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ASSESSMENT OF THE LAST SEVEN YEARS MARINE GEOID MODELS FROM MSSH AND MDT MODELS USING XGM2019e_5540, SGG-UGM-2, EGM08, AFRgeo2019 AND TZG19.

A Case Study of Tanzania Indian Ocean

MWAKYUSA, EMMANUEL JOSEPH

BSc in Geomatics (BSc GM)

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

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Ardhi University a dissertation titled **“ASSESSMENT OF LAST SEVEN YEARS MARINE GEOID MODELS FROM MSSH AND MDT MODELS USING XGM2019e_ 5540, SGG-UGM-2, EGM08, AFRgeo2019, AND TZG19”** in partial fulfillment of the requirements for the award of the degree of Bachelor of Science in Geomatics of the Ardhi University.

…………………………………..	…………………………………..
Ms. REGINA V. PETER	Mr. HUMPHREY BUSEGA
Supervisor	Supervisor
Date………………….	Date……………………

DECLARATION AND COPYRIGHT

I, MWAKYUSA EMMANUEL, declare that the contents of this dissertation report are the results of my own study and findings, to the best of my knowledge. They have not been presented anywhere else as a dissertation for a diploma, degree, or any similar academic award in any institution of higher learning.

Signature………………………….

MWAKYUSA, EMMANUEL JOSEPH

(22776/T.2019)

Date……...……...……….………

DEDICATION

‘This study is dedicated to my beloved parents, Mr. and Mrs. Joseph Mwakyusa. My brothers, sisters, and friends. Your presence always gives me strength.’’

ACKNOWLEDGEMENT

First and foremost, I sincerely thank the Almighty God, the author of knowledge and wisdom, for giving me strength and health to complete this study.

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ABSTRACT

The Assessment of the last seven years Marine Geoid models from MSSH and MDT models using XGM2019e_5540, SGG-UGM-2, EGM08, AFRgeo2019, and TZG19 in Tanzania's Indian Ocean as the case study was done using satellite altimetry data. The Mean Sea Surface Height (MSSH) and Mean Dynamic Topography (MDT) Models from DTU and AVISO centers were used as the main sources of altimetric data. The most recent models from 2015 were utilized, consisting of three models for MSSH (DTU15MSS, DTU18MSS, and DTU21MSS) and three models for MDT (DTU15MDT, MDT_CNES_CLS18, and DTU19MDT). The difference gives the nine Marine geoid models (which are N1, N2, N3, N4, N5, N6, N7, N8 and N9). The data processing was performed using Golden Surfer 16 and Microsoft Excel software.

From the obtained results, the pairs of DTU18MSS and MDT_CNES_CLS18, as well as DTU21MSS and MDT_CNES_CLS18, were found to be close to each other.

Similarly, DTU15MSS and DTU19MDT, DTU18MSS and DTU19MDT, and DTU21MSS and DTU19MDT were also close to each other. The statistics of RMS revealed that the pair of DTU15MSS and MDT_CNES_CLS18 performed best with TZG19, as it had the smallest RMS of ±0.289m and a Standard deviation of 0.063m. Therefore, this pair is the closest to TZG19.

Based on the results the pair of DTU15MSS and MDT_CNES_CLS18 provides the best marine geoid model that best fits the Tanzanian Indian Ocean. Consequently, it can be used for geodetic purposes such as vertical datum unification and as a vertical datum for orthometric heights.

KEYWORDS: MARINE, GEOID, MEAN SEA SURFACE HEIGHT (MSSH), MEAN DYNAMIC TOPOGRAPHY (MDT)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
CHAMP	Challenging Mini Satellite Payload
CNES	Centre National d'Etudes Spatiales
DT	Dynamic Topography
DTU	Technical University of Denmark
EGM2008	Earth Gravitational Model of 2008
GGM	Global Geopotential Model
GOCE	Gravity field and Ocean stead state Circulation Experiment
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
MDT	Mean Dynamic Topography
MES	Mean Earth Sphere
MSL	Mean Sea Level
MSSH	Mean Sea Surface Heights
RMS	Root Mean Square
SH	Spherical Harmonics
SLA	Sea Level Anomaly
SSH	Instantaneous Sea Surface Heights
STD	Standard Deviation
TZG13	Tanzania Gravimetric Geoid 2013
TZG19	Tanzania Gravimetric Geoid 2019

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The Geoid can be defined as the equipotential surface of the Earth's gravity field that coincides with the sea surface in the absence of disturbing factors like tsunamis, ocean currents, salinities, wind, etc., and extends through the continents (Ulotu, 2009). The Marine geoid is the geoid of the sea or ocean, The Marine geoid is the equipotential surface and the hydrostatic equilibrium shape for the sea level would take in the absence of tides, currents and winds. The geoid is not directly observable but its height above a reference ellipsoidal may be calculated from a model of the earth's gravity field (Smith, 2010). The Marine Geoid can be determined through different techniques such as Airborne Altimetry, Shipborne Altimetry and Satellite Altimetry and also through the Global Geopotential Models (GGMs).

Airborne Altimetry technique provides 3D coordinates of the ocean/ground surface points, it is based on range observation between the aircraft and the ground surface using a laser distance measurements device. The laser device measures the slant range between the aircraft and the ocean surface, the position of the ocean point can only be determined if the position and orientation of the laser system are permanently known with respect to an absolute coordinate system (Limpach, 2010). Through this, the sea surface height of ocean surface points is determined which is used to determine the marine geoid.

The Shipborne Altimetry technique relies on one or more low-cost industrial ultrasonic distance sensors mounted on a boat, providing continuous information on the distance to the sea surface in combination with position and attitude information from a multi antenna GPS system installed on the boat it allows for highly reliable sea surface height determination by direct georeferencing (Limpach, 2010).Through this sea surface height of ocean surface points is determined which is used to determine the marine geoid.

Satellite Altimetry is a unique technique among remote sensing techniques, since it provides much more than surface observations by measuring sea surface and its changes in time. Altimeters measure instantaneous Sea Surface Heights (SSH) above the reference ellipsoid and provide information on Earth's gravity field, the shape and structure of the ocean bottom, and the integrated heat and salt content of the ocean. Globally, satellite radar altimetry missions are the primary means of sea surface height monitoring over the deep sea, with dense and homogeneous coverage in space and time (Limpach, 2010). The Output of satellite altimetry missions is information on short- and long-term variability of the sea surface (Limpach, 2010).

Marine Geoid from satellite altimetry data is obtained by taking the difference between the Mean Sea Surface Height (MSSH) and the Mean Dynamic Topography (MDT) and the obtained marine geoid can be used for geodetic purposes such as a vertical datum for orthometric heights. In Tanzania, there are five dedicated gravimetric geoid models, such as the TZG07 model by Oliver (2007) ,which covered the area from $1°S$ to $12°S$ and from $29°E$ to $40°E$ .The method used to determine the model was the RCR Stokes Helmerts method, and the standard error of TZG07 was around 47cm.In 2009, The second dedicated gravimetric geoid model was TZG08 model computed by Ulotu (2009) using the KTH LSMSA, where after evaluation by GNSS/Levelling the accuracy was found to be 27.8cm (Ulotu, 2009), Another dedicated gravimetric model was TZG13 that has coverage of $1°N$ to $13°S$ and from $28°E$ to $43°E$ .It covers both continental land masses and the marine areas of Tanzania, this model was computed from airborne, land and marine gravity data , satellite gravity data from the GRACE and GOCE mission. In 2017 another gravimetric geoid model TZG17, model was determined by Peter (2018) where the method used was KTH LSMSA, and the accuracy was around 8cm (Peter, 2018).The latest gravimetric geoid model is TZG19, an update of the TZG13 geoid model in which aerial gravity survey was conducted covering the area of Tanzania in order to get airborne gravity data which later was combined with surface gravity data and by using remove restore technique the TZG19 model was determined by (Olesen & Forsberg, 2019) and after evaluation by using GNSS/Levelling the accuracy of this new geoid was around 11cm.The above models covers both marine and land areas.

However, in marine areas the marine geoids can be determined from Satellite Altimetry as the Satellite Altimetry is capable of determining mean sea surface height throughout the global ocean and sea surfaces and mean dynamic topography models, the difference between mean sea surface height and mean dynamic topography result the marine geoids. Marine geoid is the significant component of global geoids models because about 70% of the earth's surface is covered by water that making the marine geoid be important component in geoid models. The marine geoid is important because it serves as the reference surface in earths sciences as well as for many applications such as in geodesy as vertical datum and in atmospheric sciences for weather prediction sites (Vergo , 2002).The marine geoid is used in understanding ocean circulation patterns and dynamics and the knowledge of marine geoid is essential in ocean currents modelling and underwater mapping particularly in sounding activities. Therefore, the precise marine geoid is required to be used in various application of geodesy and geodynamics.

Different researches have been conducted on the search and determination of the precise Marine geoid to be used in Tanzania such as Kasala (2016) determined marine geoid using DTU 10 MSS and DTU10MDT and the validation against TZG13 showed that the two models were close to each other (Kasala, 2016). However, the marine geoid offshore did not align closely with the TZG13 geoid model. Another research study aimed to determine the Optimal marine geoid for Tanzania by the combining different MSS and MDT models. The results indicated that DTU15 MSS and DTU15 MDT produced a marine geoid that best fit the TZG13 with an RMS value of $\pm$ 0.551m (Shija, 2017). Additionally, Caroline (2018) conducted a study assessing the best marine geoid model from various global MSSH and MDT model using TZG13. Her result findings revealed that the pair of MSS_CNES_CLS2011 and DTU10MDT, with a resolution of 2 arc minutes performed better with TZG 13 yielding an RMS value of $\pm$ 0.095m. This suggest that this pair closely to the TZG 13 geoid model (Meela, 2018).

From the previous researches as shown above, the TZG13 was used to validate the marine geoids from MSSH and MDT models for Indian ocean part of Tanzania. However, there are new geoids like TZG19 AND AFRgeo19 that have not been employed to test the marine geoids. Additionally, EGM08 has not been used in the validation of marine geoids. Therefore, this study aims to assess marine geoid of the past seven years from MSSH and MDT models using XGM2019e_5540, SGG-UGM-2, EGM2008, AFRgeo2019 and TZG19 on the Tanzania Indian ocean as the case study.

1.2 Statement of the research problem

Approximately 70% of the earth's surface is covered by water, making the marine geoid a significant component of global geoid models. The marine geoid plays a crucial role in various applications including the unification of vertical datum, serving as a vertical datum for orthometric heights, understanding ocean circulation patterns and dynamics, as well as aiding in ocean current modeling and underwater mapping particularly in sounding activities. Over many years, different Satellite Altimetry observations have been conducted to obtain the MSSH and MDT models which are used in the determination of the marine geoid. Due to the deficiency of obtaining marine gravity data, especially for marine geoid data determination, this research will determine the improved models of MSSH and MDT models from satellite altimetry by assessing them using Global geopotential models (GGMs) such as

XGM2019e_5540, SGG-UGM-2, and geoid models such as EGM2008, AFRgeo2019, and TZG19.

1.3 Objectives

1.3.1Main objective

This research aims at assessing the last seven years' marine geoid models from MSSH and MDT models using XGM2019e_5540, SGG-UGM-2, EGM08, AFRgeo2019, and TZG19.

1.3.2 Specific objectives

- To compute marine geoid from different MSSH and MDT models
- To make validation between the marine geoid computed from different MSSH and MDT models and the Global geopotential model which are XGM2019e, SGG-UGM-2, EGM2008, AFRgeo2019, and TZG19.

1.4 Research Question

From the last seven years (2015 – 2022) are there marine geoids from satellite altimetry models which are MSS and MDT models that best fit the Tanzania Indian Ocean?

1.5 Significance of the study

Once accurate and precise models for MSSH and MDT are obtained, they will yield the marine geoid that closely aligns with the Tanzania Indian ocean. The marine geoid can then be utilized in various applications in geodesy and oceanography for instance, geodesists can employ it for the unification of vertical datum, ensuring consistent reference levels across different measurements and surveys. The precise marine geoid serves as a crucial reference for vertical measurements and helps establish a standardized vertical reference system.

1.6 Benefit of the study

The study will benefit many geoscientists, especially geodesists, oceanographers, and geomaticians; e.g., for geodesists the best marine geoid will be useful in unification of vertical datum and vertical datum for orthometric heights Also, for oceanographers the marine geoid will be useful in understanding the ocean circulation patterns and dynamics.

1.7 Scope and limitation of the study

This study will be limited to the last seven years' marine geoid models from MSSH and MDT models from satellite altimetry technique only and the study cover only the Indian ocean part of Tanzania. The study area is within 0°S to 12°S latitudes and 39°E to 42°E longitudes within which Tanzania Indian ocean is found as shown in Figure 1.1

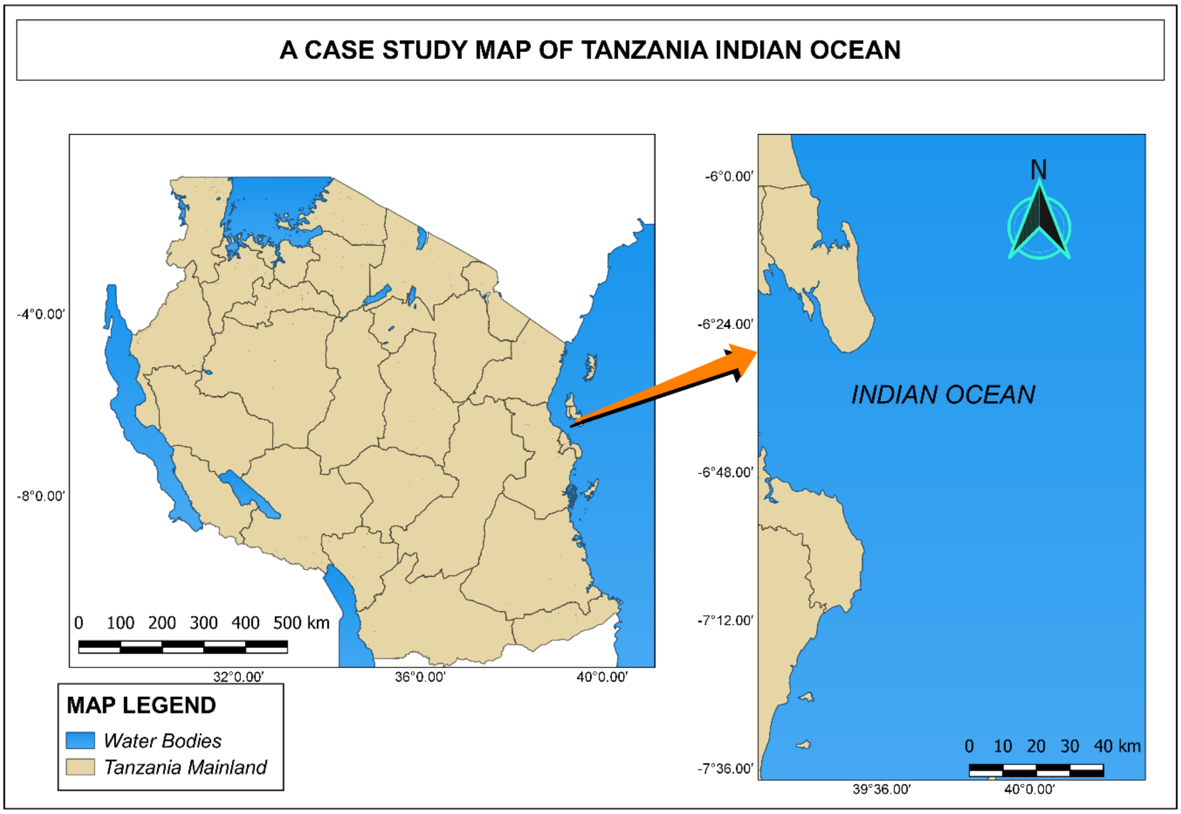

Figure 1.1 The Study Area

1.8 Structure of Dissertation

This dissertation consists of five chapters. Chapter one explains the background of the research, statement of the problem, objectives, scope and limitation, expected output, significance and beneficiaries, and the location of the research. Chapter Two comprises of literature review which explains the overview of the techniques used in determination of marine geoid, the models involved (MSSH and MDT), Global Geopotential Models and the TZG19 model. Chapter three explains about methodology, data descriptions, data preparations, mathematical models used in computations and software used in this research. Chapter four comprises of results and discussion of the results obtained. Chapter five gives conclude the research and put forward the recommendations for future related researches.

CHAPTER TWO

LITERATURE REVIEW

2.1 Satellite Altimetry Models

Satellite altimeters measure the instantaneous sea surface height above a reference Earth Ellipsoid. This height is the sum of the geoid height and the dynamic topography associated with the ocean's flows and responses to tidal and atmospheric forcing, The mean sea surface heights are obtained from the sea surface heights after the correction of geophysical effects like ocean and solid Earth tides, and the atmospheric pressure effects like inverse barometer to the instantaneous sea surface heights. The data obtained from altimetric models are used to estimate marine geoid from the mean sea surface and mean dynamic topography (Limpach, 2010).

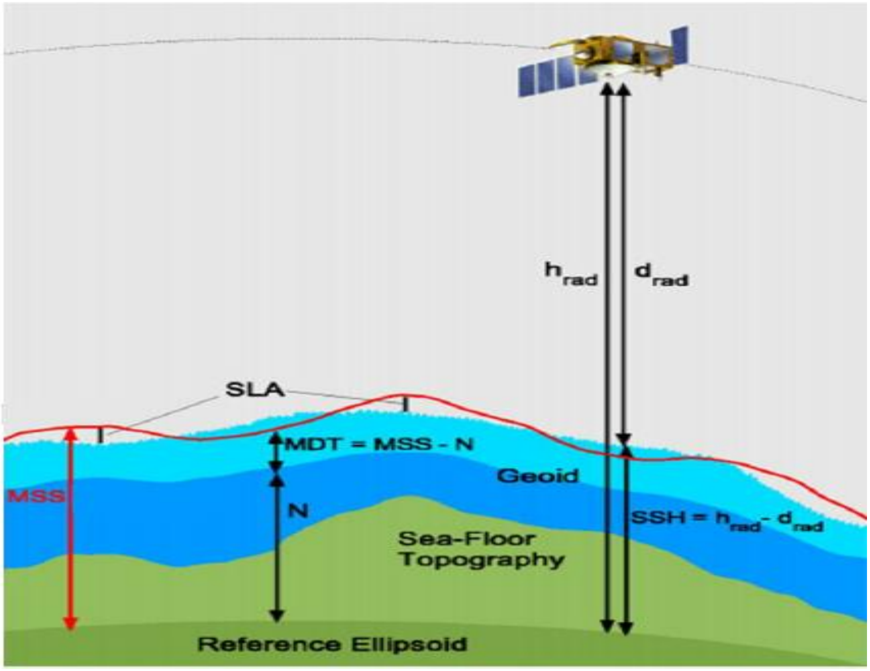

Figure 2.1 Satellite Altimeters (Limpach, 2010)

The Figure 2.1 above shows the Satellite altimeters during measurement of Sea Surface Height (SSH) above the reference ellipsoid other parameters are as;

SLA is the sea level anomaly

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

d_{rad} is the distance from satellite radar to sea surface

h_{las} is the height from airborne laser to the reference ellipsoid

d_{las} is the distance from airborne laser to sea surface

The sea surface height is obtained from the difference between the height of satellite radar or airborne laser from the reference ellipsoid and the distance of the satellite radar or airborne laser from the sea surface

$$\mathrm{SSH} = \mathrm{h}_{\mathrm{rad}} - d_{rad} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.1)}$$

The sea level anomaly is the departure of the sea surface from some long-term mean, Mean Sea surface is obtained by subtracting the Sea Level Anomaly (SLA) from the sea surface height (MSS)

$$MSSH = SSH - SLA \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

Then the marine geoid is obtained by taking the difference between the Mean Sea Surface Height (MSSH) and the Mean Dynamic Topography (MDT)

$$N = MSSH - MDT \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{(2.3)}$$

Equation (2.3) is used in this research in the computation of the marine geoid of the Indian Ocean in Tanzania that will be assessed with the Global Geopotential Models and Geoid models.

2.2 Determination of Marine Geoid

Determination of marine geoid is based on various sources according to the data type used, the data used can be from satellite gravity missions, marine gravity anomaly from satellite altimetry missions and the difference between mean sea surface heights and mean dynamic topography models from satellite altimetry data.

2.2.1 Satellite Gravity Missions

These are missions which are dedicated to provide gravity data for geoid model determination including marine geoid models. Several missions are conducted such as CHAMP (2000), GRACE (2002) and GOCE (2009). The launching of satellite gravity missions has made possible the global mapping of the Earth’s gravity field. These gravity missions present peculiar measurement system for monitoring mass and its movements in the Earth system, the variation mass are highly associated with the redistribution of water mass within and exchanges between oceans, atmosphere, land hydrology and cryosphere and with solid earth processes.

CHAMP (Challenging Mini Satellite Payload) is a small satellite mission for geoscientific and atmospheric research and application managed by GeoForschungs Zentrum (GFZ).It was the first ever global satellite gravity determination mission with highly precise, multifunction and complementary payload elements and its characteristics .It was launched on 15th July 2000 and it was placed almost into a circular near orbit of about 450KM altitude and an inclination of 87.3 degrees designed for five years lifetime. The primary objectives of CHAMP were to accurately determine the long wavelength component of the earth's gravity field and its temporal variations caused by atmospheric mass, sea level change caused by polar ice melting , ocean circulation to accurately determine the main and crustal magnetic field of the earth and profiling of troposphere and ionosphere (https://directory.eoportal.org/web/satellite-missions/CHAMP).

GRACE (Gravity Recovery and Climate Experiment) is a joint project between the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum fur Luft und Raumfahrt (DLR) OF Germany. It was launched on 17th March 2002. The mission consists of two identical CHAMP-type satellite following one another in nearly the same orbit (Low Earth Orbit (LEO)) separated by a distance of 220km. The primary objective of the mission was to determine the global high-resolution gravity field of the earth and the temporal variations of the earth's gravity field (Tapley, Bettadpur, Watkins, & Reigber, 2004).

GOCE (Gravity field and steady state Ocean Circulation Explorer) is one of the satellite missions that has been mapping the earth's gravity field to global scales with spatial resolution of approximately 100km that is considered the more precise satellite gravity mission available to date. This was launched on 17th March 2009 as the first ESA's gravity field planet programme satellite intended to map in unprecedented details of Earth's gravity field. The primary objective of this mission was to measure the earth's stationary gravity field to model the geoid with extremely high accuracy (Hofmann-Wellenhof & Moritz, 2005).

2.2.2 Marine Gravity Anomaly from Satellite Altimetry

The launching of various satellite altimetry missions conducted by different countries like Unites states and France have led to the calculation of marine gravity anomaly. Data from satellite altimetry are used to compute the marine gravity anomaly and the marine geoid and These data can provide marine gravity and seabed geophysical information and it has great significance in forming the high-precision global gravity model in various studies such as climate, exploitation and utilization of marine resources (Liu, et al., 2016) . The stokes formula is used to compute marine geoid when marine gravity anomaly is well computed from the difference between actual and normal gravity values on the geoid and reference ellipsoid respectively

Using Stokes Formula, marine geoid is computed as follows;

$$\mathrm{N} = \frac{\mathrm{R}}{4\pi\gamma}\iint_{\sigma} S(\psi)\Delta g d\sigma \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

Where; N marine geoid R- Earth average radius Δg $- Gravity\ anomaly$ $S(\psi)$- Stoke’s function γ- normal gravity ψ- spherical angle and $d\sigma - surface\ element.$

2.2.3 Combination of MSSH and MDT Models

Satellite altimetry provide data for Mean Sea Surface Height (MSSH) and Mean Dynamic Topography (MDT). Satellite Altimeters measure the instantaneous sea surface above a reference ellipsoid this height is the sum of the marine geoid height and the dynamic topography associated with the flows of ocean and responses to tidal and atmosphere forcings , to obtain the sea surface height the geophysical effects like ocean currents , tides and atmospheric pressure are removed from the instantaneous sea surface height (Smith, 2010).The mean sea surface height is the difference between the sea surface height and the sea level anomaly while mean dynamic topography is resulted from sea surface topography explained by the dynamic of the oceans, the atmospheric changes are the primary causes of ocean dynamics thus MDT is the central quantity bridging the geoid and the ocean circulation. The difference between the MSSH and MDT models gives the marine geoid which is an equipotential surface of the Earth’s gravity field within the marine area. From Satellite altimetry models the marine geoid can be obtain as in the equation 2.3

2.3 Measurements of Sea Surface Heights

In the determination of marine geoid, the sea surface height is required. There are three techniques that can be used in measurement of sea surface height, the techniques are Airborne altimetry, shipborne altimetry and satellite altimetry.

2.3.1 Airborne Altimetry

Airborne Altimetry this technique provides 3D coordinates of the ocean/ground surface points, it is based on range observation between the aircraft and the ground surface using a laser distance measurements device. The laser device measures the slant range between the aircraft and the ocean surface, the position of the ocean point can only be determined if the position and orientation of the laser system are permanently known with respect to an absolute coordinate system (Limpach, 2010). Through this the see surface height of ocean surface points are determined that is used to determine the marine geoid.

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Shipborne Altimetry this technique relies on one or more low-cost industrial ultrasonic distance sensors mounted on a boat, providing continuous information on the distance to the sea surface In combination with position and attitude information from a multi antenna GPS system installed on the boat it allows for highly reliable sea surface height determination by direct georeferencing (Limpach, 2010).

2.3.3 Satellite Altimetry

Satellite Altimetry is the unique techniques among remote sensing techniques, since it provides much more than surface observations by measuring sea surface and its changes in time. Altimeters measures instantaneous Sea Surface Heights (SSH) above the reference ellipsoid and they provide information on Earth's gravity field, shape and structure of the ocean bottom and the integrated heat and salt content of the ocean. Globally satellite radar altimetry missions are primary means of sea surface height monitoring over the deep sea with dense and homogeneous coverage in space and time (Limpach, 2010).

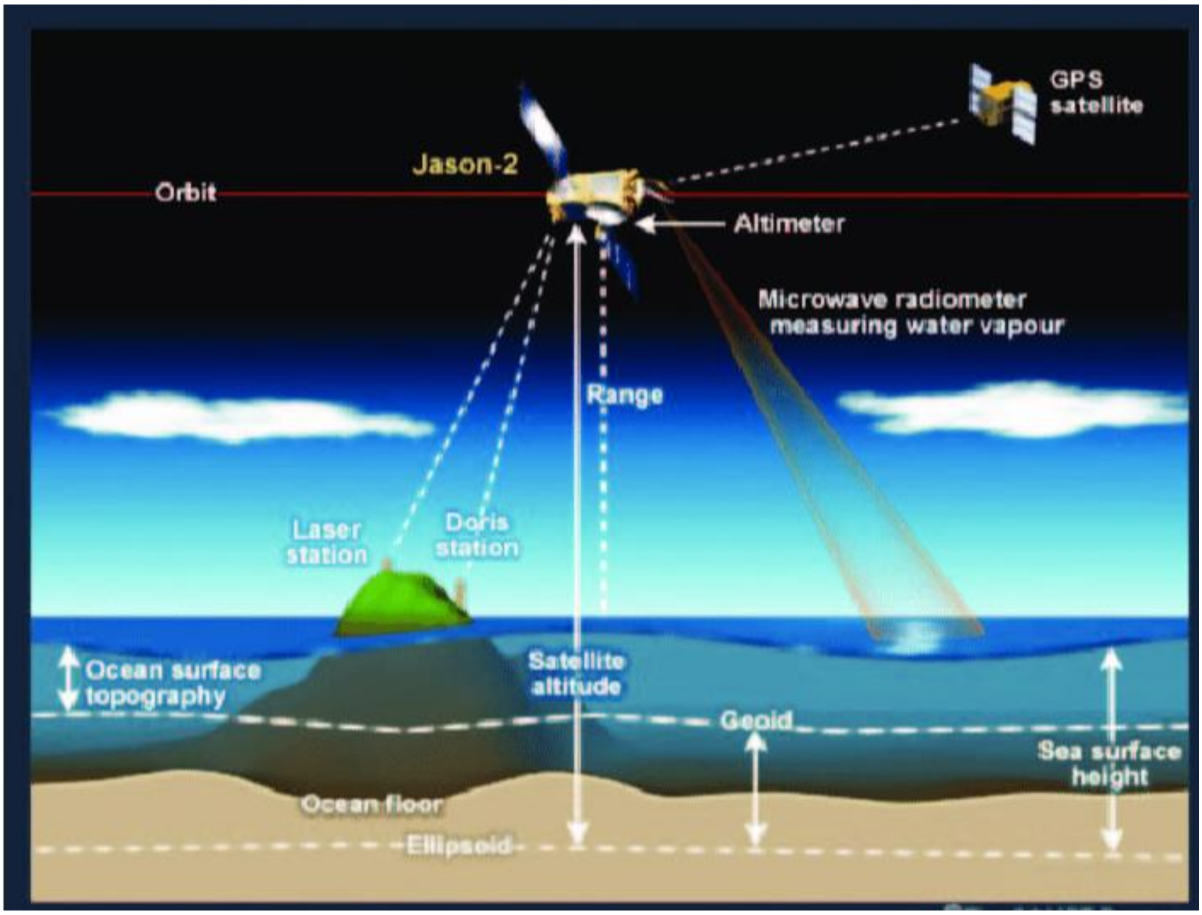

Figure 2.2 Satellite Altimetry Technique

2.4 Altimetric Geoid Models

Satellite Altimetry techniques used to measure the instantaneous sea surface height above the reference ellipsoid, from this altimetry technique the global mean sea surface height and mean dynamic topography models are obtained the difference between these models gives the marine geoid. These models are downloaded from different website such aviso website and the research institution which are the Centre National d'Etudes Spatiales (CNES) and the space research center of the Technical University of Denmark (DTU) which are constantly updating and publishing new MSS and MDT models. The following are some of the described global MSSH models;

I. DTU15MSS MODEL

In 2015 DTU space released a new global high resolution MSSH model known as DTU15MSS, this model made by combination of Cryosat-2 onto 20years mean sea surface using multiple satellites at low to medium latitude. During the creation of DTU15MSS model the Cryosat-2 were merged from different operating models like

LRM, SAR and SAR-In as these requires different retrackers (Andersen, Per Knudsen, Lars, & Piccion, 2016)

II. DTU18MSS MODEL

This model can be used as vertical offshore reference frame, it has been computed relative to reference ellipsoid WGS84/GRS80 in the non-tidal tide system. The computation has been performed for the Baltic region corresponding to latitude of 53N to 67N and longitude of 8EW to 31E and have been performed on 1 minute resolution. (Andersen , Rose, Per Knudsen, & Lars, 2018).

Globally there are various MDT models based on satellite altimetry data used for determination of marine geoid and some are derived from Global Geopotential models (GGMs). These models provide a common reference to different satellite datasets such as TOPEX/Poseidon, ERS-1, ERS-2, GFO, Jason-1, Jason-2, and ENVISAT and other models are from the Space research center of the Technical University of Denmark such DTU15MDT, DTU19MDT and DTU21MDT.The following are some of described MDT.

I. MDT_CNES_CLS18

This is an estimate of the mean over the 1993-2012 period of the sea surface height above geoid. It is used in ocean circulation and operational oceanography. It uses the latest GOCO05S geoid model (based on the complete GOCE mission 10.5 years of GRACE data) and 25 years of altimetry and in situ data (hydrologic and drifters).

II. DTU19MDT

This is an update to the global mean dynamic topography model DTU18MDT.The construction of this global mean dynamic topography model was based on the combination of DTU18MDT and the newer gravity model EIGEN-6C4.

2.5 Global Gravitational Models (GGMs)

Global Geopotential models (GGMs) are the sets of spherical harmonics (SH) coefficients of the earth’s gravity potential of external type extend to mean earth sphere (MES) as bounding surface. The emergence of dedicated satellite gravity missions that are CHAMP, GRACE and GOCE, the quality of the Global Gravity field Models (GGMs) has significantly improved, In the improvement of the global gravity field models specific measurement approaches are used based on three satellite missions: CHAMP (Challenging Mini satellite Payload, in orbit from 2000 to 2010) using satellite to satellite tracking in high-low mode as the measurement approach, GRACE (Gravity Recovery And Climate Experiment, in orbit from 2002 to 2017) that uses satellite to satellite tracking in low-low mode as the measurement system and GOCE (Gravity Field and steady state Ocean Circulation Explorer, in orbit from 2009 to 2013) using satellite gravity gradiometric as the measurement technique (Zingerle, Pail, Gruber, & Oikonomidou, 2020).

GGM are vital in computing global geoid undulation heights because there many models that provide the geoid undulation starting from global, regional up to local GGMs. GGMs provide data from satellite gravity missions such as Gravity Recovery and Climate Experiment (GRACE), Gravity Field and steady state Ocean Circulation Explorer (GOCE) and Challenging Mini Satellite Payload (CHAMP) that assist to enhance the global geoid undulation data. The GGM is used to determine the long wavelength part of the earth's gravity field and comprises of a set of fully normalized spherical harmonic coefficients that are obtained from geopotential solution. The spherical harmonic provides an efficient mathematical tool to compute an arbitrary function of geopotential for any point on the earth's surface example of these functions of geopotential include gravity anomaly, height anomaly, gravity disturbance and deflection of vertical (Bucha & Janak, 2013). In this research, XGM2019e_5540, SGG-UGM-2 EGM2008 GGMs are used. XGM2019e_ 5540 is a combined global gravity field model represented by spherical harmonics up to degree and order (d/o) 5399 and corresponding to a spatial resolution of 2´ (4km). The GGM data sources, include the satellite model GOCO06s in the longer wavelength range up to d/o 300 combined with a ground gravity grid which also covers the shorter wavelengths. This model was released in the year 2019 and it's presently the highest degree compared to existing models in the IAG website. This combined GGM seems to provide better resolution due to the improvement of the high frequency component of gravity. XGM2019e_5540 performs better over the area of Tanzania as validated by Kangele (2021).

2.5.1 XGM2019e_ 5540

XGM2019e_5540 is a combined global gravity field model represented by spherical harmonics up to degree and order (d/o) 5399, corresponding to a spatial resolution of 2´ (4km). The GGM data sources, include the satellite model GOCO06s in the longer wavelength range up to d/o 300 combined with a ground gravity grid which also covers the shorter wavelengths. This model was released in the year 2019 and it's presently the highest degree compared to existing models in the IAG website (Zingerle, Pail, Gruber, & Oikonomidou, 2020).

2.5.2 SGG-UGM-2

SGG-UGM-2 is high resolution Earth's gravity field models combined from satellite gravimetry, satellite altimetry and Earth Gravitational model 2008 (EGM08) derived gravity data based on the theory of the ellipsoidal harmonic analysis and coefficient transformation (EHA CT).The SGG-UGM-2 has up to degree of 2190 and order 2159 by combining the observation of the Gravity field and steady state ocean circulation explorer (GOCE) , the normal equation of the Gravity Recovery and Climate Experiment (GRACE), marine gravity data derived from satellite altimetry and EGM2008 derived continental gravity data (Liang, Li, Xu, Zhang, & Zhao, 2020).

2.5.3 Earth Gravitational Model of 2008 (EGM2008)

EGM2008 is the currently the most frequently used gravity field model , is constructed with possibly the best global 5'× 5' data set of gravity anomaly data from terrestrial observations, satellite altimetry and fill in gravity anomalies from RTM forward modeling and the GRACE normal equation (NEQ) of the Institute of Geodesy and Geoinformation of the University of Bonn (ITG)-GRACE03S satellite only model (Liang, Li, Xu, Zhang, & Zhao, 2020).

2.6 AFRgeo2019

AFRgeo2019 is the geoid model for Africa that was computed using the stoke's integral which requires interpolating the available data into a regular grid, in order to reduce the interpolation error, the method of remove-restore technique was used, the method of remove-restore technique based on EGM2008 geopotential model. The AFRgeo2019 has 15'×15' resolution (Abd-Elmotaal, Norbert, Kurt, & Bernhard, 2020).

CHAPTER THREE

3.0 METHODOLOGY

Marine geoid can be determined through different methods and techniques such as Satellite altimetry, Airborne, Shipborne Altimetry or combination thereof. This section describes the Satellite Altimetry method (the mean sea surface height and mean dynamic topography models) used in the determination and assessment of the best marine geoid that best fit the Indian Ocean part of Tanzania.

3.1 Determination of Marine Geoid

In this study marine geoid are determined using the Satellite Altimetry models which are Mean Sea Surface Height (MSSH) and Mean Dynamic Topography (MDT), The difference between MSSH and MDT yield the marine geoid as showed in equation 2.3

The procedures involved when using the Satellite Altimetry models are;

- First, To Acquire and extract the global Mean Sea Surface Heights (MSSH) and Mean Dynamic Topography (MDT) data based on satellite altimetry of the marine region covering the Indian Ocean part of Tanzania. This data are obtained through download from website such as https://www.aviso.altimetry.fr in Netcdf format for CNES And https://ftp.space.dtu.dk/pub for DTU
- Second Extraction are done through the Golden Surfer software 16 in order to obtain data in DAT format
- Third, after obtain the data in DAT format then equation 2.3 is used to compute for the value of marine geoid

The following are the procedure in the extraction of the models in Golden Surfer 16:

- ➢ First to Open the Golden Surfer software version 16.0 then go to grid followed by Mosaic. Then import the model using the browse button, after that the user will be required to specify the latitude and longitude of the required data example in this study 0S to 12S latitude and 39E to 42E longitude was used.
- ➢ Second Upon extraction the user is required to select the directory of the extracted data plus the format required in this study it was DAT format. After the specifications the data will be extracted and saved.

- ➢ Third then Open the extracted file (DAT file) in Golden Surfer software to view the data in XYZ format, the data will be displayed with the latitude, longitude and height information.
- ➢ Lastly, Then the data are sorted in order to remove the large fill values or no data values. After sorting out data the scale factor was applied of which in our case it was used for scale factor for MSS is 0.001 and scale factor for MDT is 0.0001.

  NOTE: The procedure of extraction for the MSS models are the same to that of MDT models.

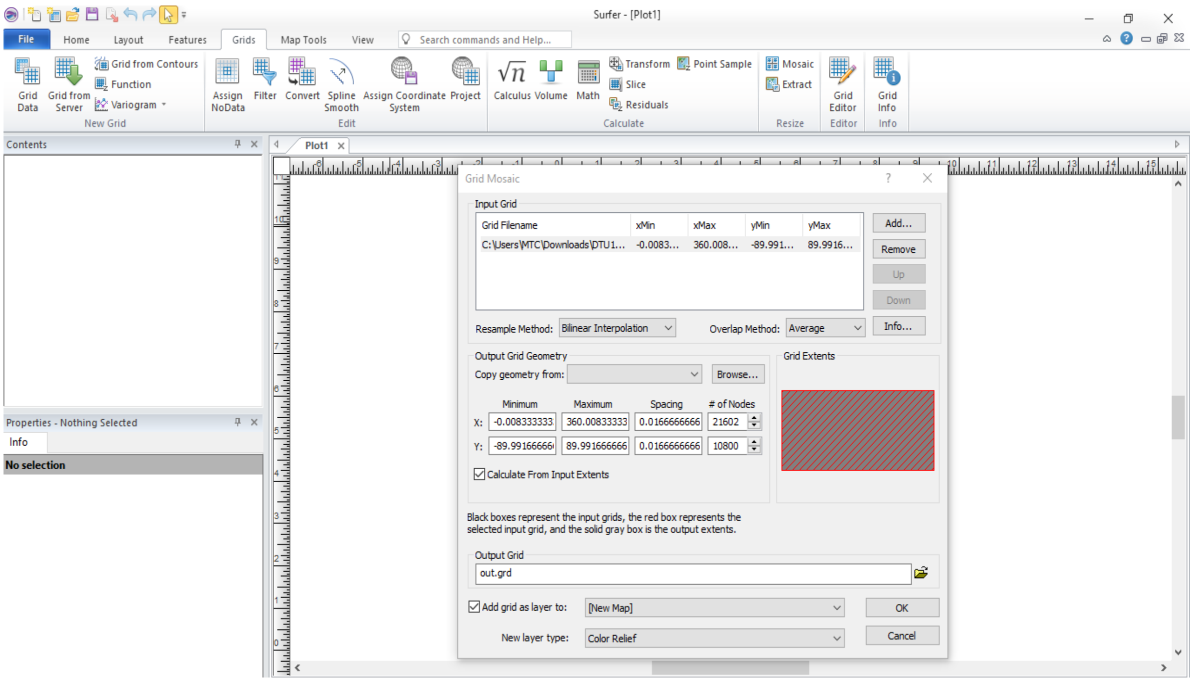

Figure 3.1 Extraction of Data in the Golden Surfer Software 16

The Marine geoids in this study is computed using the following equation respectively to the models of MSSH and MDT

$$N_1 = \mathrm{DTU15}MSS - DTU15MDT \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3a)$$

$$N_2 = \mathrm{DTU15}MSS - MDT_{CNES\_CLS\_18} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3b)$$

$$N_3 = \mathrm{DTU15}MSS - DTU19MDT \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3c)$$

$$N_4 = \mathrm{DTU18}MSS - DTU15MDT \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3d)$$

$$N_5 = \mathrm{DTU18}MSS - MDT_{CNES\_CLS\_18} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3e)$$

$$N_6 = \mathrm{DTU18}MSS - DTU19MDT \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2.3f)$$

$$\mathrm{N}_7 = \mathrm{DTU21}MSS - DTU15MDT \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3g)}$$

$$\mathrm{N}_8 = \mathrm{DTU21}MSS - MDT_{CNES\_CLS\_18} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3h)}$$

$$\mathrm{N}_9 = \mathrm{DTU21}MSS - DTU19MDT \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2..3i)}$$

3.2 Assessment of Marine Geoid Models

This process involves the assessment of the differences between geoidal heights from the assessment agent vs the marine geoid from the MSSH and MDT Models.

The following mathematical models used to determine differences;

i. Difference between geoid height from XGM2019e_5540, and the Marine geoid from models

   The difference between geoidal height from XGM2019e_5540 and that from models was determined by using the following mathematical model;

$$\Delta N_1 = N_{XGM2019e\_5540} - N_M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.1)}$$

   Where, $N_{\mathrm{XGM2019e\_5540}}$ is the Geoidal height from XGM2019e_5540

   N_M is the Marine Geoid model from MSSH and MDT models

ii. Difference between Geoidal height from EGM08 and the marine geoid from models

   The difference between geoidal height from EGM08 and the marine geoid from models is determined by using the following mathematical model;

$$\Delta N_2 = N_{EGM08} - N_M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.2)}$$

   Where, N_{EGM08} is the Geoidal height from EGM08

   N_M is the Marine Geoid model from MSSH and MDT models

iii. Difference between Geoidal height from SGG-UGM-2 and the marine geoid from models.

   The difference between geoidal height from SGG-UGM-2 and the marine geoid from models is determined by using the following mathematical model;

$$\Delta N_3 = N_{SGG-UGM-2} - N_M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.3)}$$

   Where, $N_{\mathrm{SGG\text{-}UGM\text{-}2}}$ is the Geoidal height from SGG-UGM-2

   N_M is the Marine Geoid model from MSSH and MDT models

iv. Difference between Geoidal height from AFRgeo2019 and the marine geoid from models.

The difference between geoidal height from AFRgeo2019 and the marine geoid from models is determined by using the following mathematical model;

$$\Delta N_4 = N_{AFRgeo2019} - N_M \text{ ....} \quad (3.4)$$

Where, $N_{AFRgeo2019}$ is the Geoidal height from AFRgeo2019

N_M is the Marine Geoid model from MSSH and MDT models

v. Difference between Geoidal height from TZG19 and the marine geoid from models.

The difference between geoidal height from TZG19 and the marine geoid from models is determined by using the following mathematical model;

$$\Delta N_5 = N_{TZG19} - N_M \text{ ....} \quad (3.5)$$

Where, N_{TZG19} is the Geoidal height from TZG19

N_M is the Marine Geoid model from MSSH and MDT models

The geoidal heights differences between Marine geoidal height from assessment agent and the marine geoid from MSSH and MDT Models obtained from equation 3.1 up to 3.5 were used in determination of statistics in order to asses marine geoids

The statistics are determined as follows;

i. Mean difference (ΔN_{mean})

This is the average of the geoidal heights difference between the geoidal models.

$$\Delta N_{mean} = \frac{1}{N}\sum_{i=1}^{n} \Delta N_{2i}^{n} \text{ ....} \quad (3.6)$$

ii. Standard deviation (σ) of geoidal height differences

$$\sigma_i = \pm\sqrt{\sum_{i=1}^{n} \frac{(\Delta N_{2i}^{n} - \Delta N_{mean})^2}{n-1}} \text{ ....} \quad (3.7)$$

iii. Root mean square (RMS) of the height differences

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{(\Delta N_{2i}^{n})^2}{n}} \text{ ....} (3.8)$$

3.3 Data Used

This section describes all the data used in this study;

3.3.1 The MSS Models

The Mean Sea Surface Height (MSSH) used in this study were downloaded from https://www.aviso.altimetry.fr for CNES in Netcdf format and https://ftp.space.dtu.dk/pub for

DTU also in Netcdf format. Data downloaded have longitude latitude and height information, the golden surfer 16 software was used to extract data and convert in the xyz format. The MSS models used in this study were DTUMSS15, DTUMSS18 and DTU21MSS for DTU and MSS_CNES-CLS-15 for CNES for the coverage of 0° S to 12° S and 39° E to 42° E of the Indian ocean of Tanzania.

3.3.2 The MDT Models

The Mean Dynamic Topography Models used in this study were downloaded from https://www.aviso.altimetry.fr for CNES in Netcdf format and https://ftp.space.dtu.dk/pub for DTU also in Netcdf format. Data downloaded have longitude latitude and height information, the golden surfer 16 software was used to extract data and convert in the xyz format. The MDT models used in this study were DTU15MDT, DTU19MDT and DTU22MDTfor DTU and MDT_CNES-CLS-18 for CNES for the coverage of 0° S to 12° S and 39° E to 42 E of the Indian Ocean of Tanzania.

3.3.3 Global Gravitational Models (GGMs)

GGMs models used in this study was downloaded ICGEM websites (http://icgem.gfz-potsdam.de/ICGEM), GGMs models used are XGM2019e_5540, EGM08, and SGG-UGM-2. These models were computed at d/o 5540,2190and 2190 covering the area of interest respectively, these models are provided in Spherical Harmonics Coefficients in gfc format.

3.3.4 AFRgeo2019

In this study AFRgeo2019 used to assess marine geoid model, this model was downloaded from ICGEM websites in the grid format. The Golden Surfer used to convert the grid data into latitude, longitude and height information from 0° S to 12° S and 38° E to 42°e of the Tanzanian Indian Ocean.

3.3.5 Tanzania Gravimetric Geoid 2019

In this study TZG19 used to assess marine geoid model, this was obtained from Ardhi university, department of Geospatial Science into latitude, longitude and height information from 0° S to 12° S and 38° E to 42°e of the Tanzanian Indian Ocean.

3.4 Software

In this study various software were used including;

i. IsGrafLab Software

   This was used in computation od Geoidal undulations from XGM2019e_5540

ii. Golden Surfer 16

    This was used in gridding, merging and conversion of grid formats, extraction of data and computation of statistics.

iii. MATLAB

    This was used for running IsGrafLab interface

iv. Microsoft Excel

    This was used in arranging data and computation of statistics.

v. Microsoft Word

    This was used in report writing.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The MSSH and MDT models from satellite altimetry as well as the assessment agents which are XGM2019e_ 5540, SGG-UGM-2, EGM2008, AFRgeo2019 and TZG19 data for the area of interest were prepared and processed using the Golden Surfer Software Version 16. The MSSH models used are; DTU15MSS, DTU18MSSand DTU21MSS from DTU and the MDT models used are; DTU15MDT, DTU19MDT and MDT_CNES_CLS18

4.1.1 Combinations of Marine Geoid Models from MSSH and MDT Models

In this study 1' x 1’ marine geoid models were computed from different combinations of mean sea surface heights and mean dynamic topography models such that from three MSSH models and three MDT models using equation 2.3a ,2.3b, 2.3d, 2.3e, 2.3f and 2.3h and the results are presented in Table 4.1

Table 4.1 1' x 1' Computed Marine Geoid Models

Longitude (degree)	Latitude (degree)	N1(m)	N2(m)	N4(m)	N5(m)	N7(m)	N8 (m)
39	-10.998	-23.648	-23.570	-23.648	-23.542	-23.324	-23.677
39.017	-10.998	-23.623	-23.630	-23.623	-23.595	-23.348	-23.736
39.033	-10.998	-23.596	-23.699	-23.596	-23.657	-23.373	-23.795
39.05	-10.998	-23.569	-23.775	-23.569	-23.720	-23.397	-23.846
39.067	-10.998	-23.541	-23.851	-23.541	-23.785	-23.419	-23.894
39.083	-10.998	-23.515	-23.931	-23.515	-23.853	-23.437	-23.937
39.1	-10.998	-23.489	-24.015	-23.489	-23.926	-23.453	-23.984
39.117	-10.998	-23.465	-24.097	-23.465	-24.005	-23.463	-24.036
39.133	-10.998	-23.442	-24.186	-23.442	-24.082	-23.469	-24.092
39.15	-10.998	-23.422	-24.278	-23.422	-24.168	-23.469	-24.165
39.167	-10.998	-23.403	-24.369	-23.403	-24.257	-23.466	-24.245
39.183	-10.998	-23.385	-24.463	-23.385	-24.348	-23.460	-24.326
39.2	-10.998	-23.368	-24.562	-23.368	-24.442	-23.450	-24.420
39.217	-10.998	-23.353	-24.675	-23.353	-24.537	-23.437	-24.521
39.233	-10.998	-23.341	-24.801	-23.341	-24.646	-23.425	-24.635
39.25	-10.998	-23.328	-24.928	-23.327	-24.767	-23.410	-24.755
39.267	-10.998	-23.314	-25.055	-23.314	-24.896	-23.393	-24.883
39.283	-10.998	-23.303	-25.192	-23.303	-25.026	-23.374	-25.014
39.3	-10.998	-23.294	-25.325	-23.294	-25.160	-23.353	-25.148

The 2'x2' marine geoid models were computed from different combination of mean sea surface heights and mean dynamic topography models using equations 2.3c, 2.3f, and 2.3i and the results are presented in Table 4.2

Table 4.2 2'x2' Computed Marine Geoid models

Longitude (degree)	Latitude (degree)	N3 (m)	N6 (m)	N9(m)
39	-10.967	-23.919	-23.919	-23.918
39.033	-10.967	-23.871	-23.871	-23.870
39.067	-10.967	-23.819	-23.819	-23.818
39.1	-10.967	-23.772	-23.772	-23.771
39.133	-10.967	-23.730	-23.730	-23.729
39.167	-10.967	-23.694	-23.694	-23.693
39.2	-10.967	-23.663	-23.663	-23.661
39.233	-10.967	-23.638	-23.638	-23.635
39.267	-10.967	-23.618	-23.618	-23.615

4.1.2 Validation of Marine Geoid from MSSH and MDT Models and Geoidal Height

The marine geoids were validated using XGM2019e_5540, EGM08, SGG-UGM-2, AFRgeo2019, and TZG19.

The following are results of the validation of marine geoids models using XGM2019e_5540, EGM08, SGG-UGM-2, AFRgeo2019, and TZG19 as shown in equations 3.1 up to 3.5 and the results are presented in Table 4.3,4.5,4.7,4.9 and Table 4.11

First, the marine geoid was validated using XGM2019e_5540 model and results are presented in Table 4.3

Table 4.3 Marine Geod validated using XGM2019e_5540

X1 (m)	X2 (m)	X3 m)	X4 (m)	X5 (m)	X6 (m)	X7 (m)	X8 (m)	X9 (m)
-0.786	-1.103	-0.474	-0.786	-1.061	-0.474	-1.072	-0.909	-0.475
-0.796	-1.108	-0.493	-0.796	-1.060	-0.493	-1.042	-0.907	-0.494
-0.806	-1.107	-0.507	-0.806	-1.057	-0.507	-1.008	-0.912	-0.507
-0.817	-1.101	-0.508	-0.816	-1.055	-0.508	-0.973	-0.926	-0.509
-0.825	-1.092	-0.497	-0.826	-1.054	-0.497	-0.939	-0.947	-0.498

-0.832	-1.087	-0.471	-0.832	-1.055	-0.471	-0.907	-0.979	-0.472
-0.836	-1.081	-0.428	-0.836	-1.058	-0.428	-0.876	-1.013	-0.430
-0.838	-1.077	-0.378	-0.838	-1.061	-0.378	-0.849	-1.043	-0.382
-0.836	-1.079	-0.344	-0.836	-1.068	-0.344	-0.826	-1.069	-0.346
-0.832	-1.081	-0.343	-0.832	-1.072	-0.343	-0.807	-1.081	-0.346
-0.826	-1.084	-0.379	-0.826	-1.076	-0.378	-0.791	-1.089	-0.382
-0.819	-1.093	-0.443	-0.819	-1.086	-0.443	-0.776	-1.104	-0.446
-0.814	-1.104	-0.421	-0.814	-1.100	-0.421	-0.765	-1.115	-0.425
-0.807	-1.115	-0.36	-0.807	-1.113	-0.36	-0.756	-1.123	-0.364
-0.802	-1.116	-0.279	-0.802	-1.115	-0.279	-0.746	-1.122	-0.283

The statistical results of the marine geoid as validated using XGM2019e_5540 model and the results are presented in Table 4.4.

Table 4.4 Statistics of Marine geoid as validated using XGM2019e_5540

Model XGM2019e_5540	Number of values	Minimum	Maximum	Mean (m)	Standard Deviation (m)	Root Mean Square RMS(m)
X1	50820	-2.231	-0.535	-1.608	0.328	1.641
X2	32005	-1.354	-0.483	-1.019	0.049	1.020
X3	12810	-1.469	0.332	-0.884	0.342	0.948
X4	50820	-2.228	-0.536	-1.609	0.327	1.642
X5	29235	-1.349	-0.845	-1.020	0.058	1.022
X6	12810	-1.464	0.331	-0.885	0.341	0.949
X7	48254	-2.183	-0.570	-1.654	0.284	1.678
X8	29091	-1.317	2.815	-1.024	0.067	1.025
X9	12810	-1.429	0.338	-0.893	0.340	0.955

Where;

$$X_1 = N_{XGM2019} - N_1 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (4.1)$$

$$X_2 = N_{XGM2019} - N_2 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (4.2)$$

$$X_3 = N_{XGM2019} - N_3 \qquad (4.3)$$

$$X_4 = N_{XGM2019} - N_4 \qquad (4.4)$$

$$X_5 = N_{XGM2019} - N_5 \qquad (4.5)$$

$$X_6 = N_{XGM2019} - N_6 \qquad (4.6)$$

$$X_7 = N_{XGM2019} - N_7 \qquad (4.7)$$

$$X_8 = N_{XGM2019} - N_8 \qquad (4.8)$$

$$X_9 = N_{XGM2019} - N_9 \qquad (4.9)$$

Second, the marine geoid was validated using EGM08 model and the results are presented in Table 4.4

Table 4.5 Marine Geoid as validated using EGM08

E1 (m)	**E2 (m)**	**E3 (m)**	**E4 (m)**	**E5 (m)**	**E6 (m)**	**E7 (m)**	**E8 (m)**	**E9 (m)**
-0.528	-1.077	-0.203	-0.528	-1.035	-0.203	-1.175	-0.883	-0.204
-0.544	-1.088	-0.229	-0.544	-1.041	-0.229	-1.141	-0.888	-0.230
-0.559	-1.097	-0.247	-0.559	-1.048	-0.247	-1.103	-0.902	-0.248
-0.574	-1.103	-0.256	-0.574	-1.056	-0.256	-1.063	-0.927	-0.257
-0.588	-1.103	-0.262	-0.588	-1.065	-0.262	-1.023	-0.958	-0.263
-0.603	-1.105	-0.263	-0.603	-1.074	-0.263	-0.983	-0.997	-0.264
-0.617	-1.102	-0.254	-0.617	-1.078	-0.254	-0.946	-1.033	-0.256
-0.632	-1.096	-0.239	-0.632	-1.079	-0.239	-0.912	-1.061	-0.241
-0.647	-1.092	-0.235	-0.647	-1.080	-0.235	-0.882	-1.082	-0.238
-0.659	-1.083	-0.262	-0.660	-1.075	-0.263	-0.857	-1.084	-0.265
-0.669	-1.077	-0.323	-0.669	-1.069	-0.323	-0.837	-1.082	-0.326

Then the statistical results of the validation of marine geoid using EGM08 model, the results are presented in Table 4.6.

Table 4.6 Statistics of Marine geoid as validated using EGM08

Model EGM2008	Number of values	Minimum	Maximum	Mean (m)	Standard Deviation (m)	Root Mean Square RMS(m)
E1	50004	-7.817	-0.418	-1.602	0.356	1.641
E2	34610	-1.491	-0.260	-1.026	0.082	1.030
E3	12394	-7.594	0.345	-0.878	0.395	0.963
E4	48411	-2.300	-0.419	-1.602	0.347	1.639
E5	28446	-6.252	4.207	-0.747	0.742	1.053
E6	12391	-7.594	0.344	-0.879	0.376	0.956
E7	47473	-9.815	4.471	-1.652	0.298	1.667
E8	28339	-6.116	2.118	-0.750	0.742	1.055
E9	12392	-7.586	0.351	-0.887	0.366	0.959

Where;

$$E_1 = N_{EGM08} - N_1 \quad (4.10)$$

$$E_2 = N_{EGM08} - N_2 \quad (4.11)$$

$$E_3 = N_{EGM08} - N_3 \quad (4.12)$$

$$E_4 = N_{EGM08} - N_4 \quad (4.13)$$

$$E_5 = N_{EGM08} - N_5 \quad (4.14)$$

$$E_6 = N_{EGM08} - N_6 \quad (4.15)$$

$$E_7 = N_{EGM08} - N_7 \quad (4.16)$$

$$E_8 = N_{EGM08} - N_8 \quad (4.17)$$

$$E_9 = N_{EGM08} - N_9 \quad (4.18)$$

Third, the marine geoid was validated using SGG-UGM-2 model and results are presented in Table 4.7

Table 4.7 Marine Geoid as validated using SGG-UGM-2

S1 (m)	S2 (m)	S3 (m)	S4 (m)	S5 (m)	S6 (m)	S7 (m)	S8 (m)	S9 (m)
-0.714	-1.048	-0.412	-0.714	-1.025	-0.412	-1.115	-0.855	-0.413
-0.721	-1.061	-0.421	-0.721	-1.035	-0.421	-1.079	-0.860	-0.421
-0.726	-1.070	-0.421	-0.726	-1.043	-0.421	-1.039	-0.875	-0.422
-0.731	-1.075	-0.412	-0.731	-1.054	-0.412	-0.998	-0.899	-0.413
-0.735	-1.076	-0.401	-0.735	-1.065	-0.401	-0.956	-0.932	-0.402
-0.739	-1.078	-0.385	-0.739	-1.076	-0.385	-0.915	-0.971	-0.386
-0.743	-1.077	-0.360	-0.744	-1.082	-0.360	-0.876	-1.001	-0.362
-0.749	-1.074	-0.328	-0.748	-1.084	-0.328	-0.841	-1.039	-0.331
-0.753	-1.074	-0.308	-0.753	-1.090	-0.309	-0.810	-1.065	-0.312
-0.756	-1.072	-0.322	-0.756	-1.090	-0.322	-0.784	-1.073	-0.325
-0.756	-1.072	-0.368	-0.756	-1.093	-0.368	-0.762	-1.078	-0.371

Then the statistics results of validation of the marine geoid using SGG-UGM-2 model are presented in Table 4.8

Table 4.8 Statistics of Marine geoid as validated using SGG-UGM-2

Models SGG-UGM-2	Number of values	Minimum	Maximum	Mean (m)	Standard Deviation (m)	Root Mean Square RMS(m)
S1	44400	-2.277	-0.447	-1.621	0.336	1.655
S2	29399	-1.406	-0.322	-1.038	0.058	1.040
S3	12810	-1.562	0.211	-0.891	0.337	0.953
S4	44400	-2.271	-0.453	-1.621	0.335	1.656
S5	26132	-1.271	4.133	-1.022	0.080	1.026
S6	12810	-1.555	0.206	-0.893	0.335	0.953
S7	23673	-4.507	-0.146	-1.717	0.252	1.735
S8	26085	-1.221	-0.820	-1.028	0.054	1.029
S9	12392	-1.522	0.202	-0.899	0.334	0.959

Where;

$$S_1 = N_{SGG-UGM-2} - N_1 \ldots\ldots (4.19)$$

$$S_2 = N_{SGG-UGM-2} - N_2 \ldots\ldots (4.20)$$

$$S_3 = N_{SGG-UGM-2} - N_3 \ldots\ldots (4.21)$$

$$S_4 = N_{SGG-UGM-2} - N_4 \ldots\ldots (4.22)$$

$$S_5 = N_{SGG-UGM-2} - N_5 \ldots\ldots (4.23)$$

$$S_6 = N_{SGG-UGM-2} - N_6 \ldots\ldots (4.24)$$

$$S_7 = N_{SGG-UGM-2} - N_7 \ldots\ldots (4.25)$$

$$S_8 = N_{SGG-UGM-2} - N_8 \ldots\ldots (4.26)$$

$$S_9 = N_{SGG-UGM-2} - N_9 \ldots\ldots (4.27)$$

Fourth, the marine geoid was validated using AFRgeo2019 model and results are presented in Table 4.9.

Table 4.9 Marine Geoid as validated using AFRgeo2019

A1 (m)	**A2 (m)**	**A3 (m)**	**A4(m)**	**A5 (m)**	**A6 (m)**	**A7 (m)**	**A8 (m)**	**A9 (m)**
-1.114	-0.466	0.294	-0.018	-0.425	0.294	-0.161	-0.273	0.293
0.006	-0.484	0.285	-0.023	-0.436	0.285	-0.223	-0.284	0.284
0.001	-0.493	0.274	-0.028	-0.443	0.275	-0.196	-0.298	0.273
-0.005	-0.494	0.267	-0.035	-0.448	0.2667	-0.167	-0.318	0.266
-0.012	-0.488	0.265	-0.042	-0.450	0.265	-0.137	-0.343	0.265
-0.019	-0.482	0.268	-0.047	-0.451	0.2681	-0.108	-0.374	0.267
-0.025	-0.471	0.278	-0.050	-0.447	0.278	-0.080	-0.403	0.275
-0.030	-0.456	0.293	-0.053	-0.441	0.293	-0.053	-0.422	0.291
-0.034	-0.444	0.278	-0.055	-0.433	0.278	-0.032	-0.434	0.276
-0.037	-0.425	0.231	-0.054	-0.416	0.231	-0.014	-0.426	0.228
-0.036	-0.403	0.192	-0.052	-0.395	0.192	0.014	-0.408	0.188

The statistical results of validation of the marine geoid using AFRgeo2019 model are presented in Table 4.10.

Table 4.10 Statistics of Marine geoid as validated using AFRgeo2019

Model AFRgeo2019	Number of values	Minimum	Maximum	Mean (m)	Standard Deviation (m)	Root Mean Square RMS(m)
A1	50699	-2.006	0.311	-1.124	0.523	1.242
A2	35251	-1.192	0.385	-0.630	0.318	0.705
A3	19100	-2.149	1.025	-0.551	0.543	0.773
A4	50699	-1.951	0.253	-1.111	0.531	1.232
A5	30912	-1.245	0.396	-0.653	0.316	0.725
A6	19000	-2.154	1.008	-0.546	0.537	0.766
A7	48173	-1.994	0.278	-1.688	0.494	1.269
A8	30811	-1.200	4.300	-0.654	0.331	0.733
A9	19062	-2.154	1.039	-0.555	0.539	0.773

Where;

$$A_1 = N_{AFRgeo2019} - N_1 \quad (4.28)$$

$$A_2 = N_{AFRgeo2019} - N_2 \quad (4.29)$$

$$A_3 = N_{AFRgeo2019} - N_3 \quad (4.30)$$

$$A_4 = N_{AFRgeo2019} - N_4 \quad (4.31)$$

$$A_5 = N_{AFRgeo2019} - N_5 \quad (4.32)$$

$$A_6 = N_{AFRgeo2019} - N_6 \quad (4.33)$$

$$A_7 = N_{AFRgeo2019} - N_7 \quad (4.34)$$

$$A_8 = N_{AFRgeo2019} - N_8 \quad (4.35)$$

$$A_9 = N_{AFRgeo2019} - N_9 \quad (4.36)$$

Lastly, the marine geoid was validated using TZG19 model and the results are presented in Table 4.11.

Table 4.11 Marine Geoid as validated using TZG19

T1 (m)	T2 (m)	T3 (m)	T4 (m)	T5 (m)	T6 (m)	T7 (m)	T8 (m)	T9 (m)
-0.139	-0.399	0.158	-0.139	-0.357	0.159	-0.307	-0.205	0.157
-0.144	-0.388	0.167	-0.144	-0.341	0.167	-0.266	-0.188	0.166
-0.148	-0.367	0.182	-0.148	-0.317	0.182	-0.221	-0.173	0.181
-0.153	-0.346	0.205	-0.153	-0.300	0.205	-0.175	-0.170	0.204
-0.158	-0.317	0.223	-0.157	-0.279	0.223	-0.134	-0.172	0.222
-0.159	-0.294	0.256	-0.159	-0.263	0.256	-0.097	-0.186	0.255
-0.161	-0.274	0.303	-0.161	-0.250	0.303	-0.063	-0.205	0.301
-0.171	-0.255	0.349	-0.171	-0.239	0.349	-0.033	-0.220	0.346
-0.176	-0.240	0.385	-0.176	-0.228	0.385	-0.008	-0.230	0.382
-0.18	-0.241	0.367	-0.177	-0.232	0.367	0.015	-0.241	0.365
-0.176	-0.239	0.324	-0.176	-0.233	0.324	0.036	-0.245	0.321

The statistics results of validation of the marine geoid using TZG19 model are presented in Table 4.12.

Table 4.12 Statistics of Marine geoid as validated using TZG19

Model TZG19	Number of values	Minimum	Maximum	Mean (m)	Standard Deviation (m)	Root Mean Square RMS(m)
T1	50820	-1.403	0.349	-0.870	0.340	0.934
T2	34046	-0.685	0.424	-0.283	0.063	0.289
T3	12749	-0.708	1.136	-0.153	0.354	0.386
T4	50820	-1.412	0.348	-0.872	0.339	0.935
T5	30420	-0.727	0.440	-0.283	0.070	0.292
T6	12749	-0.722	1.135	-0.155	0.353	0.385
T7	35686	-1.246	0.176	-0.978	0.216	1.002
T8	30306	-0.570	3.588	-0.284	0.063	0.291
T9	12749	-0.634	1.142	-0.161	0.353	0.388

Where;

$$T_1 = N_{TZG19} - N_1 \qquad (4.37)$$

$$T_2 = N_{TZG19} - N_2 \qquad (4.38)$$

$$T_3 = N_{TZG19} - N_3 \qquad (4.39)$$

$$T_4 = N_{TZG19} - N_4 \qquad (4.40)$$

$$T_5 = N_{TZG19} - N_5 \qquad (4.41)$$

$$T_6 = N_{TZG19} - N_6 \qquad (4.42)$$

$$T_7 = N_{TZG19} - N_7 \qquad (4.43)$$

$$T_8 = N_{TZG19} - N_8 \qquad (4.44)$$

$$T_9 = N_{TZG19} - N_9 \qquad (4.45)$$

4.2 Discussion of the Results

From the assessment the results showed that there are marine geoid models which are the closest to each other. The validation of these marine geoid models against assessment agents were done from 0°S to 12°S latitudes and 39°E to 42°E longitudes of Indian ocean in Tanzania. From Table 4.12 the result showed that the marine geoid model from the combination of DTU15MSS and MDT_CNES_CLS18 is the best to be used as marine geoid model because is close to TZG19 and also the marine geoid from combination of DTU18MSS and MDT_CNES_CLS18 and DTU21MSS and MDT_CNES_CLS18 are close to each other, together with the DTU15MSS and DTU19MDT, DTU18MSS and DTU19MDT and DTU21MSS and DTU19MDT are close to each other too.

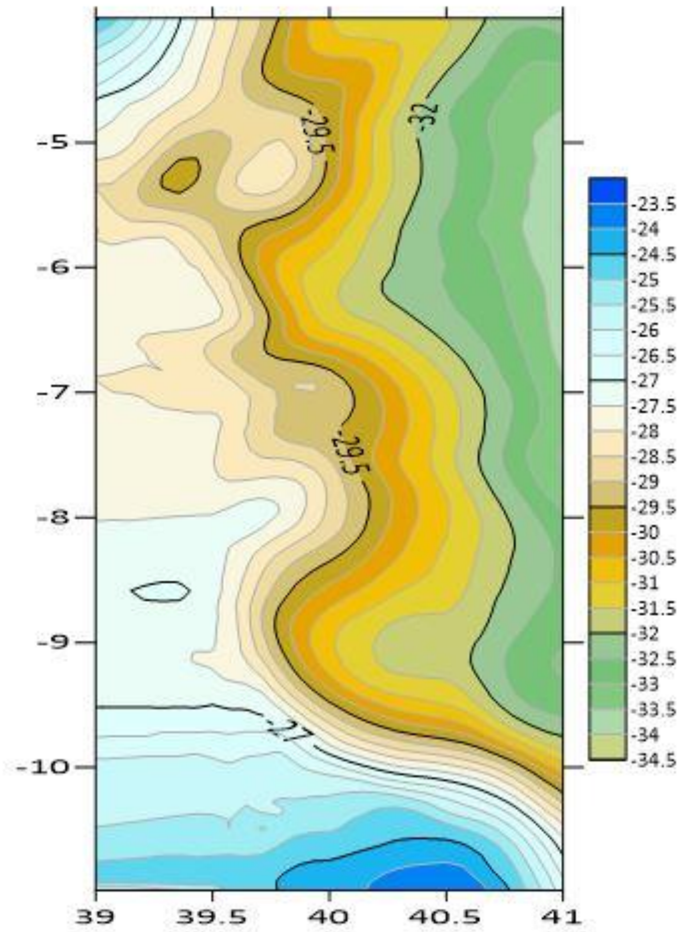

Figure 4.1 Marine Geoid from combination between DTU15MSS and MDT_CNES_CLS18

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CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study is intended to assess the last seven years of marine geoid models from MSSH and MDT models from Satellite Altimetry using XGM2019e_5540, SGG-UGM-2, EGM08, AFRgeo2019, and TZG19.

Based on the Statistical results shown in Table 4.12, it can be concluded that the marine geoid computed from DTU15MSS and MDT_CNES_CLS18 is the best marine geoid that fit the Tanzania Indian Ocean because it has the smallest root mean square of 0.289 m and a standard deviation of 0.063m as assessed with TZG19. Therefore, marine geoid models can be used for all purposes that require reliable marine geoid models, such as the computation of mean dynamic topography for weather prediction in a specific area.

Therefore, as the results show for the last seven years, marine geoid models computed from MSSH and MDT models are improved. As shown, the marine geoids computed from DTU15MSS and DTU19MDT, DTU18MSS and DTU19MDT, and DTU21MSS and DTU19MDT are good marine geoids because they are close to each other, as are the ones computed from DTU18MSS and MDT_CNES_CLS18 and from DTU21MSS and MDT_CNES_CLS18, which are close to each other too. Therefore, due to this trend, the marine geoid computed from MSSH and MDT models for the last seven years' has improved.

5.2 Recommendation

Based on the results and conclusion presented in this study the following are recommendation are suggested;

i. Next researcher is recommended to re compute the marine geoid models by using other technique such as shipborne and airborne laser collected data and assess them with the currently GGMs such as XGM2019e_5540 and geoid model such as EGM2020.
ii. To determine marine geoid model from MSSH and MDT models obtained from other sources of data apart from Aviso and DTU and assess them with TZG19 to check how they best fit Tanzania in ocean parts.

References

Abd-Elmotaal, H. A., Norbert, K., Kurt, S., & Bernhard, H. (2020). A Precise Geoid Model for AFRgeo2019. *The Next Century in Geodesy*. doi:org/10.1007/1345_2020_122

Andersen , O. B., Rose, K. S., Per Knudsen, & Lars, S. (2018). "The DTU18MSS Mean Sea Surface improvement from SAR altimetry". *(Technical University of Denmark)*. doi:10.1029/2018JC005179

Andersen, O. B., Per Knudsen, Lars, S., & Piccion, G. (2016). 'The DTU15MSS (Mean Sea Surface) and DTU15LAT(Lowest Astronomical Tide) reference surface". *(National Space Institute)*. doi:10.1029/2015JC005287

Bucha, B., & Janak, J. (2013). A MATLAB based graphical user interface program for computing functionals of the geopotential upto ultra high degree and order. *Computers and Geosciences*, 186-196.

Hofmann-Wellenhof, B., & Moritz, H. (2005). *Physical Geodesy. Technische Universitat Graz.* Graz,Austria: Springer Science & Business Media. doi:ISBN 978-3-211274-67-5

Kasala, E. (2016). *Marine Geoid on the Eastern Coastal of Tanzania from MSS and MDT and its evaluation by TZG13.* A Dissertation for Bsc. in Geomatics, Ardhi University, Department of Geospatial Sciences and Technology, Dar es Salaam. Retrieved 2016

Liang, W., Li, J., Xu, X., Zhang, S., & Zhao, Y. (2020). A High -Resolution Earth's Gravity Field Model SGG-UGM-2 From GOCE,GRACE,Satellite Altimetry and EGM2008. *Geodesy and Survey Engineering - Artcle*.

Limpach, P. (2010). *Sea Surface Topography and Marine Geoid by AIrborne Laser Alimetry and Shipborne Ultrasound Altimetry*. (Vol. vol 80). Zurich, Switzerland: Institute of Geodesy and Photogrametry. ISBN 978-3-908440-24-6

Liu, L., Xiaoguang, J., Shanwei, L., Lei, Z., Jinxia, Z., Xuehua, Z., & Longfei, L. (2016). Calculating The Marine Gravity Anomaly of the South China Sea based on the Inverse Stokes Formula. *Earth and Environment Science*, 46.

Meela, C. S. (2018). *Assessment of The Best Marine Geoid Model from Different global MSSH and MDT Using TZG17.* A Dissertation for Bsc. in Geomatics, Ardhi University, Department of Geospatial Sciences and Technology, Dar es Salaam. Retrieved 2018

Peter, R. (2018). *Tanzania Gravimetric Geoid Model TZG17 Through Quasi-Geoid by KTH Method.* MSc Thesis, Ardhi University, Department of Geospatial Science and Technology, Dar es salaam. Retrieved 2018

Shija, J. K. (2017). *Optimal Marine Geoid from combination of different MSS and MDT Models.A Bsc Dissertation of the department of Geospatial Sciences and Technology.* Dar es Salaam: Ardhi University.

Smith, W. H. (2010). The Marine Geoid and Satellite Altimetry. *Laboratory for Satellite Altimetry , National oceanic and Atmospheric Administration*, 217-231. doi:10.1007/978-90-481-8681-5_11

Tapley, B., Bettadpur, S., Watkins, M., & Reigber, C. (2004). The Gravity Recovery And Climate Experiment:Mission overview and early results. *Geophysical Research Letters*, 31(9).

Ulotu, P. (2009). *Geoid Model of Tanzania from Sparse and varying gravity data density by KTH method. Doctoral Thesis in Geodesy,* . Royal Institute of Technology (KTH), Division of Geodesy,School of Architecture and Built Environment., Stockholm, Sweden.

Vergo , G. V. (2002). (D. o. Surveying, Ed.) *"Optimal Marine Geoid Determination in the Atlantic Coastal Region og Argentina".*

Zingerle, P., Pail, R., Gruber, T., & Oikonomidou, X. (2020). The Combined global gravity field model XGM2019e. *Journal of Geodesy*. From https://doi.org/10.1007/s00190-020-01398-0