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IMPROVEMENT OF TANZANIA LOCAL GEOPOTENTIAL VERTICAL DATUM FROM $Wo^{LVD,\ TZG13}$ TO $Wo^{LVD,\ TZG19}$ AT ZANZIBAR AND TANGA TIDE GAUGE BENCHMARK USING GPS/LEVELLING AND TZG19 GEOID MODEL

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BSc Geomatics

Dissertation

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IMPROVEMENT OF TANZANIA LOCAL GEOPOTENTIAL VERTICAL DATUM FROM $Wo^{LVD,\ TZG13}$ TO $Wo^{LVD,\ TZG19}$ AT ZANZIBAR AND TANGA TIDE GAUGE BENCHMARK USING GPS/LEVELLING AND TZG19 GEOID MODEL

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A Dissertation Submitted to the Department of Geospatial Sciences and Technology in Partial Fulfilment of the Requirements for the award of Bachelor of Science in Geomatics (BSc. GM) of the Ardhi University**.**

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Ardhi University, a dissertation titled **“Improvement of Tanzania Local Geopotential Vertical Datum from $W_o^{LVD,TZG13}$ to $W_o^{LVD,TZG19}$ at Zanzibar and Tanga Tide Gauge Benchmark using GPS/levelling and TZG19 Geoid Model’’** in partial fulfillment of the requirements for the award of degree of Bachelor of Sciences in Geomatics at Ardhi University.

....

Mr. Emmanuel J Masunga

(Supervisor)

Date...

DECLARATION AND COPYRIGHT

I, ALI HUMOUD A hereby declare that, the contents of this dissertation are the results of my own findings obtained through studies and investigations and to be the best of my knowledge they have not been presented anywhere as the dissertation for an award of diploma, degree or any similar academic award in any institution of higher learning.

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ALI, HUMOUD A
(22786/T.2019)

Date..

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DEDICATION

I would love to dedicate this dissertation to my beloved, humble, caring and ever-supporting family. My parents Mr. Abdalla Ali and Mrs. Zuwena Mohd, they have been my pillar not only during the course of this research but also during the tenure of my undergraduate degree. My brothers (Yassir and Nassir) and loving sisters (Salma, Rahma and Shuwekha) who want to see me succeed in any capacity. None of this would have been possible without their kind words and motivation that keep me going every step of the way.

ABSTRACT

This dissertation focuses on improving Tanzania Local Geopotential Vertical Datum from $W_o^{LVD,TZG13}$ to $W_o^{LVD,TZG19}$ at Zanzibar and Tanga Tide Gauge Benchmark using GPS/Levelling and TZG19 Gravimetric geoid model, data from satellite altimetry models is used to validate the results obtained. Local geopotential Vertical Datum for Tanzania was determined in 2016 using TZG13 gravimetric geoid model together with GPS/Levelling and oceanic levelling data and a conventional value of Wo = 62636856.00 m^2/s^2 was used. But now, new Gravimetric Geoid Model (TGZ19) with better accuracy than TZG13 is available and in 2015 a new conventional value of Wo = 62636853.400 m^2/s^2 was released to be used as definition of global equipotential reference level. So using new conventional value, new geoid model and observation at Zanzibar and Tanga TGBM, the Tanzania local geopotential vertical datum was improved.

GPS observation was conducted at Zanzibar only while GPS positioning at Tanga TGBM determined from previous research were used and the results obtained were compared with the previous research results. A minor difference in Latitude and Longitude, and ellipsoidal height difference of 5.21cm were obtained between results of (2020 and 2016) and a difference of 0.427m was obtained between the offset determined from GPS/Levelling and MSS.

The resulted local geopotential vertical datum of Tanzania obtained in this study when referred to MSL and MSS data were 62636851.66 m^2/s^2 and 62636853.4 m^2/s^2 respectively. These results were compared to the previous research results, difference of -11.55 m^2/s^2 and -9.92 m^2/s^2 were obtained between the current and the previous results of geopotential vertical datum from GPS/Levelling and MSS respectively, due to these differences, it was necessary to improve the local geopotential value from $W_o^{LVD,TZG13}$ to $W_o^{LVD,TZG19}$

It is concluded that, the local geopotential vertical datum of Tanzania computed using GPS/Levelling and TZG19 geoid model is **62636851.66 m^2/s^2** and it is recommended that Tanzania should stop using Tide Gauge based vertical datum and a adopt a geopotential VD or VD based on most precise geoid model. If a VD based on sea level observation is to be used, then the one computed from MSS that has been accounted for MDT is to be used. Also if a gravimetric geoid model with better accuracy than TZG19 is established, it can be used for better results of the local geopotential VD.

Keywords: Local Geopotantial Vertical Datum, TZG19 Gravimetric Geoid Model, GPS/Levelling.

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ACRONYMS AND ABBREVIATIONS

BMs	Benchmark
CSRS	Canadian Spatial Reference System
DTU	Technical university of Denmark
DTU18MSS	DTU Mean Sea Surface model of 2018
DTU19MDT	DTU Mean Dynamic Topography model of 2019
FBM	Fundamental Benchmark
GGM	Global Gravitation Model
GGOS	Global Geodetic observing System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRS80	Geodetic Reference System 1980
HSRS	Horizontal Spatial Reference System
IAG	International Association of Geodesy
IBM	Intermediate Benchmark
IERS	International Earth Rotation and Reference System service
LMSL	Local Mean Sea level
LVD	Local Vertical Datum
MDT	Mean Dynamic Topography
MSS	Mean Sea Surface
MSL	Mean Sea Level
MSSH	Mean Sea surface Height
N	Geoidal Height
NSRS	National Spatial Reference System
PPP	Precise Point Positioning
RINEX	Receiver Independent Exchange Format
SMD	Surveys and Mapping Division
SSH	Sea Surface Height
SST	Sea Surface Topography

TATG	Tanga Tide gauge
TG	Tide Gauge
TGBM	Tide Gauge Benchmark
TPLN	Tanzania Primary Levelling Network
TZG13	Tanzania gravimetric Geoid Model of 2013
TZG17	Tanzania gravimetric Geoid Model of 2017
TZG19	Tanzania gravimetric Geoid Model of 2019
VD	Vertical Datum
ZATG	Zanzibar Tide Gauge

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the study

In Geodesy, Vertical datum (VD) is defined as reference surface to which height of various points are referred to (Masunga, 2016). There are number of height systems in the world (Geopotential number, Dynamic, Orthometric height and normal height), but most used is orthometric height. By definition, Orthometric height is the distance measured along the actual gravity plumb line from the geoid (vertical datum) to the level that contains the points of interest (Hoffman-Wellenhof & Moritz, 2005). The reference surface for orthometric height is geoid (Heiskanen, W & Moritz , 1967), which is an equipotential surface of the earth’s gravity field that closely approximates the mean sea level (MSL) in a least square sense. The importance of orthometric height in Geodesy, surveying and engineering can be used to determine land topography and provides conceptual framework for citizen and also can be used in field operation such as road construction, water management and also used in geodetic vertical control network.

Vertical datum is zero elevation reference surface to which height or depth are referred to (Ulotu P. E., 2015). The mean sea level has been used broadly for long time as VD all over the world. It is realized by average sea water levels over a minimum period of 18.6 years at a tide gauge station in a coastal area. By averaging the sea water levels over a long period, seasonal and periodical sea level fluctuations can be reduced to the minimum (Ulotu P. E., 2015). Such a Local Mean Sea Level is a good approximation of geoid at a particular location. Therefore, a mean sea level is the closely physical visualization of geoid and thus a kind of VD for orthometric height. MSL established from tide gauge(s) depart from the geoid by the Mean Dynamic Topography (MDT) and other coastal oceanographic effects. To determine orthometric heights referenced to the TG based VD, a series of profiles of spirit levelling and gravity observations are conducted from the closest datum benchmark(s).The mean sea level determined at a TG is generally different for different locations, and therefore MSL of a tidal station is referenced to a stable monuments on the land termed as Tide Gauge Benchmark (TGBM). Subsequently, MSL VD is realized on the land by establishing a Network of Fundamental and intermediate benchmarks (FBMs and IBMs) using geodetic levelling method, basing on TGBM reduced height.

In Tanzania Mainland, Tide gauge station are found in Dar es Salaam, Mtwara and Tanga harbours. But Tanzania uses Tanga Tide gauge as its vertical datum. Its establishment started in 1960s. By that time, the knowledge of geoid model of Tanzania did not exists. So, a local Mean Sea level (LMSL) was established in place of geoid surface. The LMSL was established using TG measurements for 28 months only that was between August 1962 and November 1964 at the Tanga harbor. A dense network of benchmark (BMs) of different accuracies were monumented and heighted to the Tanga TGBM and was named as Tanzania Primary Levelling Network (TPLN). The existing FBMs and IBMs of the TPLN were established about 50 years ago and were not provided with horizontal position. The only information that exists for the recovery of a TPLN FBM/IBM is its respective locality sketches of that time and orthometric height. Many times it requires dedicated efforts and skills to recover a benchmarks of the TPLN (Ulotu P. E., 2015).Figure 1.1 shows the TPLN finished loops, fundamental benchmarks (FBM) routes and FBMs proposed but not implemented

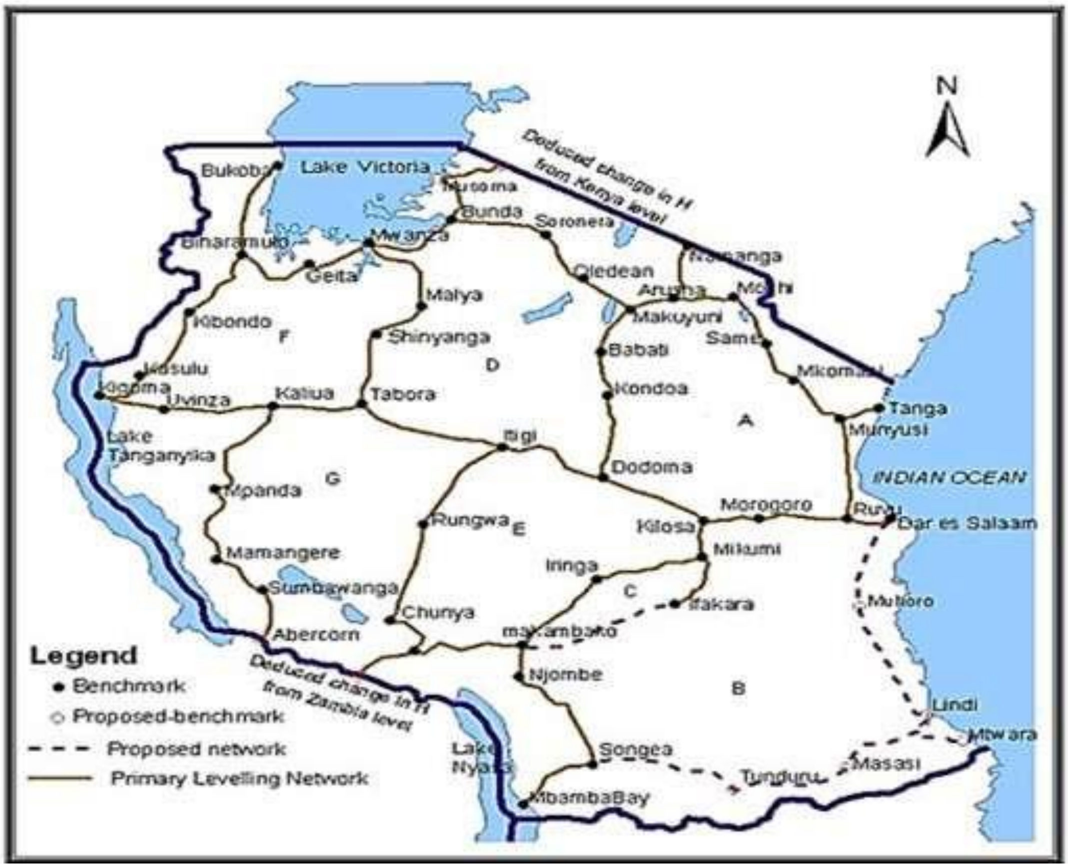

Figure 1.1: Tanzania Primary Levelling Network (TPLN) as it was in 1970s showing the finished loops, Fundamental Benchmarks (FBM) routes, and FBMs proposed but not implemented.

Source: *(Ulotu P. E., 2015)*

Due to advanced technology, it is now possible to convert ellipsoid height into orthometric or normal height if a precise and accurate geoid or quasi geoid model exist. Tanzania determined its first dedicated local geoid model in 2007 and thereafter more precise gravimetric geoid have been determined. The gravimetric geoid model is supposed to be better approximation of the geoid than the short duration Tide gauge-Vertical datum. In addition, geoid is the ideal VD for orthometric heights.

The reason that made Tanzania to adopt for the current short duration TG based VD was absence of a better approximation of the geoid of Tanzania at that time (Ulotu P. E., 2015). But now Tanzania is ready to change from TG-VD to gravimetric geoid model VD or geoid model based VD because the models are available. New Zealand and Canada have realized new geopotential VD based on geoid model 2009 (Amos, M., & Featherstone, W., 2009) and (Hyden et al., 2012) respectively, and a lot more countries and regions are determined for the same thing (Kotsakis et al., 2011).

From previous study shows that, Local geopotential VD for Tanzania was determined in 2016 using TZG13 gravimetric geoid model by Masunga, (2016). A conventional value of Wo = 62636856.00 m^2/s^2 for defining the reference global equipotential surface which was released in 2010 by the International Earth Rotation and Reference System Services(IERS) was used to determine the local geopotential vertical datum. But now, new Gravimetric Geoid Model (TGZ19) with better accuracy than TZG13 has been established.And in July 2015, the International Association of Geodesy (IAG) released a new conventional value of Wo = 62636853.400 m^2/s^2 to define global equipotential reference surface, using this new gravimetric geoid model, the new Wo value together with new GPS observation at the Zanzibar and Tanga Tide Gauge Benchmark (TGBM) will help to improve the local geopotential vertical datum for Tanzania.

1.2 Statement of the problem

Tanzania is one of the countries whose existing Vertical Spatial Reference System (VSRS) refer to local MSL which has number of defect and do not coincide with the reference equipotential surface (Geoid), also it is not suitable with the GNSS and other satellite technologies. Local geopotential vertical datum for Tanzania was determined in 2016 using TZG13 gravimetric geoid model. But now, a new gravimetric geoid model (TZG19) with better accuracy than TZG13 is available. In addition, the GGOS of IAG has a new W_o. Therefore this research aim to improve the existing local geopotential vertical datum offset for Tanzania using new gravimetric geoid model (TZG19) and new W_o.

1.3 Research Objectives

1.3.1 Main Objective

To provide Tanzania with an improved, more precise and accurate geocentric local geopotential VD suitable with GNSS and other satellite technologies under GGOS of the IAG aim of unified world VD for unified height system (WHS) which also comprise the reveal project initiatives

1.3.2 Specific objectives

i. Determination of MSL height above the reference ellipsoidal through GPS-levelling
ii. Determination of geoid height from TZG19 geoid model for the Zanzibar and Tanga TGBM
iii. Quality assurance through DTU18MSS and DTU19MDT.

1.4 Scope and limitation of the study

Tanzania has four Tide Gauge stations in Dar es Salaam, Tanga, Mtwara and Zanzibar. However, financial and time constraints have limited this study to only Zanzibar and Tanga Tide Gauge station.

1.5 Significance of the study

The gravimetric geoid model is a better approximation of the geoid than the short duration Tide Gauge vertical datum. This research is important because it will help in solving problems of current vertical datum of Tanzania which include datum inconsistencies and incompatibility with the GNSS and other satellite technologies. Also this research will contribute in achieving IAG-GGOS goals of establishing a unified global vertical datum and unified world height system (WHS)

1.6 Beneficiaries

This research will benefit government minimize cost needed to maintain and improve the current TG-VD, likewise it will allow Tanzania proceed into GNSS-levelling for orthometric height, also gather available satellite technologies more reliably

1.7 Structure of the Dissertation

The focus of this Dissertation is to Improve Tanzania Local Geopotential Vertical Datum from new world geopotential Wo from Zanzibar and Tanga Tide gauge, gravimetric geoid model TZG19 and new oceanic model DTU18MSS and DTU19MDT. Therefore, Chapter one cover the background information, identification of the research problem, main objective, scope and limitation of the study. Chapter two provides an overview of vertical datums including TG and technique often used for geopotential vertical datum offset. Chapter three cover research methodology. Chapter four contains results, analysis and discussion. Chapter five covers conclusion from this study and recommendations for the future work from this area. A list of cited reference is given at the end.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview of the Vertical Datum

Until now height systems of many countries in the World are based on the tide gauge local mean sea surface levels, which are stationary, i.e. do not consider sea level time variations after their establishments and not updated (Masunga, 2016) Since it is realized by averaging sea water levels over a long period at a Tide Gauge (TG) station, seasonal and periodical sea level fluctuations can be reduced to a minimum (Ulotu P. E., 2015).The mean sea level determined at a TG is usually different for different locations due to factors like salinity, temperature, ocean currents and therefore MSL of one region cannot be used as the reference surface for another region until unification is done and correctly paid. There are different types of Vertical Datums in the world, these are discussed as follows:

2.1.1 Tide Gauge (Mean Sea Level) vertical datum

A vertical datum derived from tide gauge observations is referred to as mean sea level (MSL). MSL is a static zero height reference surface obtained from arithmetic mean of hourly, daily, monthly and yearly sea level observations for a minimum of 18.6 years so as to account for periodical, temporal and nutation effects from the moon and sun. So far, MSL has been the prominent reference surface for orthometric heights and is used in many countries all over the world. The use of MSL as a vertical datum that is equated to geoid is affected and limited by several factors such as absence of periodical updating, inability to take care of Mean Dynamic Topography (MDT) and other periodical and temporal effects. In addition, if the observation duration does not meet the minimum requirement of 18.6 years, it displaces the MSL away from the geoid by several meters (Kileo, 2017).As a result, the heights derived from the established MSL cannot be orthometric even if they allow the other procedures described.

Tanzania has several Tide Gauge stations located along the coastline of Indian Ocean, but local vertical datum (VD) for Tanzania mainland is based on MSL reduced at Tanga Tide gauge. The Tanzania National Levelling Network (TPLN) was established from the Tanga TG-VD, and was used as Tanzania Local vertical datum. The Tide gauge measurements taken from 28 months only were reduced to get the value for the mean sea level (MSL). The Tanga TGBM is the Reference Fundamental Benchmark (FBM) and its value has been used as the datum for heights all over the TPLN benchmarks (Dickson, 1965. Deus, 2007 and Wachawandeka, 2010).

We now know that the geoid departs from the MSL by a quantity called Mean Dynamic Topography (MDT), by ignoring the MDT, heights of land monuments (Benchmarks) referred to the TGBM are equally distorted (Masunga, 2016).Figure 2 shows the establishment of reference benchmark also referred to as Tide Gauge Benchmark (TGBM) on the Tanga harbor close to the tide gauge.

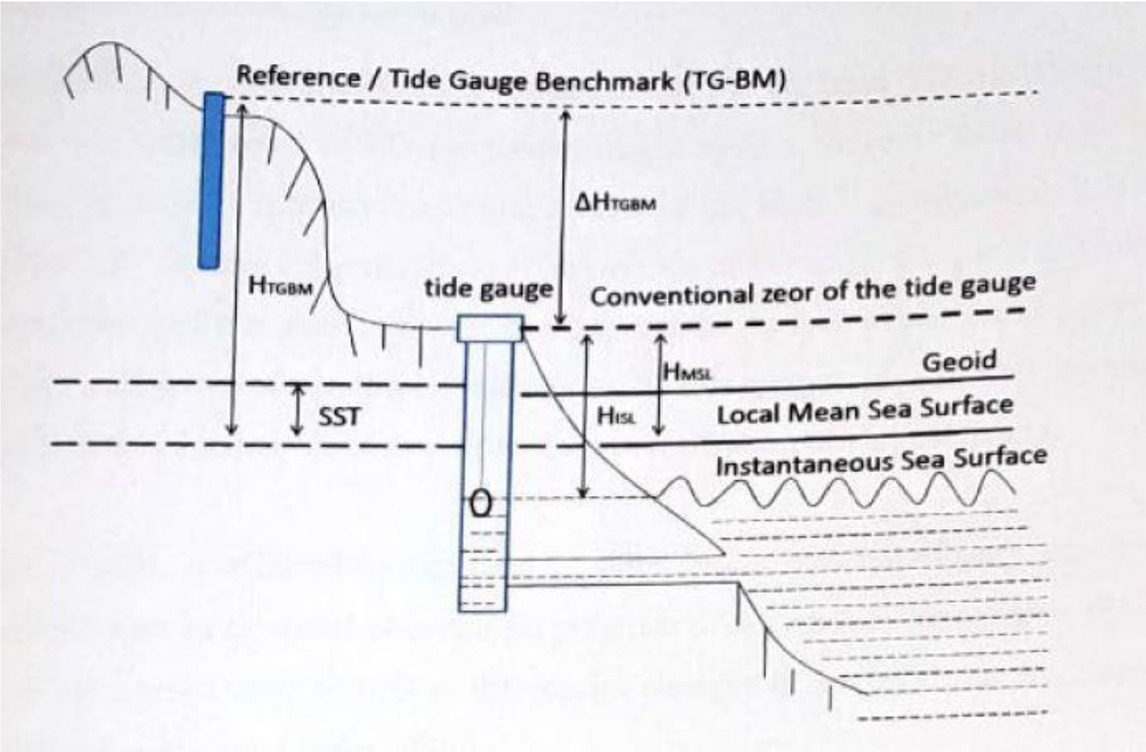

Figure 2.1: Tide Gauge Station and Established of a Reference Benchmark or Tide gauge Reference Benchmark (TG-BM)

Source: (Masunga, 2016)

From Figure 2.1

$$\mathrm{HTGBM} = \mathrm{HMSL} + \Delta\mathrm{HTGBM} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Where

H_{ISL} … Instantaneous Sea Level from the convectional zero of the tide gauge

H_{MSL} … Mean Sea Level from the convectional zero of the tide gauge

H_{TGBM} … Height of the Reference Benchmark called Tide Gauge Benchmark (TGBM)

SST … Sea Surface Topography

The Tanga mean sea level was adopted as the local height reference surface in Tanzania and the rest of the points of the vertical control network have been referred to it. At present, the TPLN consists of eight (8) loops namely A, B, C, D, E, F, G and H and are displayed in figure 1. It has been observed that a lot of potential areas for investment are outside the TPLN coverage, see Figure 1.1. That is, the current VD is not available throughout Tanzania. In such areas, GNSS levelling which uses the new geoid based VD is inevitable (Ulotu P. E., 2015)

Advantages of current Tanzania Vertical Datum;

i. Levelling instrumentation is affordable, also data validation and processing is not complicated.
ii. Error tracing is easy, and formats and procedures are well established to minimize gross and systematic errors,
iii. High relative accuracies can easily be achieved using precise levelling when complemented by gravity corrections, room for improvement is possible to remove some of the datum observational and establishment deficiencies cited earlier, and
iv. GPS levelling is a preferred method in the external quality assessment of a gravimetric geoid/quasi-geoid model as well as global gravity models (GGM). Therefore, for such undertaking, FBMs and IBMs of the TPLN, which are tide-gauge based, are necessary (Kileo, 2017)

The drawbacks that affect the current Tanzania vertical datum are so many, but few of them are;

i. Tanzania having four tidal gauge stations; at Tanga, Dar es Salaam, Mtwara and Zanzibar, the current VD of Tanzania Mainland was established only based on the Tanga tide gauge station that has problem in its establishment because, the time used to observe the mean sea level was only 28 months, besides, the effects of salinity, temperature, ocean currents and nutation effect caused by moon and sun were not accounted for, as a result, the observed MSL does not represent the best fit of the geoid.
ii. The documented heights of TPLN from the Tanzania Survey and Mapping Division show orthometric heights based on the normal gravity instead of actual gravity. Due to the normal correction applied, the resulted heights are not orthometric but normal orthometric heights, hence this shows the shortfall of the Tanzania height system.
iii. The “adjustment” (distribution of the misclosure) of the levelling network was done loop wise after the completion of the observation on each loop and some of the FBMs

were held fixed during misclosure distributions. But there is no evidence available from the Tanzania Surveys and Mapping Division, for the rigorous adjustment, such as least squares adjustment of the TPLN carried out.

iv. It is more than 50 years ago, since when the precise levelling observations were acquired; the levelled benchmarks may have been subjected to deformation due to earthquakes, geothermal draw-off, and drifting, rifting and even animal and human activities. The deformation may have occurred since the levelling was carried out and between the individual levelling campaigns that were used to complete a levelling line (or loop). Therefore, re-observation of the entire TPLN is highly needed but limited by the costs of its implementations and difficult to find location of points since, they are only provided with location sketches rather than coordinated positions (Masunga, 2016)

2.1.2 Geoid model based vertical datum

2.1.2.1 Gravimetric geoid model

The gravimetric method uses gravity measurements to determine geoid model. To determine a precise local or regional geoid, a full advantage of all types of data/ information must be taken in an integrated solution (ibid). Although the geoid model surface is somehow irregular however, it is very suitable as a vertical datum for the orthometric height system.

Tanzania has coverage of geoid models which are TZG07, EGM08, AGP07, TZG08, TZG13 and TZG17, and the knowledge of these geoids are available in (Oliver, 2007, Pavlis et al., 2008, Merry, 2007, Ulotu, 2009, Forsberg et al., 2013, Valerian, 2018) respectively. The TZG17 is the newest Tanzania geoid model referred the GRS80 reference ellipsoid. It covers and area bounded between latitudes 1ºN to 12ºS and longitudes 29º to 41ºE. It has an accuracy of 5cm compared to TZG13 of 10cm, and it was computed on a grid of 1′ x 1′ resolution. The new geoid model TZG17 was computed from 38,483 terrestrial point gravity data from Tanzania Gravity Database of 2008 (TGDB08) 5′ x 5′ airborne gravity data limited to boundaries of Tanzania, validated pure GOCE GGM (GO_CONS_GCF_2_SPW_R5) to d/o 200 and composite GGM (XGM2016) to d/o 719, combination of four validated 1- and 3-arc seconds global digital elevation models: USA SRTM1″ v3, ALOS-1″ v2, MERIT-3″ and SRTM-3″ CGAIR v4.1. Also 11 GPS/ levelling datasets validated and passed at 95% confidence level were used in evaluation of the new geoid model (Valeria, 2018)

2.1.2.2 Geometric geoid model

This method uses ellipsoidal height determined from GPS observation together with orthometric height obtained from geodetic levelling, to determine Geometric Geoidal height N_{BM}^{GPS} .This can be done through Equation (2.2)

$$N_{BM}^{GPS} = h - H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

Where

N_{BM}^{GPS} .… Geometric geoidal height

H… Orthometric height of the TGBM

h… Ellipsoidal height/ geodetic height of the TGBM

The accuracy of the established geoid depends on the distribution and number of GPS/ levelling stations, accuracy of GPS/ levelling data, characteristics of the geoid in the region, and the method of interpolation (Kataraihya, 2017).Figure 2.2 shows the relationship between ellipsoidal height, orthometric height and geoidal height.

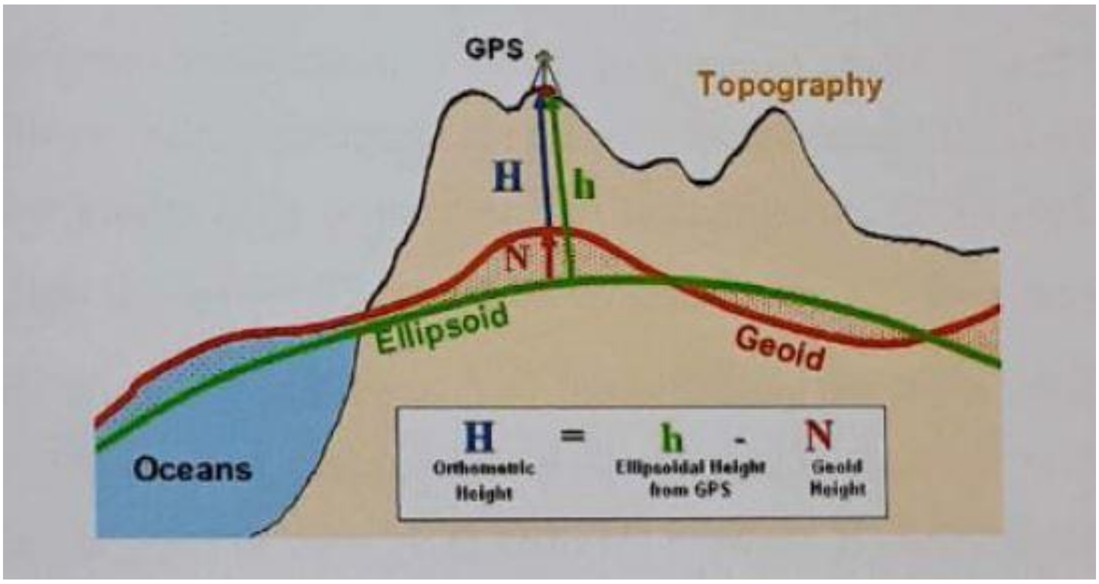

Figure 2.2: The relation between Geoidal, Geodetic and Orthometric Height

Source :(Web page:http://www.gpsseismic.com/download/manuals/GPSeismic-geodesy-principles)

2.1.2.3 Hybrid geoid model

When accurate and fairly well distributed benchmarks referred to appropriate determined TG based VD exist, together with precise gravimetric geoid model, a hybrid VD can be created out of the two using GPS observations on the BMs (Ulotu P. E., 2015).Precise GPS observations on the BMs enable determination of geometrical geoidal height as shown in (2.2). From a gravimetric geoid model, we obtain gravimetric geoidal height (N^G). When this N^G combined with geometric geiodal height N_{BM}^{GPS} .over the respective region often in least squares manner, it results into hybrid VD.When the above conditions are favorable, hybrid datum combines the advantages of both types of geoidal models, and that is often advantageous to the user (Ulotu P. E., 2015)but the unreliability of the N_{BM}^{GPS} mainly due to datum defect, limit the use of hybrid geoid model VD in many countries.

2.1.3 Quasi-geoid model based vertical datum

Quasi-geoid is a reference surface for Normal heights. It does not deviate much from the geoid, often it is less than 1m (Ulotu P. E., 2015).But the surface has no physical meaning. Adoption of the normal height instead of orthometric height system is now being recognized in the world mainly due to its easy of determination process and closeness of normal heights to orthometric height. The relationship between the geoid and the quasi-geoid is shown in Equation (2.3).

$$N = S + (\Delta g - 2\pi\rho H \div \gamma)H \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (2.3)$$

Where

N … Geoidal height

S … Height Anomaly from Quasi-Geoid Model

Δg … Bouguer gravity anomaly

p … Constant density of topographical masses

γ … Normal gravity on the telluroid close to the surface

H … Elevation of the surface point

Figure 2.3 show the relationship between Geoid, Quasi-geoid and Geodetic reference ellipsoid

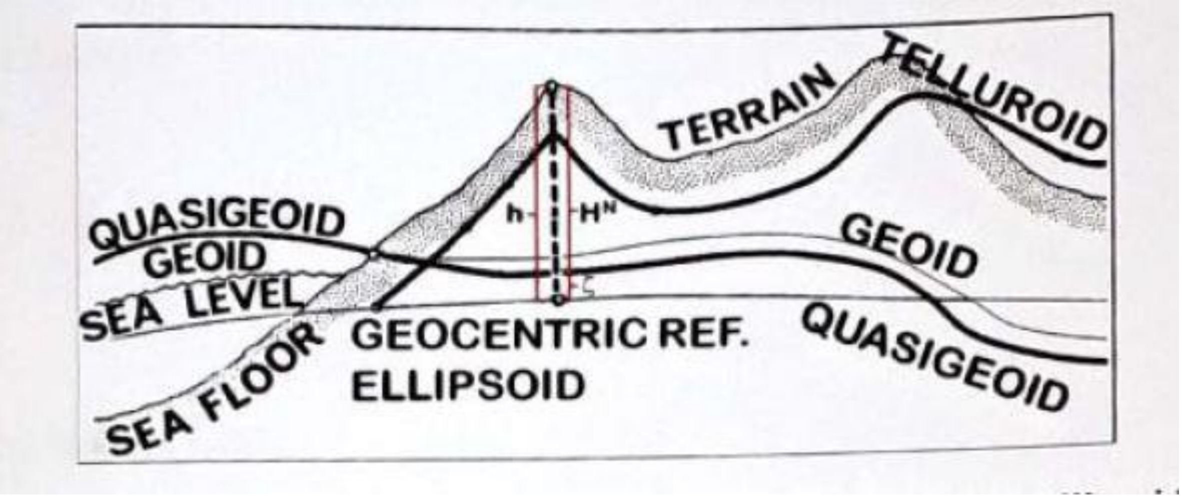

Figure 2.3: Relationship among the Quasi-geoid, Geoid and Reference ellipsoid

Source: (Masunga, 2016)

2.2 Mean Sea Surface (MSS)

The mean sea surface (MSS) represents the position of the ocean surface averaged over an Appropriate time period to remove annual, semi-annual, seasonal and spurious sea surface height signals. MSS models are based on satellite radar altimetry data, where satellite altimetry observes the SLA at regional and global level. The differences between the SSH and the SLA yields the MSS which are used for various purposes, such as computation of a long-track and cross-track geoid gradients, corrections in the repeat orbit method, for the computation of gridded gravity anomalies, for the operational computation of sea level anomalies SLA and to provide a common reference for distinct satellite missions (Limpac et al.,2010).The new DTU18MSS has been derived by including re-tracked CRYOSAT-2 altimetry also hence, increasing its resolution are issues in the Polar regions have been solved too (Knudsen et al., 2019).

2.3 Factor Affecting the Sea Surface Height

Instantaneous sea surface heights SSH_i as obtained by satellite radar altimetry, airborne laser Altimetry, ship borne ultrasound altimetry and GPS buoys, are affected by time-dependent Geophysical effects, including ocean waves, astronomical tides, atmospheric pressure (inverse Barometer effect) and wind stress (Limpac, P. H. & Geige, A., 2010) i Ocean wave

This is the rise and fall of the water in the ocean. It is characterized by the succession of rough and crest. The airborne and ship borne altimetry data as well as GPS buoy data contain the wave information. Wave component can be eliminated from data through signal filtering and wave modeling (Limpac, P. H. & Geige, A., 2010)

ii Tide effects

This includes the ocean tide, ocean loading, pole tide and solid earth tides all these causes Periodic variation of the sea surface height resulting from the actions of the celestial bodies i.e. the moon and the sun moving around the earth. The relative movements of the moon and and the sun with respect to the earth, together with the earth's own rotation, are generating periodic gravitational forces. Each of these forces generates a periodic displacement of the water masses on earth, resulting in sinusoidal variations of the sea surface.

iii Atmospheric Pressure and Wind Forcing

The sea surface can be affected of atmospheric pressure because the water is incompressible. The rise and fall of water do not result from a compression of water but from horizontal redistribution of water masses in response to horizontal variation of atmospheric pressure.

2.4 Mean Dynamic Topography (MDT)

Mean dynamic topography is the difference between the time-average sea surface and geoid. The MDT is part of the MSS induced by permanent ocean currents and is also the orthometric sea surface heights above the geoid. The MDT is mainly caused by temperature variation in the ocean and permanent current. The MDT can be obtained in two ways, the direct method and the synthetic method.The direct method requires a known, accurate and a high spatial resolution marine geoid as well as the sea surface height information. The difference between the marine geoid (N) and the Mean Sea Surface (MSS) gives the MDT in a direct method.

$$MDT = MSSH - N \quad (5)$$

Though this may seem as an easy method, it is not very accurate, because in order to determine the MDT the resolutions of the marine geoid and the SSH should have the same quality, where by this isn't the case. The resolutions from the marine geoid determined over the oceans is very low (Limpac, P. H. & Geige, A., 2010).Therefore, the marine geoid hinders proper determination of the MDT. The synthetic method, is a method that determines the MDT independent of the geoid and its uncertainties. It utilizes the absolute dynamic topography and the sea level anomalies. The difference between the two gives a mean dynamic topography (Kataraihya, 2017). New geodetic DTU19MDT was derived using the OGMOC geoid model and the new DTU18MSS mean sea surface. The processing scheme was similar to the one used for the previous geodetic DTU17MDT model. The filtering was re-evaluated by adjusting the quasi-gaussian filter width to optimize the fit to drifter velocities. The results show that the new MDT improves the resolution of the details of the ocean circulation (Knudsen, P., Andersen, O., Fecher, T. & T Gruber, N. M., 2018)

New MDT_CNES_CLS 2018 is an estimate of mean over the 1993-2016 period of the sea surface height above geoid. It is an update of MDT_CNES_CLS13 with improved processing to compute the first guess and use of an improved Ekman model to extract the geostrophic component of buoy 22 velocities, it also uses the latest GOCOO5S geoid model based on 101/2 years of GRACE data. (Mulet, et al., 2019)

2.5 Marine Geoid

Marine geoid is the hydrostatic equilibrium shape that sea level would take in the absence of tides, currents and winds. Marine Geoid can never be observed directly, but it is the height above a reference ellipsoid can be calculated from a model of the earth's gravity field. There are three methods that can be used to calculate the height above the ellipsoid, these are satellite radar altimetry, airborne laser and ship borne ((Limpac, P. H. & Geige, A., 2010).All methods observe the instantaneous sea surface heights (*SSHi*) above the ellipsoid. This height is the sum of the geoid height and dynamic topography associated with ocean flow and responses to tidal and atmospheric forcing (Smith, 2010)

2.6 Geopotential Vertical Datum Offset Techniques

2.6.1 Geodetic leveling

The geodetic leveling approach combines observed height differences by sprit leveling and gravity, in order to obtain geopotential difference or offsets. A unified height reference frame is estimated from geopotential differences and observed across border connections in a common adjustment (Rulke et al., 2012).Heights of this unified height reference frame are compared to the national heights, and offset between two or more national height reference frames can be estimated. This method is limited to datum with connected levelling points. It cannot be used to datums separated by an ocean or another body of water. This makes the method inappropriate for global approach. In comparison to other geodetic observation methods, levelling networks show low redundancy and are therefore subjected to systematic errors. This approach was used in estimating Canadian vertical datum offset (Hyden et al., 2012)

2.6.2 Oceanic leveling

This is an alternative approach to Geodetic levelling. Ocean leveling is made possible by the satellite altimetry method that is used to determine sea surface topography as a function of current, velocity, atmospheric pressure and viscosity (Masunga, 2016).This method uses oceanic information such as MSSH and MDT to determine marine geoid, which is later used in the computation of geopotential offset. The main problem with this method is that MSS models perform better in the deep sea compared to the coastline where tide gauge benchmarks are located (ibid).To overcome this problem, Tide-Gauges need to be located offshore where the sea surface topography models are good. This method was used by (ibid) to determine Geopotential vertical datum offset for Tanzania.

2.6.3 Geodetic boundary-value problem

This method is sometime known as Gravity Field (GF) approach. Ellipsoidal heights observed with Global Navigator Satellite System (GNSS), Physical heights in different national height reference frames, and gravity field model are combined and height reference frame offsets (Geopotential offsets) are estimated (Rulke et al., 2012).Unlike Geodetic levelling, this method is not limited to datums with connected levelling points. Hence, this method is also suitable for the connection of height reference frames that are separated by ocean or another body of water, such as those on island or different continents.

2.6.4 Geopotential Number

This method uses global geopotential model (GGM) and GPS-levelling information at each of the LVD origins (tides-gauges) to compute the geopotential (number) for each LVD (Amos &Featherstone, 2009).The global geopotential surface (Wo) is used as reference surface to relate vertical datums. The local geopotential vertical datum is computed by removing the geopotential number from the global geopotential. This approach has been implemented in several locations (e.g., Bursa et al.2004).

2.7 Selected Method

From the discussion made in Section 2.6 above, on the geopotential vertical datum offsets techniques, Geopotential number method is chosen as the technique to be used in this study. Its advantages are

- It is suitable for single LVD analysis
- Its simultaneously implementation over different geographical zones is also useful for unifying multiple LVDs with respect to a common reference surface that is specified by a conventional Wo value (Kotsakis et al., 2011).

Disadvantage of this method is that the use of single point for each LVD needs the assumptions that datum offsets are constant across the LVD and they are not distorted (e.g. due to multiple tide-gauges being fixed during adjustment (Masunga, 2016)

CHAPTER THREE

3.0 METHODOLOGY

This chapter explains about the method used in accomplishing the main objectives of this research. In this research, Geopotential number is used to accomplish the main objective of the dissertation which is to improve the local geopotential Vertical datum for Tanzania. To use the technique the following should be done:

i. Determination of Global Positioning System (GPS) geodetic coordinates at Zanzibar and Tanga TGBM
ii. Extraction of Geoidal height at Zanzibar and Tanga TGBM from TZG19 gravimetric geoid model
iii. Determination of Geoidal height at Zanzibar and Tanga TGBM from GPS/Levelling data
iv. Determination of Geoidal height from satellite altimetry models (DTU18MSS and DTU19MDT)

3.1 Determination of Geoid height from GPS/levelling data

From GPS/Levelling data at Zanzibar and Tanga Tide Gauge benchmark, MSL height above the reference ellipsoid was determined from the difference between ellipsoid height obtained from GPS observation and orthometric height obtained during geodetic levelling

$$\mathrm{MSLH} = \mathrm{Hgps} - \mathrm{H} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.1)$$

Where

MSLH – MSL height above reference ellipsoid of the TGBM

h^{GPS}- Ellipsoid height of TGBM from GPS observation

H- Orthometric height of the TGBM

3.2 Extraction of Geoidal height from TZG19 Geoid model

The geoid heights of the selected points were extracted from the TZG19 geoid model selected for the study. This was done importing the coordinates (Latitude and Longitude) of points along with TZG19 geoid model on surfer software. The software grids the geoid so that geoid height of the points can be interpolated. Geoidal height from gravimetric geoid model TZG19 was made available by Dr. Ulotu from Department of Geospatial Science and Technology at Ardhi University.

3.3 Satellite Altimetry data

Satellite Altimetry is a technique for measuring height of the marine surface. Sea surface height is obtained from the difference between the height from satellite radar or airbone laser to the reference ellipsoid and the distance from the satellite radar or airbone laser to the sea surface.

$$\mathrm{SSH} = \mathrm{hrad} - \mathrm{drad}\,, \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots\ (3.2)$$

Where

SSH – Sea Surface Height

h_{rad} – height from satellite radar to the reference ellipsoid

d_{rad} – height from satellite radar to Sea surface

Mean Sea Surface height is obtaining by subtracting the Sea level Anomaly (SLA) from the Sea surface height (SSH)

$$\mathrm{MSSH} = \mathrm{SSH} - \mathrm{SLA} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \ldots \ldots \ldots\ (3.3)$$

Where

MSSH – Mean Sea Surface Height

SLA – Sea Level Anomaly

From satellite altimetry data, MSSH and MDT models are used to estimate marine Geoid from Mean Sea Surface and Mean Dynamic Topography. Mean Sea surface, Mean Dynamic topography and Geoidal height above reference ellipsoid are related as follow

$$\mathrm{MDT} = \mathrm{MSSH} - \mathrm{N} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots\ (3.4)$$

Where

N – Geoidal height

MDT – Mean Dynamic Topography

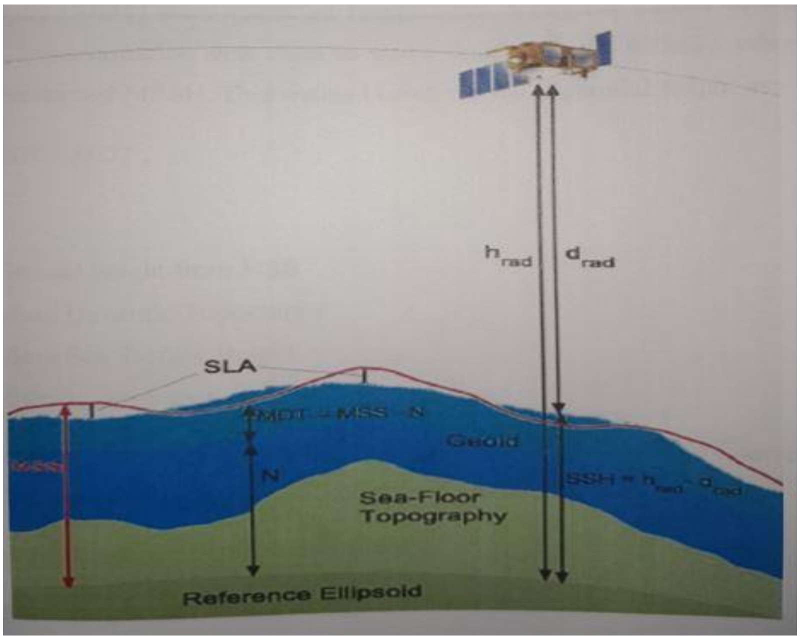

Figure 3.1: Satellite and airbone altimetry and its relationship to Sea Surface Height, Mean Sea Surface Height, Geoidal Height and Mean Dynamic Topography

Source :(Web page:http://www.star.nesdis.noaa.gov/sod/Isa/AltBathy)

From the satellite altimetry models are used to checks the results obtained using GPS/Levelling data. The following are procedures to follow when using these models;

i. Acquisition and extraction of the current global Mean Sea Surface Height (MSSH) data at Zanzibar and Tanga TGBM from DTU18MSS satellite altimetry model.
ii. Acquisition and extraction of the current global Mean Dynamic Topography (MDT) data at Zanzibar and Tanga TGBM from DTU19MDT satellite altimetry model.
iii. Computation of geoidal height (N^{MSS}) from extracted data.

3.3.1 Marine geoidal height computation from MSS

From DTU18MSS and DTU19MDT models, Mean Surface height (MSSH) and Mean Dynamic Topography (MDT) were extracted respectively, and they were used to compute marine geoid height based on equation below

$$\mathrm{NMSS} = \mathrm{MSSH} - \mathrm{MDT}, \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (3.5)$$

Where

N^{MSS} ... Geoid height from MSS

MSSH… Mean Sea Surface height

MDT… Mean Dynamic Topography

3.4 Determination of Height difference at TGBM

3.4.1 Computation of Height Difference using GPS/Levelling data

The height difference between the MSL height above reference ellipsoid (MSLH) and geoid from TZG19 Geoid model is determined from equation below

$$\Delta N^{MSL}_{TZG19} = \text{MSLH} - N^{TZG19} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3.6)$$

Where

ΔN^{MSL}_{TZG19}… Height difference between MSLH and N^{TZG19}

MSLH … Geoid height from MSL above ellipsoid

N^{TZG19} … Geoid height from TZG19 Geoid model

3.4.2 Computation of Height Difference from MSS data

Height difference between MSSH above reference ellipsoid and from TZG19 geoid model (N^{TZG19}) is determined from equation below

$$\Delta N^{MSS}_{TZG19} = \text{MSSH} - N^{TZG19} \; \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots$$

(3.7) Where

ΔN^{MSS}_{TZG19}… Height difference between MSSH and N^{TZG19}

MSSH … Geoid height from MSS above ellipsoid

N^{TZG19}… Geoid height from TZG19 Geoid model

3.5 Computation of Normal gravity on ellipsoid GRS80

This section expected to compute normal gravity γ on ellipsoid referred to GRS80 which is used in computation of potential difference by multiplying it with Geoid height difference. The formula used from this computation comes from IGF named Cassini and it is given as follow

$$\gamma = 9.7803267715(1 + 0.0053024 \sin^2\emptyset - 0.0000058 \sin^2 2\emptyset) \text{ m/s}^2 \;\dots\dots\dots (3.8)$$

Where

$\emptyset$… Latitude

γ … Normal gravity

3.6 Computation of Potential Difference

The potential Difference between local and global reference surfaces using GPS/Levelling and MSS data is computed based on equations below

$$\delta w_{TZG19}^{MSL} = \gamma\, \Delta N_{TZG19}^{MSL} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.9)$$

$$\delta w_{TZG19}^{MSS} = \gamma\, \Delta N_{TZG19}^{MSS} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.10)$$

Where

δw_{TZG19}^{MSL} … Potential difference using GPS/Levelling data

δw_{TZG19}^{MSS} … Potential difference using MSS data

3.7 Determination of Local Geopotential Vertical datum (W_0^{LVD})

Local Geopotential Vertical Datum using GPS/Levelling and MSS data is computed using equation below

$$W_0^{LVD, MSL} = W_0 - \delta W_{TZG19}^{MSL} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.11)$$

$$W_0^{LVD, MSS} = W_0 - \delta w_{TZG19}^{MSS} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.12)$$

Where

$W_0^{LVD, MSL}$ … Local geopotential VD of TGBM from GPS/Levelling data

$W_0^{LVD, MSS}$… Local geopotential VD of TGBM from MSS data

W_0 … Global reference geopotential value

3.8 Data requirements

In determination of geopotential vertical offset, the main dataset used include the followings:

i. Geoidal height of Zanzibar and Tanga TGBM from TZG19
ii. Geoidal height of Zanzibar and Tanga TGBM from MSL
iii. GPS geodetic coordinates(ϕ, λ, h) of Zanzibar and Tanga TGBM
iv. Orthometric height of Zanzibar and Tanga TGBM
v. Geiodal height of Zanzibar and Tanga TGBM from mean sea surface (MSS) using DTU18MSS and DTU19MDT models

3.9 Data Source and Preparation

This part explains the source of data used in this research, how they have been obtained and Prepared to achieve the main objective. The data used to this research were GPS observations data, Mean Dynamic Typography Model (DTU19MDT), Mean Sea Surface Model (DTU18MSS), Published orthometric height of Zanzibar and Tanga Tide Gauge and gravimetric Geoid Model TZG19.

3.9.1 GPS Data Collection

It involved field work where GPS observations were made at Zanzibar tide gauge only in two hours at five seconds interval using Precise Point Positioning technique (PPP) to obtain 3D coordinate i.e. Geodetic latitude, longitude and ellipsoidal height (ϕ, λ, h) while Geodetic coordinates at Tanga Tide gauge was obtained from previous study where observation were six hours in five seconds interval.PPP uses highly precise satellite clock and orbit information estimates in processing. These satellite clock and orbit information estimates are derived from a solution using data from a globally distributed network of GPS/GNSS receivers. It is possible to position using a single receiver with PPP online processing service, it is possible to obtain precision better than 1cm in horizontal position. Figure 3.2 show GPS observation at Zanzibar TGBM

Figure 3.2: GPS observation at Zanzibar TGBM

3.9.2 GPS Data Preparation

To obtain the geodetic coordinates from GPS observations at the TGBMs the following were done, first was GPS observation files conversion to RINEX file format, then the merging and quality check of the observed GPS data in RINEX format was done by Translating Editing and Quality Check (TEQC) software. The files were sent to the internet service called Canadian Spatial Reference System for processing.

3.9.3 Tanzania Geoid Model of 2019 (TZG19)

The TZG19 is an update of TZG13 with an improvement and addition of some aerial and surface gravity data, the value of geoid height are respective TGBMs from this model were made available by Dr. Ulotu (via personal communication, 2023).

3.9.4 Mean Dynamic Topography Model (DTU19MDT) and Mean Sea Surface Model (DTU18MSS)

These DTU18MSS and DTU19MDT models were made available by O. B. Anderson from DTU Space (via Email Communications) and the data were in XYZ format. The Preparation of data, removing unnecessary data and extraction of value were done using Surfer version 20 software. The scale factors used to convert data into meter were applied accordingly; in this research 0.001 and 0.0001 were applied to MSS and MDT respectively.

3.9.5 Orthometric height

The published value of orthometric height for Tanga tide gauge benchmark was obtained from (Masunga, 2016) while, orthometric height for Zanzibar tide gauge benchmark was obtained from commission for land Zanzibar which were then used to compute Geoidal height according to equation 3.1 and were represented in table 3.1 below.

Table 3.1: Orthometric height of Zanzibar and Tanga TGBM

Tide Gauge Station	Orthometric Height (m)	Source
Zanzibar	3.925	Commission for land Zanzibar
Tanga	3.317	(Masunga,2016)

3.10 Devices, Services and Software Used

A computer equipped with Golden Surfer Software version 20 software, Microsoft excel and word, TEQC software and CSRS online service were used. Field observation were done using GPS receiver, tripod stand and logger

CHAPTER FOUR

4.0 RESULTS, ANALYSIS AND DISCUSSION

This chapter involves processing and computation of the data obtained from data collection process i.e. GPS observation files, MSS and MDT models, Geoid model (TZG19) as they are used in improvement of Tanzania local geopotential vertical datum

4.1 Processed GPS data

The GNSS observations were done to Zanzibar tide gauge benchmark only whereby data was processed by Canadian Spatial Reference System while geodetic coordinates at Tanga was obtained from previous study and results were shown in table 4.1 below. For the processing see appendix 1.

Table 4.1: Processed geodetic coordinates of Zanzibar and Tanga TGBM

TGBM (m)	Latitude			Longitude			Ellipsoidal Height (m)
	deg	min	Sec	Deg	Min	Sec	
Zanzibar	-6	9	24.10987	39	11	31.0007	-23.725
Tanga	-5	3	50.6436	39	6	26.5991	-23.934

4.2 Geoidal Height computation

4.2.1 Geoidal height from TZG19 geiod model

Geiodal height from TZG19 were made available by Dr. Ulotu and the results were shown in table 4.2 below

Table 4.2: Extracted Geoidal height of Zanzibar and Tanga TGBM from TZG19 geoid model

Tide Gauge Station	Latitude	Longitude	N^{TZG19}
Zanzibar	-6.15670	39.19194	-27.865
Tanga	-5.05806	39.12417	-27.392

4.2.2 MSL geoid height above the reference ellipsoid

MSL geoid height above the reference ellipsoid (MSLH) was computed according to the equation (3.1) and results were shown in table 4.3 below.

Table 4.3: Computed MSL height above the reference ellipsoid of the Zanzibar and Tanga TGBM

Tide Gauge Station	h^{GPS}(m)	H_{BM}(m)	MSLH (m)
Zanzibar	-23.725	3.925	-27.650
Tanga	-23.934	3.317	-27.251

4.2.3 Geoidal height from MSSH and MDT models

MSSH and MDT were extracted from DTU18MSS and DTU19MDT models respectively using golden surfer 20 software and were used to compute the marine geoid as per equation (3.4) and computed at $1' \times 1'$ grid interval. The table 4.4 below show the obtained results.

Table 4.4: Computes geoidal height of the Zanzibar and Tanga TGBM from MSSH and MDT referenced to WGS84

Tide Gauge Station	MSSH referenced to WGS84	MDT (m)	N^{MSS}(m)
Zanzibar	-26.7843	0.7940	-27.5783
Tanga	-26.8817	0.7963	-27.6780

4.3 Computation of Height difference

Height difference between MSLH and N^{TZG19}, as well as MSSH and N^{TZG19} were computed according to equation (3.6) & (3.7) and the results are presented in table 4.5 below.

Table 4.5: Height difference of the Zanzibar and Tanga TGBM between MSLH and N^{TZG19}, and MSS and N^{TZG19}

Tide Gauge Sation	MSLH (m)	MSSH (m)	N^{TZG19} (m)	ΔN^{MSL}_{TZG19} (m)	ΔN^{MSS}_{TZG19} (m)
ZATG	-27.650	-27.5783	-27.865	0.215	0.2867
TATG	-27.251	-27.6780	-27.392	0.141	-0.2860

4.4 Computation of Potential Difference

Computation of potential difference require gravity measurement and geiodal height difference. Before obtaining potential difference between local and global reference surfaces, normal gravity of the Zanzibar TGBM was computed first using equation (3.8) and the results are presented in table 4.6 below

Table 4.6: Computed normal gravity at Zanzibar and Tanga TGBM

Tide Gauge Station	Latitude (Deg)	Longitude (Deg)	Normal gravity (γ) (m/s^2)
ZATG	-6.15670	39.19194	9.780920683
TATG	-5.05806	39.12417	9.780728128

After obtaining normal gravity, potential difference between the two surfaces using MSL $\eth W_{TZG19}^{MSL}$ and MSS $\eth W_{TZG19}^{MSS}$ were obtained using equation (3.9) and (3.10) respectively. The results are presented in table 4.7 below

Table 4.7: Computed potential difference of the Zanzibar and Tanga TGBM form MSL and MSS referenced to WGS84 reference ellipsoid

Tide Gauge Sation	ΔN_{TZG19}^{MSL} (m)	ΔN_{TZG19}^{MSS} (m)	Normal gravity (γ) (m/s^2)	$\eth W_{TZG19}^{MSL}$	$\eth W_{TZG19}^{MSS}$
ZATG	0.215	0.2867	9.780920683	2.1029	2.8042
TATG	0.141	-0.2860	9.780728128	1.3791	-2.7973

4.5 Computation of local Geopotential Vertical Datum (W_0^{LVD})

After obtaining geopotential number, local geopotential VD value using GPS/Levelling and MSS data was computed using equation (3.11) and (3.12) .The reference potential value of global reference level used were 62636853.4 m^2/s^2. The results are represented in table 4.8 below.

Table 4.8: Local geopotential vertical datum value from MSL and MSS

Tide Gauge Sation	δW_{TZG19}^{MSL} (m^2/s^2)	δW_{TZG19}^{MSS} (m^2/s^2)	W_0 ^{MSL,TZG19} (m^2/s^2)	W_0 ^{MSS,TZG19} (m^2/s^2)
ZATG	2.1029	2.8042	62636851.30	62636850.60
TATG	1.3791	-2.7973	62636852.02	62636856.20
Average			**62636851.66**	**62636853.40**

4.6 Discussion of the Results

This section discusses the results obtained in this research to come with an improved Geopotential vertical datum Wo^{LVD} for Tanzania, that is through new conventional value and new gravimetric geoid model TZG19. TG-VD i.e. MSL for Tanzania mainland uses Tanga Tide gauge only whereas the other Tide gauge like Zanzibar have not been used for vertical network, therefore the average results obtained from Zanzibar and Tanga Tide Gauge will be used in this research.

4.6.1 Results from GPS observation at Tanga Tide Gauge Benchmark

Geodetic coordinates determined from previous research (Silas,2020) at Tanga Tide Gauge were compared with the results obtained during the computation of the Optical local geopotential value in 2016 (Masunga, 2016) and the ones obtained in 2019 (Kamungisha,2019).GPS observation of 2016 was conducted for about (37 to 40hours) and GAMIT software was used to process the data while the GPS observation of 2019 and 2020 was both done for about six hours and Canadial reference System was used to process the data. The differences between the results are shown in table 4.9 below.

Table 4.9: Difference between current and previous GPS observation at Tanga TGBM

Year of Observation	TGBM (m)	Latitude			Longitude			Ellipsoidal Height (m)	Mode of processing
		Deg	Min	Sec	Deg	Min	Sec		
2016	TATG	-5	03	50.64581	39	06	26.59593	-23.9861	GAMIT
2019	TATG	-5	03	50.6443	39	06	26.5986	-23.920	CSRS
2020	TATG	-5	03	50.6436	39	06	26.5991	-23.934	CSRS
2016-2019	Difference			0.0015			0.0027	0.0661	
2019-2020	Difference			0.0007			0.0005	0.0140	
2016-2020	Difference			0.0022			0.0032	0.0521	

From the table 4.9, it is observed that there is minor difference in horizontal position (Latitude and Longitude) of the point, meaning that all the three observations occupied the same point. A big different is in ellipsoidal height. The difference between ellipsoidal height of 2019 and 2020 is 1.4cm, this different could be due to sea level change which is caused by factors like Earth tides, global warming and others. This affect the TGBM since it is located near the sea

The difference between ellipsoidal height of 2016 and 2020, as well as 2016 and 2019 are 5.21cm and 6.61cm respectively. So due to these differences there must be problem somewhere. Since the observation done in 2016 was conducted for a longer period (30 to 40 hours) and then processed by a powerful software (GAMIT), its results is expected to be better than others. So this is means there is problem with data obtained in 2019 as well as 2020 since GPS observation was processed by Canadian Spatial Reference System, this means that very likely a blunder was made during observation. A possible blunder could be made during measurement of antenna height or recording it or both measurement and recording it.

4.6.2 Discussion of the results of datum offsets from MSL and MSS

The summary of the results of geoidal height from MSL and MSS, together with their offsets from TZG19 geoid model are shown in table 4.10 below.

Table 4.10: Summary of the results of geoidal height and datum offsets

Tide Gauge Sation	MSLH (m)	MSSH (m)	N^{TZG19} (m)2	ΔN_{TZG19}^{MSL} (m)	ΔN_{TZG19}^{MSS} (m)	ΔN_{MSL}^{MSS} (m)
ZATG	-27.251	-27.678	-27.392	0.141	-0.286	0.427

From the results obtained above, datum offset from Mean Sea level is significantly different from the one obtained from Mean Sea Surface. The different could be caused by the following reasons

i. The datum offset between MSS and TZG9 has the following advantages when compared with geopotential offset from MSL ;
    - Unlike the short time observed data from MSL, data from DTU18MSS and DTU19MDT models are current, and have been observed for than 19 years now. The data from TZG19 geoid model is also current since current gravity data were used in its determination. So MSSH and N^{TZG19} are compatible in terms of time

ii. Data from oceanic models (DTU18MSS and DTU19MDT) which are obtained by satellite altimetry have one shortcoming. Satellite altimetry work best in deep sea but poor near the shore. Most of the Tide gauge (including Zanzibar tide gauge) are located near the shore where satellite altimetry does not perform well. This causes the results to suffer from spatial and temporal resolution and forcing factors such as ocean currents, wind stress, temperature and salinity. As a results the computed vertical datum offset suffer from storm surges.

4.6.3 Discussion of the results of the local geopotential vertical datum

The local geopotential vertical datum for Tanzania obtained from this research using both i.e. MSL and MSS were compared with the results of the local geopotential vertical datum obtained from (Masunga, 2016).The summary of the numerical results was presented in table 4.11 below

Table 4.11: Differences between the current and the previous local geopotential vertical datum of Tanzania

Tide Gauge Benchmark	2023		2016		Difference (m^2/s^2)
TATG & ZATG	Data source	$W_0^{LVD,\ TZG19}$ (m^2/s^2)	Data source	$W_0^{LVD,MSL}$ (m^2/s^2)	
	MSL and TZG19 Geoid Model	62636851.66	MSL and TZG13 Geoid Model	62636864.68	-11.55
	MSS,MDT and TZG19 Geoid Model	62636853.40	MSS,MDT and TZG13 Geoid Model	62636861.311	-9.92
	Difference (m^2/s^2)	1.74		0.11	

From the table 4.11, it is shown that during the determination of the current and previous local geopotential vertical datum, two different data sources were used i.e. data from GPS/Levelling and data from MSS. The different of -11.55 m^2/s^2 and -9.92 m^2/s^2 were obtained between the current and previous local geopotential vertical datum at Zanzibar tide gauge station obtained from MSL and MSS data respectively. The negative sign means the current value is less than the previous one. These different could be due to the following reasons;

i. In the computation of the current local geopotential vertical datum new gravimetric geoid model of 2019 (TZG19) was used, but in the computation of the previous local geopotential vertical datum in 2016, TZG13 gravimetric geoid model was used. Due to the use of different geoid models, the results must be different
ii. During determination of the previous value of the local geopotential vertical datum, a conventional value W_o =62636856.00 m^2/s^2 which was released in 2010 by international Earth rotation and Reference System Services (IERS) was used. But latter, this value was found not to be in agreement and consequently not reproductive with the newest

geodetic models, describing the geometry and physics of the Earth (Sanchez et al, 2016). So in 2015, a new conventional value W_o =62636853.4 m^2/s^2 was released by international association of Geodesy (IAG) to be used as definition as global reference level. This new value was used in determination of the new value of the local geopotential vertical datum of the Zanzibar TGBM

iii. New GPS observation at Zanzibar and New Geodetic coordinates from previous study (Silas, 2020) at Tanga TGBM. Since different value of ellipsoidal height obtained from GPS observation conducted in 2016 and 2020 were used in computation of local geopotential vertical datum for 2016 and 2020 respectively, the value of local geopotential vertical datum must be different. The different of GPS observation conducted in 2016 and 2020 are shown in table 4.9.

iv. New satellite altimetry models (DTU18MSS and DTU19MDT). In the computation of previous local geopotential vertical datum using data from salellite altimetry, DTU10MSS and DTU10MDT models were used. But in the computation of current local geopotential vertical datum, new models i.e. DTU18MSS and DTU19MDT were used.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The aim of this research was to improve the local geopotential vertical datum for Tanzania at Zanzibar and Tanga Tide gauge station using TZG19 gravimetric geoid model, GPS/Levelling and the data from MSS to validate the results obtained. As discussed in section 4.6.2 the vertical datum offset from MSS, the models used were observed for a long period (more than 19 years) and compatible with the current TZG19 gravimetric geoid model as well as GNSS positioning. So from the above discussion, the results from satellite altimetry models should provide more reliable local vertical datum for Tanzania than the one from MSL. Also from the discussion in section 4.6.3 significant different of -11.55 m^2/s^2 and -9.92 m^2/s^2 were found between the current and previous local geopotential vertical datum obtained using GPS/Levelling and MSS respectively. So due to these differences, it was necessary to improve the local geopotential vertical datum from $W_0^{LVD,\ TZG13}$ to $W_0^{LVD,\ TZG19}$. Therefore it is concluded that, the Local Geopotential Vertical Datum $W_0^{LVD,\ TZG19}$ for Tanzania computed from the newest Gravimetric Geoid Model of Tanzania, TZG19, using data from GPS/Levelling (MSL) at Zanzibar and Tanga Tide gauge station was **62636851.66m^2/s^2**

5.2 Recommendations

From the results obtained in this study, the discussion of the results done in section 4.6 and the conclusion drawn in section 5.1, the following are recommended:

i. Tanzania should adopt a geopotential vertical datum or a vertical datum based on geoid model (currently TZG19 geoid model) since it is current , stable, and compatible with requirements of GGOS of IAG
ii. If there will be an update of TZG19 geoid model i.e. new gravimetric geoid model with better accuracy than TZG19, it should be used for better results of local geopotential vertical datum
iii. Recording the sea water level at the Tide gauge station for more than 18.6 years to establish proper MSL should be exercised. This will help in the future to minimize most of the periodic effects

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APPENDIX