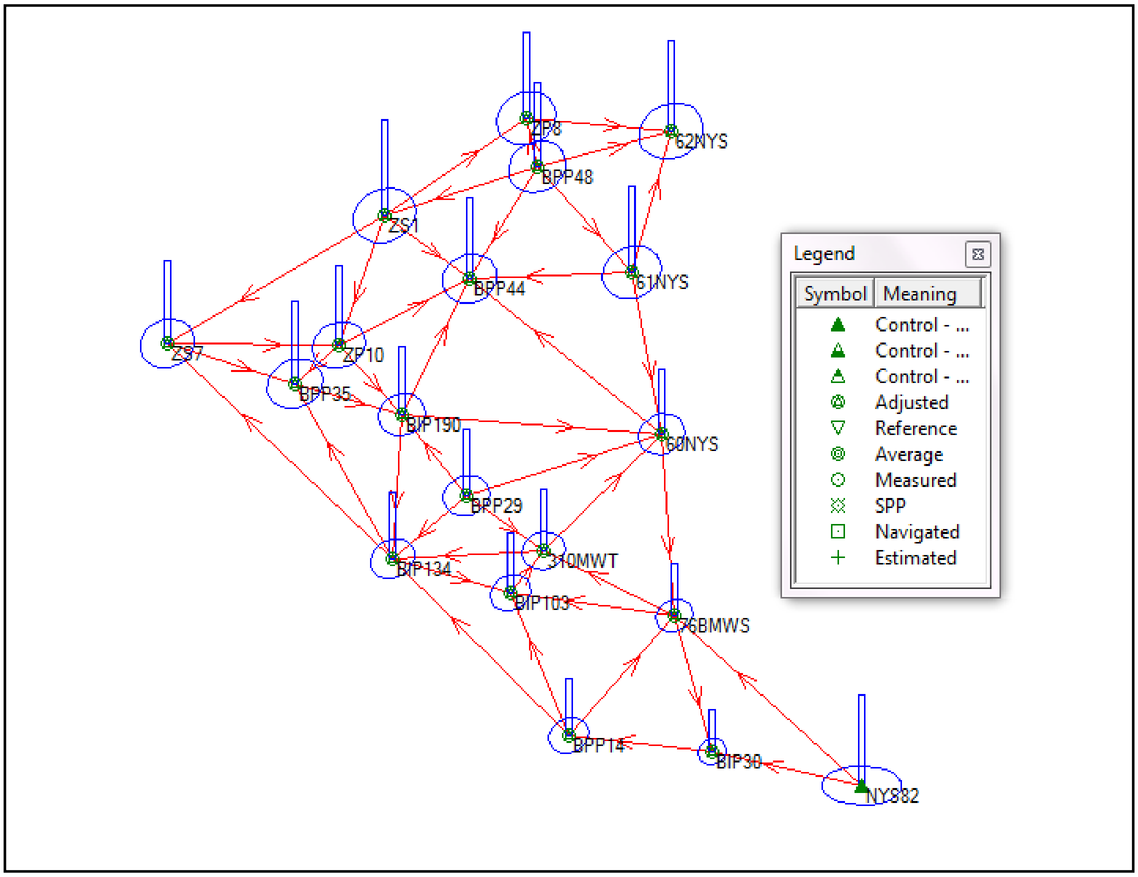


Figure 7. Part of Zambia-Malawi LGO Network Adjustment

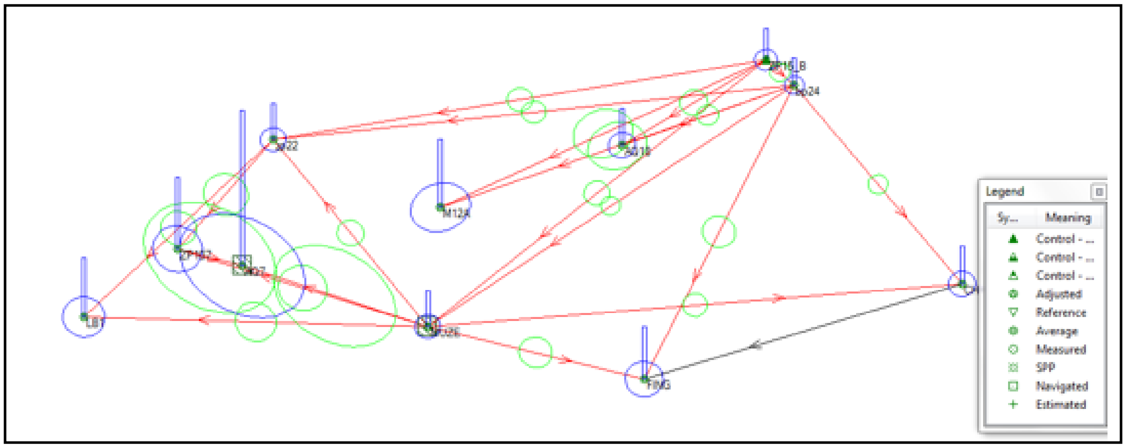


Figure 8. Part of Zambia-Mozambique LGO Network Adjustment

4.3.3 HGO Baseline Processing

The GNSS raw data for Zambia-Malawi boundary, was downloaded in LGO software and then converted to Receiver Independent Exchange (RINEX) format after which it was imported into HGO software for an alternative analysis. The control baseline was selected from baselines with common observation time and the automatic processing of possible baselines was selected from the software and baselines were processed. The HGO baseline processing and network adjustment were only done on the Zambia-Malawi GNSS network in order to check the discrepancy between the LGO and HGO Geomatic softwares. Figure 8. shows part of the processed baselines.

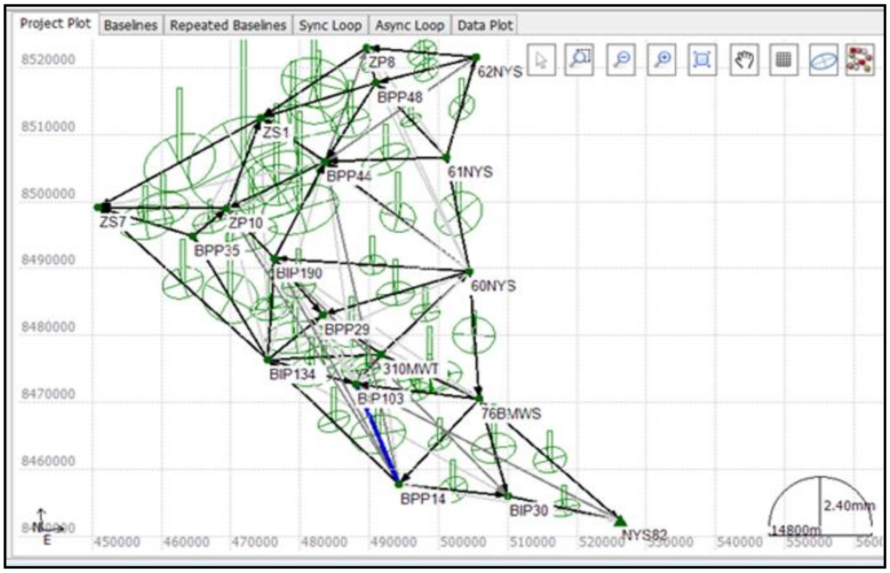


Figure 9. Part of the Zambia-Malawi HGO Processed Baselines

4.3.4 HGO Network Adjustment

In the Zambia-Malawi GNSS network, the NYS82 with WGS 84 coordinates computed online via OPUS, were held fixed in the network and the three-dimensional (3D) minimally constrained adjustment was used to adjust the network. Figure 9. shows part of the Zambia-Mozambique adjusted network.

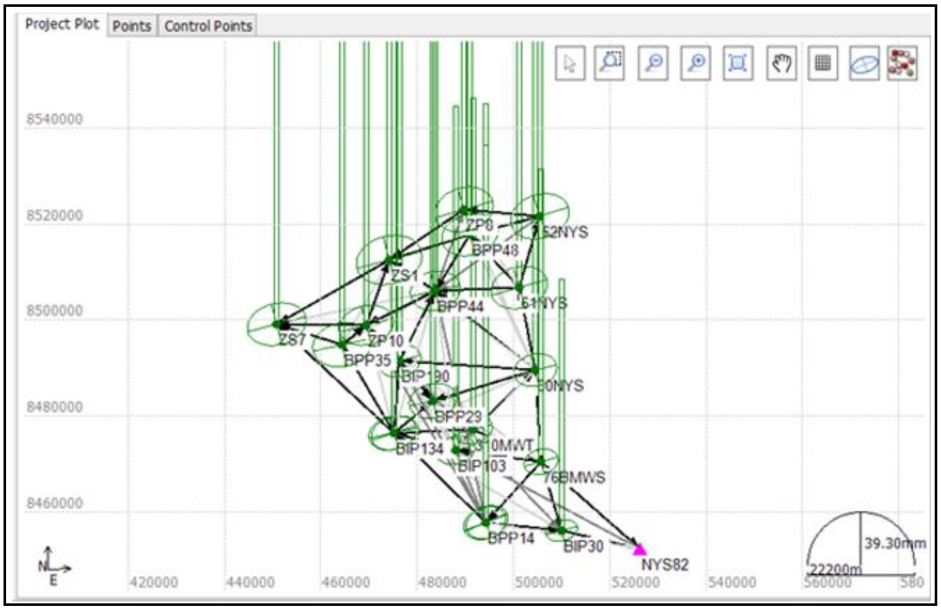


Figure 10. Part of Zambia-Malawi HGO Network Adjustment

4.3.5 Comparison of LGO and HGO Adjusted Coordinates

The adjustment results computed in LGO software, were compared with those computed in HGO software. The computed root mean square (r.m.s) in the Eastings difference, ΔE, was 0.005m and the r.m.s error in the Northings difference, ΔN, was 0.007m. The deviations in the computed set of coordinates could be attributed to human error in data analysis using to different softwares. However, the computed r.m.s in the Eastings and Northings are smaller than the absolute error of 0.010m of the first-order geodetic survey at 95 per cent confidence interval (Rear et. al, 1989), as such, the two softwares can be used for geodetic computations and network adjustment. Table 6. shows the discrepancy of the LGO and HGO computed coordinates.

Table 6. Residuals Between LGO and HGO Computed Coordinates

PID	**E_{LGO} (m)**	**N_{LGO} (m)**	**E_{HGO} (m)**	**N_{HGO} (m)**	**ΔE (m)**	**ΔN (m)**
310MWT	491760.087	8477126.291	491760.087	8477126.294	0.000	-0.003
60NYS	504552.861	8489480.284	504552.862	8489480.291	-0.001	-0.007
61NYS	501272.797	8506612.165	501272.796	8506612.168	0.001	-0.003
62NYS	505554.135	8521439.055	505554.128	8521439.051	0.007	0.004
76BMWS	505934.438	8470336.492	505934.443	8470336.504	-0.006	-0.013
BIP 134	475395.373	8476325.543	475395.381	8476325.548	-0.008	-0.006
BIP103	488169.055	8472715.106	488169.065	8472715.108	-0.010	-0.002
BIP134	475395.387	8476325.553	475395.381	8476325.548	0.005	0.004
BIP14	494402.599	8457703.575	494402.599	8457703.566	0.000	0.009
BIP190	476394.743	8491444.948	476394.747	8491444.962	-0.004	-0.014
BIP30	510048.233	8455933.197	510048.242	8455933.188	-0.009	0.009
BPP14	494402.593	8457703.553	494402.599	8457703.566	-0.007	-0.013
BPP29	483313.452	8482986.852	483313.455	8482986.849	-0.004	0.003
BPP35	464652.530	8494693.793	464652.534	8494693.798	-0.004	-0.005
BPP44	483766.444	8505889.314	483766.444	8505889.317	0.000	-0.004
BPP48	491077.238	8517664.727	491077.236	8517664.727	0.001	0.000
NYS82	526293.230	8452290.815	526293.230	8452290.815	0.000	0.000
ZP10	469533.634	8498829.643	469533.637	8498829.649	-0.003	-0.006
ZP8	489802.462	8522912.244	489802.462	8522912.241	0.001	0.003
ZS1	474440.369	8512489.465	474440.368	8512489.471	0.001	-0.005
ZS7	450928.896	8499108.018	450928.898	8499108.029	-0.002	-0.010
RMS =					**0.005**	**0.007**

$$RMS = \sqrt{\frac{1}{n}\sum_{i}^{n}(x_i - a_i)^2} \tag{4-1}$$

Where;

n = number of points,

x = LGO coordinates and

a = HGO coordinates

4.3.6 Estimation of Transformation Parameters

The transformation parameters were computed on Zambia-Mozambique and Zambia-Malawi international boundaries based on a selection of a few well distributed common points. Figures 10. and 11. show the distribution of common points in Zambia-Mozambique and Zambia-Malawi networks respectively.

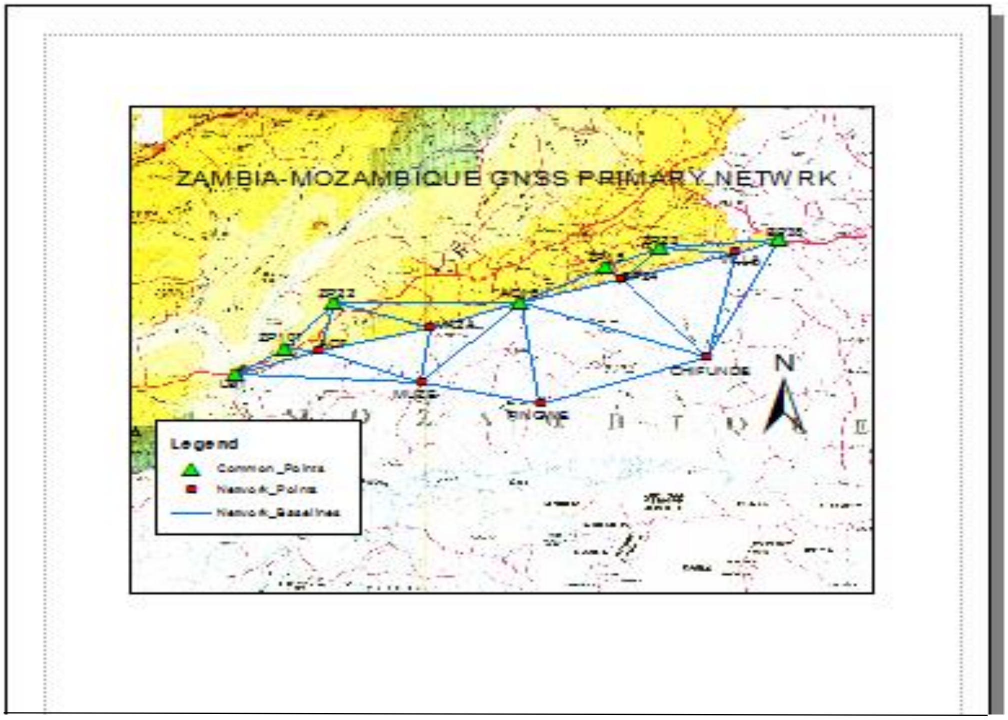


Figure 11. Distribution of Common Points on Zambia-Mozambique Network

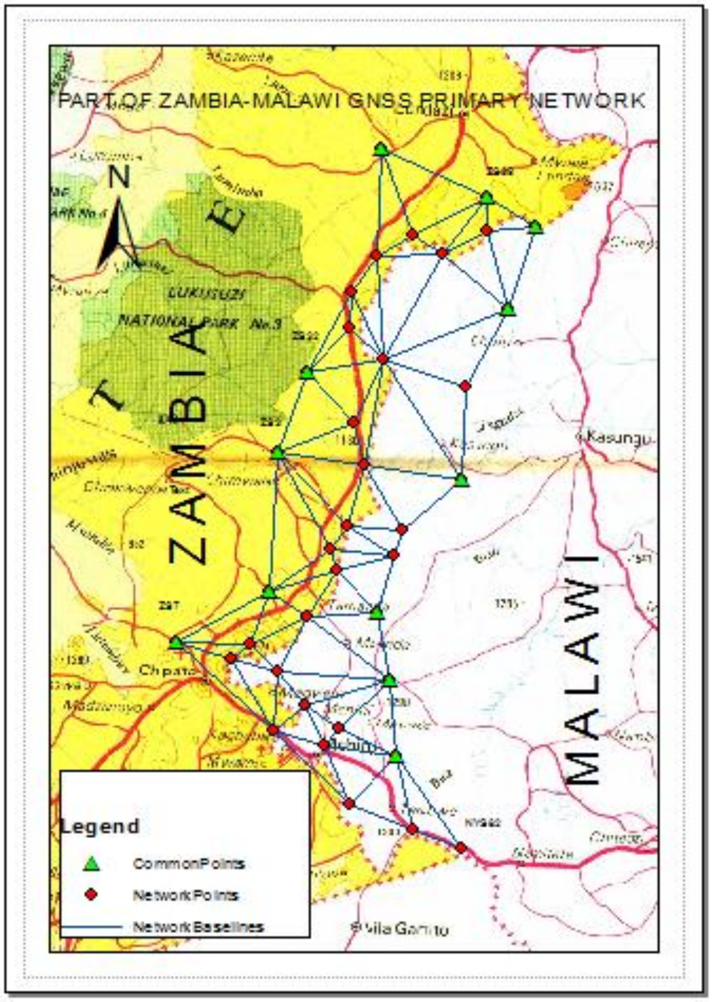


Figure 12. Distribution of Common Points on Zambia-Malawi

CHAPTER FIVE: RESULTS AND DISCUSSION

This chapter presents the results and further discusses the results. The international boundaries under study were tied to the geocentric WGS 84 datum which has a reference epoch of 2005.0. The GNSS broadcast orbit has an epoch at half-mark of the Calendar year. This means an epoch of the GNSS broadcast orbit between January to June 2015 would be 2015.0 and July to December 2015 would be 2015.5. In this case, data was collected between October and December 2015, as such, the observation epoch was 2015.5.

The current WGS 84 is consistent with ITRF2008 frame, which imply that the two reference frames are homogeneous and could be used interchangeably. For instance, the resulting WGS 84 coordinates obtained could also be referred to as ITRF2008 coordinates.

The official seven-transformation parameters (see Tables 3. and 4.) used in Zambia were computed in Static Kinematic (SKI) software using linearised Molodensky-Badekas mathematical model which uses the centroid of the network as the rotation origin. This research also employed the Molodensky-Badekas mathematical models in the determination of the seven transformation parameters for Zambia-Mozambique and Zambia-Malawi international boundaries. The accuracy of the parameters largely depends on the size and extent of the land covered and how well-spaced the common points are in relation to the area of interest.

5.1 Background

The local coordinates of the international boundaries under study were tied to the global geocentric World Geodetic System 1984 (WGS84) coordinate system by employing GNSS and its datum. The Online Positioning User Service (OPUS) was used to determine the WGS84 coordinates for ZP15 and NYS82 Trigonometric stations for Zambia and Malawi respectively. The points, ZP15 and NYS82, were then used to compute and adjust the GNSS primary networks in Leica Geomatic Office (LGO) software for Zambia-Mozambique and Zambia-Malawi international boundaries respectively. The official seven transformation parameters for Eastern Zambia (UTM 33, Zone 36L) and the whole Zambia as shown in Tables 3.0 and 4.0 respectively, were computed in Static Kinematic

(SKI) software using Molodensky-Badekas mathematical model which uses the centroid of the network as the rotation origin. Owing to the fact that it uses the centroid of the network as the rotation origin, the Molodensky-Badekas model is also sometimes referred to as the 7 + 3 parameter model.

The seven-transformation parameters from WGS 84 to Clarke 1880 were determined between Zambia-Mozambique on the Zambian side. However, the relation from WGS 84 to Clarke 1866 on the Mozambican side could not be determined owing to the fact that Mozambique shifted from the use of the non-geocentric Tete datum in 1998 and now uses the geocentric datum, MOZNET98 which is consistent with ITRF94. In the case of Zambia-Malawi, the transformation parameters were computed and could be used on either side of the two countries due to the common Arc 1950 datum which is used within and across the international boundary.

5.2 Results

The WGS 84 coordinates for the international boundaries (Zambia-Malawi and Zambia-Mozambique) positioned on ITRF2008 were computed and adjusted in LGO software. The adjusted coordinate lists are included under appendix 1.

The seven-transformation parameters for Zambia-Malawi and Zambia-Mozambique boundaries had been determined using the Molodensky-Badekas mathematical model in SKI software. The seven parameters comprise three shift parameters (ΔX, ΔY, ΔZ), three rotation parameters (R_x, R_y, R_z) and one scale factor (s). The shift parameters are translations in X, Y and Z axes of the local ellipsoid with respect the global or geocentric ellipsoid whereas the rotation parameters represent the rotation tilts or angles in X, Y, and Z axes with respect to the reference (global or geocentric) ellipsoid. Table 7. and Table 10. present the results for the seven transformation parameters for Zambia-Malawi and Zambia-Mozambique international boundaries respectively.

5.2.1 WGS 84 Coordinate List for the Primary Control Networks

The resulting coordinates of the Zambia-Malawi and Zambia-Mozambique international boundaries are presented in UTM 33 (Zone 36L) and Geodetic WGS 84 coordinates respectively. The coordinate lists have been included under appendix 1 as Table 13. and Table 14. for Zambia-Malawi and Zambia-Mozambique respectively.

5.2.2 WGS 84 Coordinate List for the International Boundary Beacons

The coordinate list for the international boundary beacons have been included under appendix 1 as Table 15. and Table 16. for Zambia-Malawi and Zambia-Mozambique respectively.

5.2.3 Loop Misclosure on Zambia-Malawi GNSS Network

According to the specifications of the Federal Geodetic Control Committee (FGCC) the allowable error of the first-order surveys is given by an absolute error as 0.010m plus a relative error is 10 ppm (1:100 000) of the distance at 95 per cent confidence level (Hofmann et. al, 1994). With the introduction of GPS techniques the accuracy standards were modified to accommodate the higher accuracies possible with GNSS (Rear, et. al, 1989). Prior to first-order class of survey, is the B-order class of survey with allowable error of 0.008m + 1 ppm of the distance at 95 per cent confidence level. The allowable Loop Misclosure is given by;

$$\text{Loop Misclosure} = \text{SQRT}\left((\text{Absolute Accuracy})^{2} + (\text{Loop length}/1000000)^{2}\right) \quad (5\text{-}1)$$

The GNSS Loop Misclosure on selected network loops, for example, Loop 1 (NYS82, 76BMWS and BIP30) of length 58, 866.8319m, Loop 2 (61NYS, 60NYS and BPP44) of length 61, 483.7861m and Loop 3 (BPP44, 60NYS and BIP190) of length 70, 968.7882m were determined as 0.0449m, 0.0317m and 0.0141m respectively. In order to check if the network met the B-order specifications, the allowable Loop Misclosure of Loop 1 of length 58, 866.8319m was computed as follows;

$$\text{All. Misclosure} = \text{SQRT}\left((0.008)^{2} + (58866.8319/1\,000\,000)^{2}\right) = 0.0594\text{m}$$

The GNSS Loop Misclosure computed by LGO software on Loop 1 was 0.0449m, Loop 2, 0.0317m and Loop 3, 0.0141m whereas the allowable misclosures of Loops 1, 2 and 3 were 0.0594m, 0.0620m and 0.0714m respectively. Since the GNSS Loop Misclosures were less than the allowable misclosure, this entails that the survey met the B-order class of survey according to specifications of the Federal Geodetic Control Committee.

5.2.4 Loop Misclosure on Zambia-Mozambique GNSS Network

The highest class of survey, is the AA-order with allowable error of 0.003m + 0.01 ppm of the distance at 95 per cent confidence level (Rear et. al, 1989). The GNSS Loop Misclosure on selected network loops, for example, Loop 1 (Chifunde, ZP23 and Villa) of length 21, 6079.6911m and Loop 2 (Chifunde, BP38 and Villa) of length 22, 0662.9495m were determined as 0.0020m and 0.0016m respectively. In order to check if the network met the AA-order specifications, the allowable Loop Misclosure of Loop 1 of length 21, 6079.6911m was computed as follows;

$$\text{All. Misclosure} = \text{SQRT}\ ((0.003)^2 + (21,\ 6079.6911/100\ 000\ 000)^2) = 0.0037\text{m}$$

The GNSS Loop Misclosure on Loop 1 was 0.0022m the same as on Loop 2, whereas the allowable misclosure of Loops 1 and 2 was 0.0037m. Since the GNSS Loop Misclosures were less than the allowable misclosure, this entails that the survey met the AA-order class of survey according to specifications of the Federal Geodetic Control Committee.

5.2.5 Zambia-Malawi Transformation Parameters

The transformation parameters for Zambia-Malawi were based on 12 common points which were known both in Arc 1950 and WGS 84 datums. As earlier alluded to, the common points used for the transformation parameters included, ZS1, ZS7, ZS3, ZS32, ZS39 and ZS49 on the Zambian side and 540MWT, 76BMWS, 514MWT, 516MWT, 61NYS and 60NYS on the Malawian side. Table 7. shows the transformation parameters to transform coordinates from WGS 84 to Arc 1950 datum on the southern part of Zambia-Malawi international boundary.

Table 7. 7-Transformation Parameters for Zambia-Malawi

Number of Common points 12			
Rotation Origin		ΔX_o = 5209545.197m	
		ΔY_o = 3385668.285m	
		ΔZ_o = -1441109.365m	
Parameter	Value	r.m.s	units
ΔX	166.705	0.103	m
ΔY	75.034	0.103	m
ΔZ	307.072	0.103	m
R_x	-11.267585	0.3862	"
R_y	-3.557593	0.5159	"
R_z	2.337567	0.9193	"
S.F.	2.429121	1.8187	[ppm]
σ_o, sigma a posteriori: 0.3560m			

5.2.6 Zambia-Malawi Transformed Coordinates

Some selected points (11 in number) were transformed from WGS 84 to Arc 1950 datum using the determined transformation parameters in order to test the accuracy of the parameters. The selected points included points, whose coordinates were already known in Arc 1950 datum. Table 8. shows the 12 common points used in the determination of transformation parameters and the 11 transformed WGS 84 coordinates to Clarke 1880 coordinates using the transformation parameters.

Table 8. Transformed Clarke 1880 UTM Coordinates on Zambia-Malawi Boundary

Point	**E_{WGS} (m)**	**N_{WGS} (m)**	****h (m)**	**E_{CLK} (m)**	**N_{CLK} (m)**	***H (m)**	**Remarks**
ZS7	450928.898	8499108.029	1328.841	450903.552	8499421.042	1339.410	Common
ZS3	476279.055	8547629.871	1104.711	476250.565	8547944.360	1117.390	Common
ZS32	483563.178	8568204.861	1396.950	483533.669	8568519.824	1409.670	Common
ZS39	528794.650	8613164.337	1312.367	528762.989	8613481.928	1324.480	Common
ZS1	474440.368	8512489.471	1220.886	474414.128	8512803.882	1232.820	Common
ZS49	502347.497	8625624.753	1169.671	502315.153	8625940.672	1182.230	Common
540MWT	522370.532	8540908.717	1119.618	522342.754	8541225.951	1131.00	Common
76BMWS	505934.443	8470336.504	1129.584	505910.493	8470652.865	1140.600	Common
60NYS	504552.862	8489480.291	1279.933	504527.791	8489796.642	1290.30	Common
61NYS	501272.796	8506612.168	1192.403	501246.836	8506928.038	1202.80	Common
514MWT	541053.484	8605557.817	1235.126	541022.090	8605876.050	1247.30	Common
516MWT	534112.669	8584562.372	1069.134	534082.468	8584880.297	1081.60	Common
ZP8	489802.462	8522912.241	1170.293	*489775.556*	*8523227.501*	*1181.882*	Transformed
ZP10	469533.637	8498829.649	1659.616	*469508.207*	*8499143.784*	*1176.726*	Transformed
ZS4	495424.338	8555672.211	1116.612	*495395.547*	*8555987.852*	*1128.970*	Transformed
NYS82	526293.230	8452290.815	1150.566	*526270.336*	*8452608.307*	*1160.909*	Transformed
62NYS	505554.128	8521439.051	1096.079	*505527.338*	*8521755.226*	*1107.118*	Transformed
310MWT	491760.087	8477126.294	1322.565	*491735.781*	*8477441.824*	*1333.301*	Transformed
284MWT	507494.926	8527701.096	1100.998	*507467.790*	*8528017.404*	*1112.243*	Transformed
51NYS	523348.325	8564689.169	1101.692	*523319.190*	*8565006.464*	*1113.782*	Transformed
543MWT	528552.577	8604584.992	1233.568	*528521.320*	*8604902.558*	*1245.811*	Transformed
BPP14	494402.599	8457703.566	1143.209	*494379.405*	*8458019.236*	*1153.876*	Transformed
BP38	526034.956	8452396.608	1144.492	*526012.055*	*8452714.086*	*1154.840*	Transformed

NB: The Clarke 1880 Coordinates E_{CLK}, $N_{CLK,}$ and H in italics, are the computed coordinates

* orthometric height

**ellipsoidal height

The computed or transformed Clarke 1880 coordinates, nine (9) in number out of the eleven (11) points shown in Table 8. were subtracted from the known Clarke 1880 coordinates and the residuals were tabulated as shown in Table 9.. The r.m.s in the Eastings difference, ΔE and Northings difference, ΔN were 0.093m and 0.061m respectively. The height differences were not taken into consideration owing to the fact that the two heights of the WGS 84 and Arc 1950 datums are referenced to different surfaces. The former is referenced to the ellipsoid while the latter is referenced to the geoid.

Table 9. Known and Computed Clarke 1880 Coordinate Differences

	Known Coordinates		**Computed Coordinates**		**Residuals**	
Point	**E (m)**	**N (m)**	**E (m)**	**N (m)**	**ΔE (m)**	**ΔN (m)**
ZP8	489775.554	8523227.554	489775.556	8523227.501	-0.002	0.053
ZP10	469508.229	8499143.780	469508.207	8499143.784	0.022	-0.004
ZS4	495395.545	8555987.871	495395.547	8555987.852	-0.002	0.019
284MWT	507467.882	8528017.499	507467.79	8528017.404	0.092	0.095
543MWT	528521.367	8604902.628	528521.32	8604902.558	0.047	0.070
NYS82	526270.105	8452608.376	526270.336	8452608.307	-0.231	0.069
62NYS	505527.414	8521755.305	505527.338	8521755.226	0.076	0.079
51NYS	523319.100	8565006.486	523319.190	8565006.464	-0.090	0.022
310MWT	491735.801	8477441.894	491735.781	8477441.824	0.020	0.070
RMS =					**0.093**	**0.061**

5.2.7 Zambia-Mozambique Transformation Parameters

The transformation parameters for Zambia-Mozambique were based on seven common points namely; ZP15, ZP22, ZP107, ZP23, AQ1 and BP38 (a tri-union point among Zambia, Malawi and Mozambique) which are all on the Zambian side. The coordinates for the common points were known in both Arc 1950 and WGS 84 datums. The computed transformation parameters could only be applied on the Zambian side, since the two countries use two different local datums. However, Mozambique has shifted to the use of the geocentric datum which is homogeneous with ITRF94 and thus requires a plate tectonic model with station velocities to relate ITRF94 to the latest ITRF2008. This explains why common points with both local and WGS 84 coordinates were only selected on the Zambian side and hence the application of transformation parameters.

Table 10. below show the transformation parameters to transform coordinates from WGS 84 to Arc 1950 datum on the Zambia-Mozambique international boundary on the Zambian side.

Table 10. 7-Transformation Parameters for Zambia-Mozambique

Number of Common points 7			
Rotation Origin	ΔX_o = 5260391.453m		
	ΔY_o = 3239199.932m		
	ΔZ_o = -1580682.477m		
Parameter	Value	r.m.s	Units
ΔX	161.159	0.081	m
ΔY	82.201	0.081	m
ΔZ	298.851	0.081	m
R_x	-11.2863	0.8161	″
R_y	-2.0981	1.5582	″
R_z	5.8898	0.5399	″
s	-5.3155	0.8584	ppm
σ_o, sigma a posteriori: 0.2724m			

5.2.8 Zambia-Mozambique Transformed Coordinates

The above parameters were used to transform 13 points from WGS 84 to Clarke 1880 in order to test the accuracy of the parameters. Owing to the non-adjustment of the geodetic network in the international boundaries and also the quality of coordinates in the National Trigonometric Control Database particularly for the international boundary coordinates, left much to be desired. To that effect, the selected points on the network to be transformed, had Clarke 1880 coordinates which were obtained by transformation using the official UTM 33 (Zone 36L) seven-transformation parameters for Zambia. The UTM33 parameters were also used to Transform BP38, AQ1 and AQ18 in Table 11. All the transformed points were the international boundary points between Zambia and Mozambique. Table 11. shows the coordinates of the transformed points and also the seven common points which were used in determining the parameters.

Table 11. Transformed Clarke 1880 UTM Coordinates on Zambia-Mozambique

Point	**E_{WGS} (m)**	**N_{WGS} (m)**	****h (m)**	**E_{CLK} (m)**	**N_{CLK} (m)**	***H (m)**	**Remarks**
ZP107	230260.203	8364240.685	1213.896	230244.359	8364541.591	1221.330	Common
ZP15	419144.509	8426216.135	1201.934	419124.032	8426527.549	1212.492	Common
ZP22	260849.458	8399721.127	928.172	260831.469	8400023.573	936.649	Common
ZP23	451312.680	8436913.585	1303.020	451291.341	8437227.023	1314.600	Common
BP38	526034.977	8452396.641	1144.547	526012.395	8452713.798	1156.251	Common
AQ1	200857.759	8340144.760	444.271	200843.888	8340444.664	451.874	Common
AQ18	372838.590	8398578.248	1057.064	372820.186	8398887.319	1066.878	Common
AQ2	201002.862	8340084.873	444.281	*200988.993*	*8340384.784*	*451.830*	Transformed
AQ3	203834.224	8340904.176	524.746	*203820.260*	*8341204.205*	*532.339*	Transformed
AQ5	229009.936	8350244.176	821.830	*228995.017*	*8350545.258*	*829.377*	Transformed
AQ6	238396.945	8354076.757	818.065	*238381.709*	*8354378.279*	*825.685*	Transformed
AQ7	250855.493	8359245.581	936.649	*250839.872*	*8359547.754*	*944.489*	Transformed
AQ8	263161.030	8363893.910	890.974	*263145.082*	*8364196.760*	*899.064*	Transformed
AQ9	280175.924	8368018.591	1050.588	*280159.662*	*8368322.406*	*1058.986*	Transformed
AQ10	293436.816	8371371.207	1108.679	*293420.304*	*8371675.778*	*1117.295*	Transformed
AQ11	300065.871	8373699.841	1095.894	*300049.197*	*8374004.786*	*1104.618*	Transformed
AQ14	330777.941	8381654.038	1016.329	*330760.684*	*8381960.741*	*1025.509*	Transformed
AQ16	344941.660	8387873.001	1051.608	*344923.986*	*8388180.497*	*1061.007*	Transformed
AQ17	358059.656	8395362.157	1187.541	*358041.498*	*8395670.375*	*1197.151*	Transformed
AQ24	428113.379	8418315.019	943.983	*428093.304*	*8418627.071*	*954.7204*	Transformed

NB: The Clarke 1880 Coordinates E_{CLK}, N_{CLK}, and H in italics, are the computed coordinates
* orthometric height
**ellipsoidal height

The transformed coordinates of the points were subtracted from the transformed coordinates based on UTM33 parameters and the differences are as shown in Table 12. below. As earlier alluded to, the height differences were not taken into consideration owing to the fact that the two heights of the WGS 84 and Clarke 1880 datums are referenced to different surfaces. The r.m.s in the Eastings difference, ΔE and Northings difference, ΔN were 0.205m and 0.253m respectively. The large r.m.s errors computed could be attributed to the fact that the known Clarke 1880 coordinates of the transformed points were computed using the UTM33 seven-transformation parameters for Zambia while the other set of coordinates were computed using the transformation parameters determined on Zambia-Mozanbique border. In essence, this entails comparison of two sets transformation parameters determined on different extent of land sizes. However, the parameters are okay for practical purposes within the international boundary particularly on the Zambian side.

Table 12. Known and Computed Clarke 1880 Coordinate Differences

	***Computed Coordinates**		**Computed Coordinates**		**Residuals**	
Point	**E (m)**	**N (m)**	**E (m)**	**N (m)**	**ΔE (m)**	**ΔN (m)**
AQ2	200988.993	8340384.785	200988.993	8340384.784	0.000	0.001
AQ3	203820.288	8341204.242	203820.260	8341204.205	0.028	0.037
AQ5	228995.282	8350545.584	228995.017	8350545.258	0.265	0.326
AQ6	238382.020	8354378.662	238381.71	8354378.279	0.311	0.383
AQ7	250840.187	8359548.145	250839.872	8359547.754	0.315	0.391
AQ8	263145.376	8364197.127	263145.082	8364196.760	0.294	0.367
AQ9	280159.913	8368322.727	280159.662	8368322.406	0.251	0.321
AQ10	293420.520	8371676.059	293420.304	8371675.778	0.216	0.281
AQ11	300049.396	8374005.046	300049.197	8374004.786	0.199	0.260
AQ14	330760.796	8381960.895	330760.684	8381960.741	0.112	0.154
AQ16	344924.062	8388180.601	344923.986	8388180.497	0.076	0.104
AQ17	358041.541	8395670.43	358041.498	8395670.375	0.043	0.055
AQ24	428093.456	8418627.012	428093.304	8418627.071	0.152	-0.059
RMS =					**0.205**	**0.253**

*transformed coordinates using UTM33 parameters for Zambia (also referred to as known coordinates).

5.3 Discussion

The Zambia-Mozambique boundary is a stretch of about 400 Km and was completed and the coordinates of the boundary beacons were now based on the global WGS 84 datum positioned on ITRF2008. Unlike the Zambia-Mozambique boundary, the Zambia-Malawi international boundary was not completed. The stretch of about 350 Km out the stretch of about 800 Km starting from the *Coumba* tri-union point in the southern part to Kasungu National Park on the central part of Malawi, was tied to the WGS 84 datum. This implies that only 44% of the boundary had been observed. The Zambia-Mozambique boundary beacons are now referenced to the WGS 84 datum of epoch 2005.0 which is consistent with ITRF2008 within one centimeter, while MOZNET98 datum for the whole Mozambique, has a reference epoch of 1994.0 which is consistent with ITRF94 within ten (10) centimeters (see Table 1.). The Zambia-Mozambique international boundary has wholly been tied to WGS 84 datum whereas Zambia-Malawi has been partially tied to the same datum. This entails that the challenges faced by land surveyors more especially the Joint Survey Team in the survey of Zambia-Mozambique boundary has been greatly minimized.

The results of the Similarity (Helmert) transformation parameters for Zambia-Malawi shown in Table 7., were determined based on 12 well distributed common points. The parameters have an r.m.s of 0.103m in shift parameters while those of the Zambia-Mozambique have an r.m.s of 0.081m. As a basis of comparison, the seven-transformation parameters for eastern Zambia (UTM33-Zone 36L) have an r.m.s of 0.304m in shift parameters and a quality of fit of 1.006m as seen from sigma a posteriori, σ_o (Table 3.0). The quality of fit of the transformation parameters determined for Zambia-Mozambique and Zambia-Malawi boundaries were 0.2724m and 0.3560m respectively. The small (better) quality of fit on the former boundary could be attributed to the fact that the same class of points, from the first order geodetic network, the Zambia Primary (ZP), were selected to compute transformation parameters whereas the large quality of fit on the latter boundary, could be attributed to the fact that two different class of points from the second and third order geodetic networks, which are secondary and tertiary geodetic networks respectively, were selected to compute the parameters. The combination of points from different classes of geodetic networks, imply combining points with different accuracies.

The accuracy of geodetic networks, increase with the decrease in the network order. For instance, surveys tied to the first order geodetic network are more accurate compared to surveys tied to the second order geodetic network. The parameters for Zambia-Malawi network were used to transform coordinates with known Clarke 1880 coordinates from WGS 84 to Clarke 1880 in order to test the accuracy of the parameters. Similarly, the parameters for Zambia-Mozambique network were used transform Clarke 1880 coordinates (transformed from UTM33 parameters) in order to test the accuracy of the parameters. In the case of Zambia-Malawi network, the residuals between 9 known and transformed points were tabulated as shown in Table 9. The computed r.m.s of the Eastings difference, ΔE, and Northings difference, ΔN, were 0.093m and 0.061m respectively. The transformation parameters for Zambia-Mozambique network, applicable on the Zambian side, were used to transform 13 points with Clarke 1880 coordinates and the residuals were tabulated as shown in Table 12.0. The r.m.s in the ΔE and ΔN, were computed as 0.205m and 0.253m respectively. The large r.m.s obtained on the Zambia-Mozambique transformed points despite having a better quality of fit of the parameters as compared to the Zambia-Malawi parameters, could be attributed to the fact that the set of coordinates being compared are both computed coordinates from transformation parameters that were estimated on different sizes of land extent. For instance, the set of computed coordinates on the left column of Table 12, were transformed using the official UTM33 (Zone 36L) seven-transformation parameters for Zambia whereas the computed set of coordinates were transformed using seven-transformation parameters determined on the Zambia-Mozambique boundary which covered a smaller extent of land compared to the whole eastern region. The official parameters (UTM33) cover the whole eastern Zambia which include three complete international boundaries (i.e Zambia-Malawi, Zambia-Mozambique and Zambia-Tanzania) as could be seen from Figure 1. The different quality of fit 1,006m and 0.2724m from the two parameter sets, UTM33 and Zambia-Mozambique respectively, imply a computation of parameters with different errors. However, the computed r.m.s errors of 0.205m and 0.253m in Eastings and Northings respectively, compare well with the average r.m.s error of 0.254m in both Eastings and Northings of the shift parameters of the two sets of transformation parameters.

Further check on quality control was done using Loop Misclosure on selected loops on Zambia-Malawi and Zambia-Mozambique GNSS networks. The Loop Misclosures on the Zambia-Malawi and Zambia-Mozambique network computed using LGO software on Loops 1, 2 and 3 were 0.0449m, 0.0317m and 0.0141m whereas the allowable misclosures, equation (5-1), on Loops 1, 2, and 3 computed with regard to the B-order class of survey (with accuracy 0.008m + 1ppm) were 0.0594m, 0.0620m and 0.071m respectively. In the case of Zambia-Mozambique GNSS network, the Loop Misclosure on Loops 1 and 2 was 0.0022m whereas the allowable misclosure on both loops computed with respect to the AA-order class of survey (with accuracy 0.003m + 10^{-2}ppm) was 0.0037m. it would be important to note that all loop misclosures were computed at 95 per cent confidence level. Since the GNSS Loop Misclosure were less than the allowable misclosure, this meant that the survey on Zambia-Malawi and Zambia-Mozambique international boundaries met the B-order and AA-order class of survey respectively. However, the two international boundary surveys met the first-order survey specifications with allowable error of 0.010m + 10ppm.

In addition, the transformation equations from Geodetic to Cartesian coordinates given in equation (2-3), show evidence that ellipsoidal height, h, for both systems were required to come up with optimum transformation parameters. In the Clark1880 datum, only orthometric heights, H, were available which needed to be converted to their corresponding ellipsoidal heights using the geoid model. The negligence of the separation (geoidal undulation) could lead to inconsistent solution of parameters giving a significant error in height. Nonetheless, according to Hofmann and Moritz (2005), incorrect height of the common points often have a negligible effect on the plane coordinates (x, y). For example, incorrect heights may cause a tilt of 20km by 20km network by an amount of 5m in space, however, the effect on the plane coordinates is only approximately 1mm. This implies that the estimated parameters are reliable and valid in two dimensional (x, y) plane in spite of the estimated height in the three-dimensional coordinate transformation. At the time of writing this dissertation, there was no precise geoid information available, as such, no optimal unique set of transformation parameters exists in Zambia's international boundaries. However, research on the precise geoid model for Zambia is underway.

Despite the project being moderately funded by German Corporation for International Cooperation (GIZ) through Ministry of Lands, Natural Resources and Environmental Protection, there was a financial and time constraint to finish the Malawi stretch of about 800 kilometers and the Mozambique stretch of about 400 kilometers. Owing to that, only about 350 kilometre stretch had been done on Zambia-Malawi border leaving a stretch of about 450 kilometres, implying a 44% completion on the boundary. The other challenge included inadequate field vehicles which prevented the use of all GNSS receivers available on site, however, this challenge was combated by combining field teams in the available field vehicles. Irrespective of the challenges, the Mozambique stretch was completed.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

The chapter presents the conclusion and recommendations on unification of geodetic datums in Zambia-Malawi and Zambia-Mozambique international boundaries.

The GNSS equipment together with its datum WGS 84 datum, indeed played a role in the unification of geodetic datums under study. The international boundary beacons for Zambia-Mozambique were tied to the geocentric WGS 84 datum whereas about half of the Zambia-Malawi boundary beacons were tied to the WGS 84 coordinate system owing to the reason earlier alluded to. The Malawi stretch, on which GNSS static observations were carried out and tied to the WGS 84 datum, ranges from the *Coumba* tri-union point connecting Zambia, Malawi and Mozambique to Mpingozi area of Lundazi in Zambia and Kasungu National Park of Malawi covering a stretch of about 350Km out of a total distance of about 800Km.

The parameters were computed on the Zambia-Mozambique and Zambia-Malawi boundaries based on twelve (12) and seven (7) common points respectively, which were well distributed on the GNSS networks**.** The transformation parameters computed on the Zambia-Malawi primary network, are only valid in the southern region of the international boundary about mid-way the entire stretch because it was partially completed due to financial and time constraints.

The error in height could be attributed to the non-unification of the vertical datum which was beyond the scope of the research. However, incorrect height of the common points often have a negligible effect on the plane coordinates (x, y) as already explained in the previous section.

6.1 Conclusion

The Zambia-Mozambique international boundary coordinates were tied to global coordinate system (WGS84) positioned on ITRF2008 and about 44% of the Zambia-Malawi international boundary covering a stretch of about 350 kilometres, had been tied to the WGS84 datum.

The Helmert transformation relation from WGS 84 to Clarke 1880 was determined between Zambia-Mozambique on the Zambian side. However, the relation from WGS 84 to Clarke 1866 on the Mozambican side could not be determined owing to the fact that Mozambique no longer uses the non-geocentric Tete datum but uses the geocentric datum which is consistent with ITRF94. In the case of Zambia-Malawi, the seven-transformation parameters were determined and could be used in both countries on the southern part of the international boundary because the two countries base their coordinate system on the Arc 1950 datum which has been tied to the WGS 84 datum positioned on ITRF2008.

In a nutshell, the following objectives were achieved;

- The Zambia-Mozambique International boundary had been unified to a global geocentric WGS 84 datum, which is a datum used by GNSS receivers.
- The Seven-Parameter Datum Transformation relationship was determined on the Zambia-Mozambique boundary to transform coordinates from WGS 84 Clarke 1880 particularly on the Zambian side. A similar relation could not be determined on the Mozambican side owing to the aforementioned reasons.
- About half of the Zambia-Malawi international boundary had been unified to a geocentric WGS 84 datum.
- The Seven-Parameter Datum Transformation relationship was determined on the Zambia-Malawi boundary to transform coordinates from WGS 84 to Clarke 1880. As already alluded to, the parameters are applicable on either side of the southern part of the international boundary.

What is more, the findings could be used as a basis for the unification of other international boundaries as well as AFREF at large. Further, the international boundary surveys or engineering projects would be executed with minimal or without difficulties. The amicable resolution of international boundary disputes would be promoted particularly on the Zambia-Mozambique and partly on the Zambia-Malawi boundaries and cross border cooperation would be enhanced.

6.2 Recommendations

In view of the research findings, future research must be carried out on the following;

1. Completion of the Zambia-Malawi International Boundary Survey based on WGS 84 datum and the Determination of Transformation Parameters.
2. Unification of Geodetic Datums on the Zambia-Tanzania International Boundary based on WGS 84 datum.
3. Unifiation of the Vertical Datum in International Boundaries
4. Tying the Classical Geodetic Network of Zambia to the Latest ITRF

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Appendix 1: Coordinate List in WGS 84 (ITRF2008) Coordinate System

Table 13.0 Zambia-Malawi Primary Network UTM 33 (Zone 36L) Coordinates

Point ID	**Eastings (m)**	**Northings (m)**	**Ell. Height (m)**	**Remarks**
NYS82	526293.230	8452290.815	1150.566	Control
284MWT	507494.926	8527701.096	1100.998	Adjusted
310MWT	491760.087	8477126.294	1322.565	Adjusted
514MWT	541053.484	8605557.817	1235.126	Adjusted
516MWT	534112.669	8584562.372	1069.134	Adjusted
51NYS	523348.325	8564689.169	1101.692	Adjusted
540MWT	522370.532	8540908.717	1119.618	Adjusted
543MWT	528552.577	8604584.992	1233.568	Adjusted
60NYS	504552.862	8489480.291	1279.933	Adjusted
61NYS	501272.796	8506612.168	1192.403	Adjusted
62NYS	505554.128	8521439.051	1096.079	Adjusted
76BMWS	505934.443	8470336.504	1129.584	Adjusted
BIP103	488169.065	8472715.108	1170.211	Adjusted
BIP134	475395.381	8476325.548	1558.449	Adjusted
BIP190	476394.747	8491444.962	1330.380	Adjusted
BIP30	510048.242	8455933.188	1084.403	Adjusted
BIP445	502962.096	8571672.267	1298.550	Adjusted
BIP494	494610.926	8588906.315	1224.267	Adjusted
BPP14	494402.599	8457703.566	1143.209	Adjusted
BPP29	483313.455	8482986.849	1415.733	Adjusted
BPP35	464652.534	8494693.798	1560.192	Adjusted
BPP44	483766.444	8505889.317	1232.381	Adjusted
BPP48	491077.236	8517664.727	1092.608	Adjusted
BPP50	493645.188	8528945.789	1105.579	Adjusted
BPP57	498138.900	8544539.659	1065.171	Adjusted
BPP63	501662.923	8564038.345	1090.910	Adjusted
BPP67	494211.594	8579766.214	1166.081	Adjusted
BPP74	501191.727	8598005.901	1201.071	Adjusted
BPP77	509564.982	8607684.222	1250.556	Adjusted
BPP81	519425.038	8602277.153	1235.213	Adjusted
ZS49	502347.497	8625624.753	1169.671	Adjusted
ZP10	469533.637	8498829.649	1659.616	Adjusted
ZP8	489802.462	8522912.241	1170.293	Adjusted
ZS1	474440.368	8512489.471	1220.886	Adjusted
ZS3	476279.055	8547629.871	1104.711	Adjusted
ZS32	483563.178	8568204.861	1396.950	Adjusted
ZS39	528794.650	8613164.337	1312.367	Adjusted

ZS4	495424.338	8555672.211	1116.612	Adjusted
ZS7	450928.898	8499108.029	1328.841	Adjusted

Table 14.0 Zambia-Mozambique Primary Network Geographical Coordinates

Point ID	Lat. (Deg., Min., Sec)	Lon. (Deg., Min., Sec)	Ell. Height (m)	Remarks
ZP15	14° 14' 03.96343" S	32° 15' 01.89722" E	1201.934	Control
AQ18	14° 28' 57.15556" S	31° 49' 12.17505" E	1057.064	
AQ7	14° 49' 46.11922" S	30° 41' 05.69380" E	937.901	
CHIF	14° 52' 47.72318" S	32° 50' 21.68065" E	427.955	
FING	15° 09' 31.79514" S	31° 53' 15.59082" E	865.929	
LB1	14° 58' 32.48514" S	30° 12' 38.00708" E	383.518	
M12A	14° 39' 40.73174" S	31° 16' 43.24822" E	1082.749	
MUZE	15° 00' 28.10188" S	31° 14' 22.30834" E	863.240	
ZP107	14° 46' 56.47496" S	30° 29' 39.06230" E	1213.896	
ZP23	14° 08' 18.46294" S	32° 32' 55.98854" E	1303.020	
ZP22	14° 27' 52.95584" S	30° 46' 53.07937" E	928.172	
AQW38	13° 59' 55.56661" S	33° 14' 27.89978" E	1144.547	or BP38
VILLA	14° 09' 42.94666" S	32° 59' 08.82680" E	903.903	
AQ24	14° 18' 22.01780" S	32° 20' 00.41206" E	943.983	or BP24

Table 15.0 Zambia-Malawi Boundary WGS 84 - UTM 33, Zone 36L Coordinates

Point ID	Eastings (m)	Northings (m)	Ell. Height (m)	Remarks
BIP1	525499.205	8452422.421	1134.244	
BIP1A	525984.924	8452399.028	1142.068	
BIP2	524402.750	8452482.447	1111.653	
BIP3	523803.249	8452492.364	1111.732	
BIP4	523152.942	8452302.542	1108.047	
BIP5	522482.574	8452082.824	1103.070	
BIP6	522133.070	8452172.196	1101.847	
BIP7	521662.864	8452862.385	1093.302	
BIP8	521283.168	8453492.477	1089.706	
BIP9	520702.889	8454152.759	1093.302	
BIP10	520622.661	8455002.076	1090.207	
BIP11	520652.775	8455541.998	1090.525	
BIP12	520552.991	8456111.940	1090.356	
BIP13	519973.128	8456902.620	1086.592	
BIP14	519542.919	8457202.250	1085.794	
BIP15	519183.368	8457432.445	1082.496	
BIP16	518383.195	8457533.316	1072.457	
BIP17	517683.025	8457723.123	1069.260	

BIP18	517143.394	8458112.914	1076.688	
BIP19	516924.019	8458503.390	1081.466	
BIP20	516180.039	8458897.271	1082.597	
BIP21	515580.993	8458685.860	1077.139	
BIP22	515053.592	8458003.585	1076.153	
BIP23	514720.339	8457483.923	1078.250	
BIP24	514603.748	8456933.514	1081.228	
BIP25	513893.170	8456583.073	1083.576	
BIP26	512981.228	8456616.253	1095.748	
BIP27	512473.245	8456707.766	1095.279	
BIP28	512023.230	8456783.005	1092.273	
BIP29	510923.273	8456332.954	1088.875	
BIP30	510048.242	8455933.189	1084.402	
BIP31	509448.314	8455633.084	1078.860	
BIP32	509023.056	8455332.417	1077.994	
BIP33	508593.145	8454933.233	1074.446	
BIP34	508124.221	8454432.402	1075.146	
BIP35	507723.033	8454033.317	1076.573	
BIP36	507273.336	8453383.656	1091.733	
BIP37	506823.809	8452083.010	1107.641	
BIP38	506914.331	8450568.712	1112.209	
BIP39	506264.900	8449143.833	1119.435	
BIP40	505814.972	8448818.801	1124.657	
BIP41	505384.821	8448318.806	1122.536	
BIP42	504715.187	8447718.912	1132.803	
BIP43	504514.843	8446968.825	1128.288	
BIP44	504039.945	8446343.985	1129.315	
BIP45	503315.383	8446918.772	1131.026	
BIP46	503415.424	8447219.016	1125.110	
BIP47	503415.016	8447419.103	1123.646	
BIP48	503239.748	8447719.359	1126.012	
BIP49	503064.715	8447868.700	1124.669	
BIP50	501965.135	8448969.153	1138.821	
BIP51	501232.579	8449403.431	1147.943	
BIP52	500583.069	8449563.456	1158.391	
BIP53	500183.337	8449743.735	1152.088	
BIP54	499963.421	8450323.989	1150.520	
BIP55	499643.065	8452583.651	1153.185	
BIP56	499653.143	8452923.603	1150.239	
BIP57	499463.285	8453703.829	1157.775	
BIP58	499782.977	8454363.839	1148.759	

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BIP60	500082.627	8455153.428	1140.109	
BIP61	500102.794	8456263.327	1142.426	
BIP62	499972.779	8457123.151	1131.606	
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BIP65	496742.870	8458863.390	1123.637	
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BIP68	493932.671	8457843.639	1144.646	
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BIP77	494752.283	8462910.843	1137.719	
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BIP82	493872.275	8465183.766	1183.148	
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BIP85	492760.274	8466041.666	1324.809	
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BIP87	491659.204	8466565.263	1255.214	
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BIP89	491164.645	8466710.838	1307.760	
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BIP119	481344.308	8476025.143	1240.333	
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BIP147B	478114.150	8479820.102	1290.636	
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BIP179	479363.631	8487185.394	1404.236	
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BIP183	478043.871	8488645.361	1402.436	
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BIP187	478419.285	8489936.503	1399.630	
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BIP192	475284.256	8491745.359	1370.598	
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BIP194	474249.738	8492442.648	1355.669	
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BIP222	464506.234	8494225.964	1566.778	
BIP223	464727.405	8494453.678	1555.710	
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BIP241	470143.671	8498486.233	1641.542	
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BIP243	472468.494	8498349.438	1510.974	
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BIP246	473456.009	8499234.884	1265.065	
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BIP272	482876.689	8510485.066	1123.284	
BIP273	483211.112	8510904.090	1117.772	
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BIP275	483283.404	8511098.637	1116.890	
BIP276	483312.793	8511262.105	1116.950	
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BIP278	483281.910	8511444.677	1118.002	
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BIP379	499875.227	8543362.060	1074.511	
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BIP406	498786.815	8554404.901	1074.502	
BIP407	498953.567	8554605.195	1075.840	
BIP408	499002.290	8555187.335	1074.151	
BIP409	499273.274	8555680.813	1081.381	
BIP410	499563.798	8555960.170	1089.676	
BIP411	499497.109	8556360.512	1087.721	
BIP412	499647.262	8556688.388	1086.930	
BIP413	499688.089	8557242.431	1088.974	
BIP414	499668.214	8557555.298	1090.893	
BIP415	499765.615	8557644.226	1091.180	
BIP416	499452.862	8558125.593	1086.585	
BIP417	499081.805	8558484.610	1087.790	
BIP418	498603.829	8558801.551	1084.326	
BIP419	498365.003	8559053.256	1087.863	
BIP420	498595.476	8559503.155	1083.249	
BIP421	499290.106	8559999.166	1087.432	
BIP422	499497.588	8560311.031	1087.707	
BIP423	499528.748	8560886.116	1084.309	
BIP424	499700.046	8561246.981	1089.378	
BIP425	499619.876	8561732.099	1090.600	
BIP426	499980.993	8562270.127	1084.697	
BIP427	500317.133	8562642.950	1082.186	
BIP428	500702.335	8562996.907	1079.760	
BIP429	501212.522	8563342.564	1084.519	

BIP430	501358.198	8563753.774	1083.950	
BIP431	501632.878	8564562.763	1094.816	
BIP432	501244.690	8565188.062	1090.072	
BIP433	501525.995	8565989.622	1084.967	
BIP434	501703.852	8566440.484	1084.400	
BIP435	501648.356	8567112.145	1084.143	
BIP436	501944.744	8567486.685	1083.918	
BIP437	501883.759	8567987.967	1085.840	
BIP438	501973.495	8568517.331	1095.933	
BIP439	502150.075	8569006.960	1143.727	
BIP440	502174.842	8569514.159	1097.745	
BIP441	502030.674	8570064.465	1094.041	
BIP442	502260.829	8570688.510	1112.921	
BIP443	502583.896	8570994.052	1277.280	
BIP444	502847.457	8571184.246	1312.595	
BIP445	502962.096	8571672.267	1298.548	
BIP446	503037.919	8572171.436	1272.700	
BIP447	503083.842	8572576.163	1244.858	
BIP448	502692.612	8572856.188	1118.621	
BIP449	502474.502	8573274.980	1117.580	
BIP450	502406.283	8573764.562	1112.333	
BIP451	502403.428	8574317.330	1114.708	
BIP452	501989.274	8574872.238	1106.897	
BIP453	501483.736	8575015.564	1105.758	
BIP454	501034.788	8575157.282	1107.851	
BIP455	500480.144	8575128.594	1105.751	
BIP456	499801.038	8575315.951	1106.544	
BIP457	499468.952	8575471.466	1108.766	
BIP458	499087.877	8575492.960	1111.388	
BIP459	498521.619	8575628.450	1119.692	
BIP460	498248.877	8575637.933	1126.142	
BIP461	497871.722	8575818.275	1132.452	
BIP462	497421.390	8575917.886	1131.779	
BIP463	496966.601	8576216.933	1134.422	
BIP464	496830.914	8576608.514	1133.800	
BIP465	496585.369	8577002.366	1136.395	
BIP466	496287.077	8577493.788	1138.043	
BIP467	495895.174	8577892.341	1144.609	
BIP468	495524.702	8578192.697	1152.019	
BIP469	495196.798	8578402.624	1157.116	
BIP470	495035.572	8578708.430	1155.521	

BIP471	494832.374	8579029.257	1153.167	
BIP472	494675.374	8579213.932	1154.215	
BIP473	494386.183	8579502.693	1162.544	
BIP474	494493.497	8580038.275	1164.425	
BIP475	494648.152	8580524.576	1164.024	
BIP476	494768.705	8580767.128	1164.665	
BIP477	495102.546	8581149.840	1157.268	
BIP478	495114.874	8581665.763	1152.397	
BIP479	495176.024	8582156.830	1155.183	
BIP480	494802.673	8582863.866	1163.207	
BIP481	494685.057	8583307.444	1167.542	
BIP482	494515.212	8583443.036	1167.927	
BIP483	494676.444	8583860.162	1164.819	
BIP484	494457.755	8584441.765	1165.354	
BIP485	494153.525	8584839.001	1175.597	
BIP486	494255.856	8585447.020	1181.713	
BIP487	494306.293	8585925.580	1184.295	
BIP488	494164.580	8586384.569	1192.728	
BIP489	493815.303	8586767.747	1201.962	
BIP490	493725.883	8587155.897	1198.668	
BIP491	493569.406	8587477.660	1205.304	
BIP492	493639.282	8588327.208	1210.751	
BIP493	494123.740	8588556.526	1214.541	
BIP494	494610.926	8588906.315	1224.266	
BPP1	522323.084	8452072.525	1103.841	
BPP2	520522.839	8454682.119	1093.811	
BPP3	520353.804	8456512.991	1087.467	
BPP4	516563.572	8458892.975	1085.202	
BPP5	514341.711	8456682.391	1083.192	
BPP6	511548.546	8456732.896	1095.595	
BPP7	506724.014	8452533.141	1101.530	
BPP8	506929.669	8449788.878	1117.437	
BPP9	503766.978	8446118.808	1135.454	
BPP10	500003.080	8449943.442	1150.537	
BPP11	499343.007	8451663.570	1167.493	
BPP12	499592.487	8457883.305	1122.052	
BPP13	495572.518	8458823.124	1133.776	
BPP14	494402.599	8457703.566	1143.208	
BPP15	493612.752	8458043.904	1147.638	
BPP16	495002.542	8462383.782	1134.631	
BPP17	492653.210	8466371.967	1375.318	

BPP18	489488.864	8470274.945	1178.620	
BPP19	484994.132	8474625.822	1239.319	
BPP20	479951.937	8476090.770	1493.760	
BPP21	479442.320	8474247.704	1529.953	
BPP22	478664.001	8474265.217	1360.069	
BPP23	477726.064	8475922.997	1455.263	
BPP24	475249.650	8476456.313	1594.623	
BPP25	476301.417	8480044.346	1472.080	
BPP26	477934.354	8479729.360	1298.836	
BPP27	479084.301	8481885.105	1259.890	
BPP28	482424.353	8482035.704	1335.183	
BPP29	483313.455	8482986.849	1415.732	
BPP30	478106.634	8487759.027	1472.479	
BPP31	478680.229	8489839.138	1412.991	
BPP32	473851.077	8492493.713	1449.499	
BPP33	473251.326	8490775.703	1368.413	
BPP34	464597.040	8493947.776	1575.760	
BPP35	464652.534	8494693.799	1560.191	
BPP36	466299.680	8496528.793	1482.476	
BPP37	465423.362	8497825.915	1498.885	
BPP38	467005.302	8498886.419	1449.411	
BPP39	466062.713	8499544.556	1498.145	
BPP40	472165.924	8498140.389	1623.639	
BPP41	473959.546	8500681.347	1630.840	
BPP42	476471.732	8501645.813	1576.915	
BPP43	480505.101	8502995.152	1160.745	
BPP44	483766.444	8505889.318	1232.381	
BPP45	482995.138	8507158.772	1266.717	
BPP46	483308.496	8511634.410	1121.051	
BPP47	487546.923	8512104.279	1099.733	
BPP48	491077.236	8517664.728	1092.606	
BPP49	492287.035	8524104.891	1077.415	
BPP50	493645.188	8528945.789	1105.579	
BPP51	494356.871	8532822.792	1101.924	
BPP52	497624.069	8535698.960	1097.621	
BPP53	497973.866	8537106.420	1096.463	
BPP54	502165.717	8539458.398	1102.551	
BPP55	500869.741	8540246.599	1089.621	
BPP56	499377.715	8544013.559	1073.168	
BPP57	498138.856	8544539.661	1065.292	
BPP58	497697.791	8545195.989	1075.881	

BPP59	498144.792	8546501.266	1075.065	
BPP60	497244.063	8550188.894	1078.146	
BPP61	497959.893	8553829.294	1086.921	
BPP62	498775.696	8560097.171	1088.795	
BPP63	501662.922	8564038.345	1090.909	
BPP64	502005.121	8570409.411	1096.243	
BPP65	502527.315	8574549.666	1119.169	
BPP66	497607.123	8575699.945	1134.233	
BPP67	494211.594	8579766.214	1166.080	
BPP68	495148.946	8582619.443	1161.208	
BPP69	493316.334	8587929.956	1217.312	
BPP353	496025.080	8533838.037	1088.099	
BP 38	526034.956	8452396.608	1144.492	Tri-union (Coumba)
Kunguye	465624.042	8498251.710	1561.795	Not part of boundary
NYS82	526293.230	8452290.815	1150.566	Not part of boundary
ZP10	469533.637	8498829.650	1659.615	Not part of boundary
ZS4	495424.338	8555672.211	1116.610	Not part of boundary
ZS10	491749.774	8465766.391	1468.443	Not part of boundary

Table 16.0 Zambia-Mozambique Boundary WGS 84 – Geographical Coordinates

Point ID	Lat. (Deg., Min., Sec)	Lon. (Deg., Min., Sec)	Ell. Height (m)	Remarks
17.1	14° 30' 05.49196" S	31° 43' 41.34856" E	977.025	
17.5	14° 29' 31.76745" S	31° 46' 24.73087" E	967.787	
17A	14° 30' 32.45079" S	31° 41' 30.63337" E	980.436	
17AA	14° 29' 04.68469" S	31° 48' 35.75467" E	992.141	
17B	14° 30' 29.21615" S	31° 41' 46.32096" E	964.744	
17BB	14° 29' 01.42907" S	31° 48' 51.50378" E	1003.066	
17C	14° 30' 25.71320" S	31° 42' 03.31579" E	962.056	
17E	14° 30' 18.97485" S	31° 42' 35.99346" E	973.963	
17F	14° 30' 15.60242" S	31° 42' 52.33014" E	971.529	
17G	14° 30' 12.23290" S	31° 43' 08.67043" E	968.140	
17H	14° 30' 08.86196" S	31° 43' 25.00834" E	967.849	
17J	14° 30' 02.12082" S	31° 43' 57.68776" E	983.258	
17K	14° 29' 58.74905" S	31° 44' 14.02737" E	979.509	
17L	14° 29' 55.37474" S	31° 44' 30.36370" E	974.466	
17M	14° 29' 52.00305" S	31° 44' 46.70603" E	978.458	
17P	14° 29' 45.25807" S	31° 45' 19.37901" E	982.271	
17Q	14° 29' 41.88090" S	31° 45' 35.71692" E	979.034	
17R	14° 29' 38.51151" S	31° 45' 52.05566" E	969.350	
17S	14° 29' 35.13327" S	31° 46' 08.39178" E	967.202	
17U	14° 29' 25.00876" S	31° 46' 57.40516" E	983.264	

17V	14° 29' 21.63691" S	31° 47' 13.74114" E	984.698	
17W	14° 29' 18.25914" S	31° 47' 30.07892" E	997.146	
17X	14° 29' 14.88013" S	31° 47' 46.41894" E	995.208	
17Y	14° 29' 11.50674" S	31° 48' 02.75289" E	998.239	
17Z	14° 29' 08.12835" S	31° 48' 19.08934" E	992.778	
AQ17	14° 30' 39.18975" S	31° 40' 57.95484" E	1187.541	
AQ18	14° 28' 57.15556" S	31° 49' 12.17505" E	1057.064	
14A	14° 37' 53.79454" S	31° 26' 02.36618" E	1004.229	
14B	14° 37' 47.97806" S	31° 26' 21.15297" E	1004.581	
14C	14° 37' 42.16252" S	31° 26' 39.94280" E	1010.521	
14D	14° 37' 36.34581" S	31° 26' 58.73168" E	1017.558	
14E	14° 37' 30.52970" S	31° 27' 17.52242" E	1032.644	
14F	14° 37' 24.71131" S	31° 27' 36.31137" E	1040.024	
14G	14° 37' 13.49051" S	31° 28' 12.55021" E	1036.613	
14H	14° 37' 08.38861" S	31° 28' 29.01356" E	1039.814	
14J	14° 37' 03.24288" S	31° 28' 45.63526" E	1050.998	
14K	14° 36' 58.09472" S	31° 29' 02.25829" E	1053.225	
14L	14° 36' 52.94392" S	31° 29' 18.88214" E	1053.868	
14M	14° 36' 47.79634" S	31° 29' 35.50299" E	1058.170	
14N	14° 36' 42.64458" S	31° 29' 52.12622" E	1059.459	
15.1	14° 35' 37.26918" S	31° 31' 56.43712" E	1031.278	
15A	14° 36' 26.12496" S	31° 30' 29.10802" E	1057.520	
15B	14° 36' 18.02132" S	31° 30' 43.59644" E	1053.702	
15C	14° 36' 09.91784" S	31° 30' 58.08321" E	1049.888	
15D	14° 36' 01.81281" S	31° 31' 12.56876" E	1048.945	
15E	14° 35' 53.70782" S	31° 31' 27.05645" E	1043.220	
15F	14° 35' 45.60282" S	31° 31' 41.54315" E	1032.291	
15G	14° 35' 29.39002" S	31° 32' 10.51673" E	1028.271	
15H	14° 35' 21.20536" S	31° 32' 25.14722" E	1030.671	
15J	14° 35' 13.17849" S	31° 32' 39.48641" E	1026.944	
15K	14° 35' 05.03935" S	31° 32' 54.02984" E	1019.557	
15L	14° 34' 56.96606" S	31° 33' 08.45613" E	1013.976	
AQ14	14° 37' 59.60928" S	31° 25' 43.57242" E	1016.329	
AQ16	14° 34' 40.30922" S	31° 33' 38.21525" E	1051.608	
12A	14° 39' 40.73246" S	31° 16' 43.24620" E	1083.891	
13.1	14° 38' 30.23292" S	31° 23' 09.48542" E	984.887	
13A	14° 38' 57.50874" S	31° 20' 52.11343" E	1004.011	
13B	14° 38' 54.09614" S	31° 21' 09.30615" E	995.814	
13C	14° 38' 50.68272" S	31° 21' 26.49641" E	985.420	
13D	14° 38' 46.88273" S	31° 21' 45.65166" E	976.945	
13E	14° 38' 43.00716" S	31° 22' 05.16833" E	967.438	
13F	14° 38' 40.44259" S	31° 22' 18.06972" E	970.702	

13G	14° 38' 37.03312" S	31° 22' 35.26145" E	975.773	
13H	14° 38' 33.61814" S	31° 22' 52.45221" E	984.295	
13J	14° 38' 26.79836" S	31° 23' 26.77289" E	987.660	
13K	14° 38' 23.40426" S	31° 23' 43.86513" E	980.571	
13L	14° 38' 20.00807" S	31° 24' 00.95494" E	985.206	
13M	14° 38' 16.66485" S	31° 24' 17.78788" E	992.013	
13N	14° 38' 13.21424" S	31° 24' 35.14086" E	980.726	
13P	14° 38' 09.81764" S	31° 24' 52.23378" E	994.056	
13R	14° 38' 06.41945" S	31° 25' 09.32565" E	1000.016	
13S	14° 38' 03.04130" S	31° 25' 26.31828" E	1002.430	
10.1	14° 42' 47.66766" S	31° 06' 44.46749" E	993.099	
10A	14° 43' 19.23779" S	31° 05' 09.58423" E	1012.144	
10B	14° 43' 13.97555" S	31° 05' 25.39958" E	996.546	
10C	14° 43' 08.71699" S	31° 05' 41.21143" E	986.972	
10D	14° 43' 03.45672" S	31° 05' 57.02733" E	1008.343	
10E	14° 42' 57.77219" S	31° 06' 14.10819" E	985.746	
10F	14° 42' 52.93213" S	31° 06' 28.65662" E	989.686	
10G	14° 42' 42.40564" S	31° 07' 00.28248" E	990.947	
10H	14° 42' 37.14473" S	31° 07' 16.09643" E	1002.364	
10J	14° 42' 31.88075" S	31° 07' 31.91023" E	1009.620	
10K	14° 42' 26.61791" S	31° 07' 47.72301" E	1022.135	
10L	14° 42' 21.35394" S	31° 08' 03.53591" E	1019.903	
10M	14° 42' 16.08986" S	31° 08' 19.34915" E	1033.691	
AQ10	14° 43' 24.77302" S	31° 04' 52.94315" E	1108.679	
AQ11	14° 42' 10.82441" S	31° 08' 35.16185" E	1095.894	
9.1	14° 44' 38.89336" S	30° 59' 40.24286" E	910.874	
9A	14° 45' 05.76695" S	30° 57' 46.55904" E	950.673	
9B	14° 45' 01.85495" S	30° 58' 03.25636" E	956.638	
9C	14° 44' 58.11901" S	30° 58' 19.04180" E	954.951	
9D	14° 44' 58.11976" S	30° 58' 19.04162" E	955.290	
9G	14° 44' 46.58400" S	30° 59' 07.76159" E	928.051	
9K	14° 44' 30.92789" S	31° 00' 13.88134" E	917.270	
9L	14° 44' 26.96848" S	31° 00' 30.59262" E	915.618	
9N	14° 44' 19.27538" S	31° 01' 03.07224" E	926.272	
9P	14° 44' 15.42605" S	31° 01' 19.31286" E	923.780	
9Q	14° 44' 11.54057" S	31° 01' 35.70320" E	932.899	
9R	14° 44' 03.88177" S	31° 02' 08.02660" E	950.210	
9S	14° 44' 00.03127" S	31° 02' 24.26707" E	953.774	
9T	14° 43' 56.18282" S	31° 02' 40.50271" E	955.453	
9U	14° 43' 52.33409" S	31° 02' 56.74185" E	972.836	
9V	14° 43' 48.48398" S	31° 03' 12.98027" E	983.834	
9W	14° 43' 44.63342" S	31° 03' 29.21890" E	993.686	

9X	14° 43' 40.78409" S	31° 03' 45.45586" E	997.858	
9Z	14° 43' 33.07708" S	31° 04' 17.93021" E	1056.244	
AQ9	14° 45' 10.03769" S	30° 57' 28.70413" E	1050.588	
7.1	14° 49' 00.06715" S	30° 43' 15.01094" E	754.058	
7.2	14° 48' 14.60776" S	30° 45' 22.60293" E	796.662	
7A	14° 49' 33.22210" S	30° 41' 41.92477" E	765.699	
7B	14° 49' 27.63107" S	30° 41' 57.62220" E	754.268	
7C	14° 49' 22.04127" S	30° 42' 13.32213" E	737.133	
7F	14° 49' 05.25797" S	30° 43' 00.44735" E	749.697	
7G	14° 48' 54.08492" S	30° 43' 31.80737" E	761.718	
7H	14° 48' 47.73330" S	30° 43' 49.64014" E	759.587	
7J	14° 48' 42.90056" S	30° 44' 03.20185" E	754.833	
7K	14° 48' 37.30886" S	30° 44' 18.89985" E	765.521	
7N	14° 48' 19.93577" S	30° 45' 07.64918" E	776.711	
7P	14° 48' 09.21667" S	30° 45' 37.72405" E	805.019	
7Q	14° 48' 03.74593" S	30° 45' 53.07446" E	799.408	
7R	14° 47' 58.15226" S	30° 46' 08.76795" E	807.105	
7S	14° 47' 52.55525" S	30° 46' 24.46529" E	827.036	
7T	14° 47' 46.33413" S	30° 46' 41.91679" E	835.810	
7U	14° 47' 41.36087" S	30° 46' 55.85583" E	848.059	
7V	14° 47' 35.76582" S	30° 47' 11.55005" E	847.765	
7W	14° 47' 30.17084" S	30° 47' 27.24333" E	846.590	
7X	14° 47' 24.57235" S	30° 47' 42.93754" E	860.506	
AQ7	14° 49' 46.12038" S	30° 41' 05.68991" E	936.649	
AQ8	14° 47' 18.97334" S	30° 47' 58.63505" E	890.974	
11.1	14° 41' 21.11348" S	31° 11' 14.28073" E	1063.375	
11.2	14° 40' 31.86371" S	31° 13' 51.79260" E	1063.854	
11A	14° 42' 05.30998" S	31° 08' 52.82174" E	1048.125	
11B	14° 41' 59.78904" S	31° 09' 10.48635" E	1053.880	
11C	14° 41' 54.27298" S	31° 09' 28.14691" E	1039.332	
11D	14° 41' 48.75639" S	31° 09' 45.81091" E	1035.759	
11E	14° 41' 43.23794" S	31° 10' 03.47265" E	1050.661	
11F	14° 41' 37.71955" S	31° 10' 21.13471" E	1062.283	
11G	14° 41' 32.19927" S	31° 10' 38.79595" E	1054.654	
11H	14° 41' 26.67953" S	31° 10' 56.45941" E	1057.459	
11J	14° 41' 15.59273" S	31° 11' 31.94294" E	1072.432	
11K	14° 41' 10.07263" S	31° 11' 49.60209" E	1069.961	
11L	14° 41' 04.54893" S	31° 12' 07.26285" E	1084.913	
11M	14° 40' 59.03092" S	31° 12' 24.92085" E	1082.679	
11N	14° 40' 53.50565" S	31° 12' 42.58401" E	1078.706	
11P	14° 40' 47.98536" S	31° 13' 00.24663" E	1067.438	
11R	14° 40' 42.46439" S	31° 13' 17.90562" E	1075.454	

11S	14° 40' 36.93992" S	31° 13' 35.56292" E	1070.221	
11T	14° 40' 25.51169" S	31° 14' 12.09642" E	1081.115	
11U	14° 40' 19.16403" S	31° 14' 32.39396" E	1094.900	
11V	14° 40' 12.81132" S	31° 14' 52.69192" E	1089.814	
11W	14° 40' 05.46810" S	31° 15' 16.17685" E	1070.383	
11X	14° 40' 00.11061" S	31° 15' 33.29233" E	1087.387	
11Y	14° 39' 55.00316" S	31° 15' 49.61535" E	1084.969	
16.1	14° 33' 20.19991" S	31° 36' 04.38346" E	985.241	
16.2	14° 32' 00.65922" S	31° 38' 29.45174" E	987.792	
16A	14° 34' 32.33083" S	31° 33' 52.77793" E	1008.556	
16B	14° 34' 23.95392" S	31° 34' 08.06166" E	1009.747	
16C	14° 34' 16.29377" S	31° 34' 22.03946" E	1006.161	
16D	14° 34' 08.36228" S	31° 34' 36.51002" E	1001.447	
16E	14° 34' 00.41744" S	31° 34' 51.01219" E	996.685	
16F	14° 33' 52.43809" S	31° 35' 05.56960" E	992.988	
16G	14° 33' 44.34730" S	31° 35' 20.33361" E	989.423	
16J	14° 33' 28.49852" S	31° 35' 49.24178" E	970.586	
16K	14° 33' 12.53843" S	31° 36' 18.35804" E	985.273	
16L	14° 33' 04.55975" S	31° 36' 32.91637" E	988.977	
16M	14° 32' 56.61137" S	31° 36' 47.41376" E	991.947	
16N	14° 32' 48.59874" S	31° 37' 02.02979" E	986.549	
16P	14° 32' 40.64970" S	31° 37' 16.52805" E	979.372	
16Q	14° 32' 32.66813" S	31° 37' 31.08384" E	972.945	
16R	14° 32' 24.65387" S	31° 37' 45.69726" E	973.559	
16S	14° 32' 16.67293" S	31° 38' 00.25089" E	985.503	
16T	14° 32' 08.65829" S	31° 38' 14.86499" E	987.550	
16U	14° 31' 52.67800" S	31° 38' 44.00309" E	985.432	
16V	14° 31' 44.69419" S	31° 38' 58.55653" E	990.221	
16W	14° 31' 36.70975" S	31° 39' 13.11023" E	997.429	
16X	14° 31' 28.72538" S	31° 39' 27.66229" E	1004.034	
16Y	14° 31' 20.74335" S	31° 39' 42.21733" E	1011.000	
16Z	14° 31' 14.83440" S	31° 39' 52.98642" E	1020.295	
AQ13	14° 39' 00.92026" S	31° 20' 34.92129" E	1045.320	
AQ15	14° 36' 37.47111" S	31° 30' 08.82506" E	1122.557	
8.2	14° 46' 20.09984" S	30° 52' 19.14170" E	876.191	
8M	14° 46' 31.14937" S	30° 51' 30.29868" E	880.779	
8N	14° 46' 27.46805" S	30° 51' 46.57959" E	874.234	
8P	14° 46' 23.82762" S	30° 52' 02.67114" E	866.778	
8Q	14° 46' 16.43098" S	30° 52' 35.40231" E	873.364	
8R	14° 46' 12.73970" S	30° 52' 51.69924" E	884.825	
8S	14° 46' 09.05920" S	30° 53' 07.98114" E	874.267	
8T	14° 46' 05.37521" S	30° 53' 24.26467" E	863.828	

8U	14° 46' 01.97061" S	30° 53' 39.30818" E	855.869	
8V	14° 45' 58.00592" S	30° 53' 56.82495" E	859.566	
8K	14° 46' 38.50930" S	30° 50' 57.73703" E	901.760	
18F	14° 28' 11.79442" S	31° 50' 40.90265" E	964.582	
18.1	14° 27' 41.68581" S	31° 51' 39.70428" E	971.802	
18B	14° 28' 42.03402" S	31° 49' 41.78524" E	987.036	
18D	14° 28' 26.91648" S	31° 50' 11.32766" E	978.545	
18E	14° 28' 19.35518" S	31° 50' 26.11593" E	964.580	
18H	14° 27' 56.67299" S	31° 51' 10.47533" E	984.064	
18L	14° 27' 26.42164" S	31° 52' 09.62044" E	991.600	
8.1	14° 46' 49.54952" S	30° 50' 08.89255" E	879.602	
8.2	14° 46' 20.10089" S	30° 52' 19.14236" E	875.296	
8.3	14° 45' 50.38499" S	30° 54' 30.52621" E	882.380	
8A	14° 47' 15.29784" S	30° 48' 14.91784" E	840.963	
8B	14° 47' 11.61725" S	30° 48' 31.19834" E	837.604	
8BB	14° 45' 43.27144" S	30° 55' 01.94812" E	902.892	
8C	14° 47' 07.94149" S	30° 48' 47.48311" E	836.500	
8CC	14° 45' 39.58549" S	30° 55' 18.22498" E	888.230	
8DD	14° 45' 36.30251" S	30° 55' 32.71328" E	873.656	
8E	14° 47' 00.58618" S	30° 49' 20.04679" E	852.882	
8EE	14° 45' 32.21245" S	30° 55' 50.78301" E	874.127	
8F	14° 46' 56.90822" S	30° 49' 36.32847" E	860.170	
8FF	14° 45' 28.51535" S	30° 56' 07.11121" E	865.848	
8G	14° 46' 53.23027" S	30° 49' 52.60597" E	868.520	
8GG	14° 45' 24.83893" S	30° 56' 23.34153" E	873.949	
8HH	14° 45' 21.52102" S	30° 56' 37.99184" E	879.461	
8J	14° 46' 42.19175" S	30° 50' 41.45725" E	900.821	
18A	14° 28' 49.59691" S	31° 49' 26.96370" E	1000.774	
18C	14° 28' 34.32616" S	31° 49' 56.83575" E	980.182	
18G	14° 28' 04.23216" S	31° 50' 55.68794" E	977.211	
18J	14° 27' 49.10487" S	31° 51' 25.22948" E	976.706	
18K	14° 27' 33.98678" S	31° 51' 54.83333" E	982.289	
18L	14° 27' 26.42159" S	31° 52' 09.62045" E	991.594	
12G	14° 39' 19.30729" S	31° 18' 47.98083" E	1043.823	
12.1	14° 39' 22.36592" S	31° 18' 30.17634" E	1046.062	
12B	14° 39' 37.67627" S	31° 17' 01.05212" E	1063.459	
12C	14° 39' 34.11209" S	31° 17' 21.81641" E	1063.563	
12D	14° 39' 31.55769" S	31° 17' 36.66310" E	1065.414	
12E	14° 39' 28.50103" S	31° 17' 54.46735" E	1058.522	
12F	14° 39' 25.44263" S	31° 18' 12.27237" E	1054.844	
12J	14° 39' 12.21937" S	31° 19' 29.21672" E	1020.720	
12K	14° 39' 10.12504" S	31° 19' 41.39595" E	1024.043	

12L	14° 39' 07.06398" S	31° 19' 59.20070" E	1017.124	
AQ1	14° 59' 48.58270" S	30° 13' 06.48803" E	444.271	
AQ2	14° 59' 50.58893" S	30° 13' 11.31598" E	444.281	
AQ3	14° 59' 25.10414" S	30° 14' 46.35584" E	524.746	
AQ5	14° 54' 31.14785" S	30° 28' 52.00597" E	821.830	
AQ6	14° 52' 29.91026" S	30° 34' 07.31118" E	818.065	
MZ1	14° 59' 48.99964" S	30° 13' 09.10207" E	444.363	

Appendix 2: NYS82 NGS OPUS SOLUTION REPORT

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                              ========================

  USER: kamangenic@gmail.com                 DATE: October 07, 2015
RINEX FILE: nys8279k.15o                     TIME: 17:56:50 UTC

  SOFTWARE: page5  1209.04 master53.pl 022814      START: 2015/10/06  10:40:00
 EPHEMERIS: igr18652.eph [rapid]                 STOP: 2015/10/06  14:59:00
  NAV FILE: brdc2790.15n                  OBS USED:  9127 /  9723   :  94%
  ANT NAME: LEIAX1202       NONE           # FIXED AMB:    61 /    68   :  90%
ARP HEIGHT: 0.294                    OVERALL RMS: 0.012(m)


REF FRAME: IGS08 (EPOCH:2015.7631)
        X:      5177847.125(m)   0.038(m)
        Y:      3393902.346(m)   0.019(m)
        Z:     -1533230.433(m)   0.014(m)

      LAT:  -13 59 59.00275      0.008(m)
    E LON:   33 14 36.51246      0.017(m)
    W LON:  326 45 23.48754      0.017(m)
   EL HGT:         1150.566(m)   0.037(m)

                    UTM COORDINATES
                    UTM (Zone 36)
          Northing (Y) [meters]     8452290.815
          Easting (X)  [meters]      526293.230
          Convergence  [degrees]    -0.05890130
          Point Scale              0.99960855
          Combined Factor           0.99942772

                              BASE STATIONS USED
          PID      DESIGNATION                   LATITUDE    LONGITUDE
          DISTANCE(m)
                RBAY                                  1638274.0
                ZAMB                                   554029.8
                HARB                                  1434605.1

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```

Appendix 3:   ZP15 NGS OPUS SOLUTION REPORT

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                     =======================

 USER: mwalimusilwembe@ymail.com           DATE: July 22, 2016
RINEX FILE: zp15270q.15o                  TIME: 15:30:53 UTC


  SOFTWARE: page5  1209.04 master50.pl 160321      START: 2015/09/27  16:37:00
EPHEMERIS: igs18640.eph [precise]               STOP: 2015/09/28  08:39:00
  NAV FILE: brdc2700.15n                     OBS USED: 39327 / 39566  :  99%
  ANT NAME: LEIAX1203+GNSS  NONE          # FIXED AMB:    92 /  102  :  90%
ARP HEIGHT: 0.2400                      OVERALL RMS: 0.009(m)


REF FRAME: IGS08 (EPOCH:2015.7398)

        X:      5230568.179(m)  0.012(m)
        Y:      3300310.005(m)  0.004(m)
        Z:    -1558431.876(m)  0.002(m)

      LAT:  -14 14  3.96318      0.003(m)
    E LON:  32 15  1.89714      0.008(m)
    W LON:  327 44 58.10286      0.008(m)
    EL HGT:        1201.892(m)  0.009(m)

                  UTM COORDINATES
                  UTM (Zone 36)
Northing (Y) [meters]    8426216.143
Easting (X)  [meters]      419144.506
Convergence  [degrees]     0.18429796
Point Scale              0.99968086
Combined Factor            0.99949196

                     BASE STATIONS USED
PID      DESIGNATION                  LATITUDE    LONGITUDE DISTANCE(m)
     RBAY                                        1608243.5
     ZAMB                                          444022.7
     HARB                                        1372002.0

This position and the above vector components were computed without any
knowledge by the National Geodetic Survey regarding the equipment or
field operating procedures used.
```
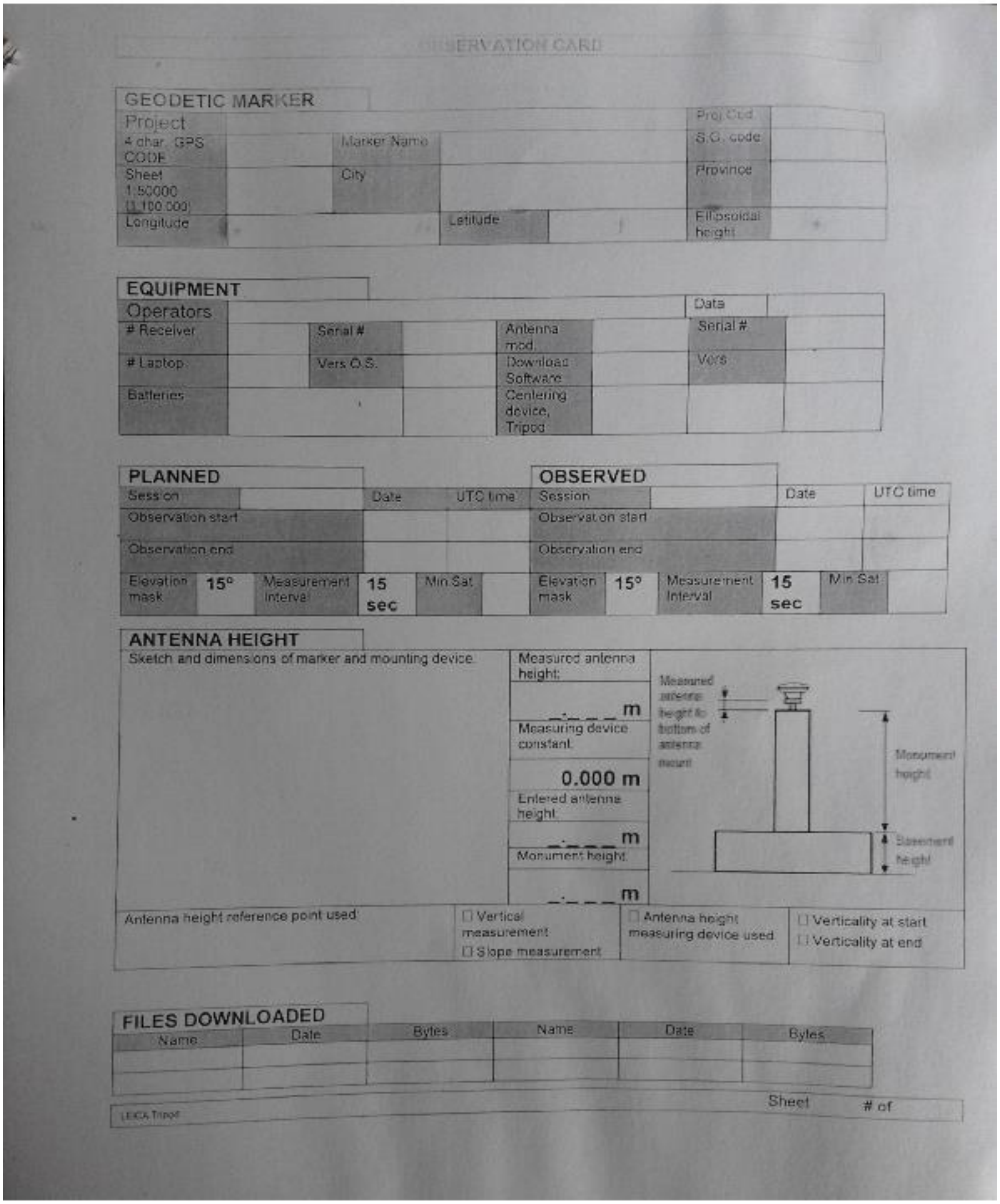

Appendix 4: Observation Field Sheet



OBSERVATION CARD

GEODETIC MARKER

Project				Proj Cod	
4 char. GPS CODE		Marker Name		S.G. code	
Sheet 1:50000 (1:100 000)		City		Province	
Longitude		Latitude		Ellipsoidal height	

EQUIPMENT

Operators						Data	
# Receiver		Serial #		Antenna mod.		Serial #	
# Laptop		Vers O.S.		Download Software		Vers	
Batteries				Centering device, Tripod			

PLANNED

Session		Date		UTC time	
Observation start					
Observation end					
Elevation mask	15°	Measurement interval	15 sec	Min Sat	

OBSERVED

Session		Date		UTC time	
Observation start					
Observation end					
Elevation mask	15°	Measurement Interval	15 sec	Min Sat	

ANTENNA HEIGHT

Sketch and dimensions of marker and mounting device

Measured antenna height: _._ _ _ m

Measuring device constant: 0.000 m

Entered antenna height: _._ _ _ m

Monument height: _._ _ _ m

Antenna height reference point used:

☐ Vertical measurement
☐ Slope measurement

☐ Antenna height measuring device used

☐ Verticality at start
☐ Verticality at end

FILES DOWNLOADED

Name	Date	Bytes	Name	Date	Bytes

LEICA Tripod

Sheet # of

Appendix 5: Photos of Static and RTK Observations

Figure 13. Photo of RTK Measurements

Figure 14. Photo of Static Observations