**ARDHI UNIVERSITY**

# COMPUTATION OF 1'×1' RESIDUAL TERRAIN EFFECT OF THE OCEAN AREA OF TANZANIA USING SRTM15PLUS DATA AND IT'S ASSESSMENT.

**NYARADANI GABRIEL GEOPHREY**

**BSc Geomatics**

**Dissertation**

**Ardhi University, Dar es Salaam**

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NYARADANI GABRIEL GEOPHREY

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 the acceptance by Ardhi University, a dissertation titled "**Computation of $1' \times 1'$ residual terrain effect of the Ocean area of Tanzania using SRTM15plus data and it's assessment**" partial fulfillment of the requirements for the award of Bachelor of Science in Geomatics of the Ardhi University.

…………………………………………………

Ms. Regina V. Peter

(Supervisor)

Date……………………………….

# DECLARATION AND COPYRIGHT

I, NYARADANI GABRIEL GEOPHREY, hereby declare that, the contents of this dissertation are the results of my own findings through my study and investigation, and to the best of my knowledge they have not been presented anywhere else as a dissertation for diploma, degree or any similar academic award in any institution of higher learning.

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**NYARADANI GABRIEL GEOPHREY**

22781/T.2019

(Candidate)

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Above all, I express my gratitude to the divine presence in my life, My Heavenly Father, for the boundless affection and plentiful blessings bestowed upon me. I am profoundly thankful for the unwavering love and abundant favor that have graced my journey, particularly throughout my academic pursuits and, above all, in this particular research endeavor. The merciful guidance I have received has been a constant source of enlightenment and direction.

Secondly, I extend my heartfelt appreciation to my dear parents and cherished family for their unwavering love, constant support, and unwavering commitment to my education. Their unquenchable desire to nurture my intellectual growth and witness the very best in both my academic pursuits and life as a whole fills me with profound gratitude. Their provision and guidance have been invaluable, fueling my aspirations and enabling me to strive for excellence.

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heartfelt appreciation. Their presence has been a source of strength and encouragement, and I am deeply grateful for their contributions. May God bless them abundantly, guiding them towards success in all their future endeavors.

# DEDICATION

*I wholeheartedly dedicate this dissertation to my dear parents, Geophrey Nyaradani and Hosiana Sheunei, as well as to my beloved brother, Isacck Nyaradani, and my cherished sisters, Sabitina Nyaradani and Catherine Nyaradani. Their unwavering encouragement, heartfelt prayers, boundless love, infinite patience, unwavering support, and nurturing care have been invaluable throughout my academic journey. I am genuinely grateful for everything they have done for me. My love for them knows no bounds, and I pray that God blesses them abundantly in all aspects of their lives.*

# ABSTRACT

The Earth's gravity field and its response to density variations in oceanic regions are essential aspects of physical geodesy. The Indian Ocean, with its notable density disparities between water and rock in the ocean bed, offers a unique opportunity to study gravitational reactions. However, assessing the Residual Terrain Effect (RTE) in oceanic areas poses challenges due to limited access to precise gravity data and the absence of a bathymetry grid in most digital elevation models (DEM). Fortunately, the SRTM15plus dataset includes bathymetry grid information, enabling the computation of RTE while considering density variations of water masses above the oceanic crust. This research aims to compute the RTE in the ocean area of Tanzania by incorporating water mass density variations using the SRTM15plus dataset and TGF software. The computed RTE values, accompanied by a comprehensive set of statistical measures, including mean, STD,RMS, minimum, and maximum values, were found to be 1.155 mGal, 0.364 mGal, 1.211 mGal, -19.134 mGal, and 3.330 mGal, respectively.

To validate the computed RTE, a substantial dataset of 15,112 aerial gravity data within the area of interest was utilized. Statistical analysis revealed a consistent bias between the computed RTE and actual aerial gravity RTE, with a mean difference of 2.990 mGal. The spread of differences around the bias was represented by the STD of 4.025 mGal, while the RMS value of 5.011 mGal highlighted the overall scatter between the computed and actual values. The minimum and maximum differences of -19.316 mGal and 12.040 mGal, respectively, further emphasized the significant range of variations encountered in the comparison. While the computed RTE values provide valuable insights into the gravity field in the ocean area of Tanzania, it is crucial to acknowledge the systematic biases and variations identified during the assessment. These discrepancies should be considered when interpreting results for geological modeling, resource exploration, or any application relying on precise gravity data. By employing the RTE technique in the R-C-R approach, this research has demonstrated the potential to densify gravity measurements and obtain a more comprehensive dataset with broader applications in geodetic and geomatics studies. Overall, this study contributes significant groundwork for future gravity-related investigations in the ocean area of Tanzania and underscores the importance of conducting comprehensive validations to enhance the credibility and reliability of computed RTE values. Understanding and addressing these discrepancies will facilitate advancements in gravity-related

research, leading to improved comprehension of the geological and geophysical processes influencing the gravity field in the region.

**Keywords;** Computation, Residual terrain effect, Ocean area, Tanzania, SRTM15plus, Assessment

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| | |
|---|---|
| AOI | Area of Interest |
| DEM | Digital Elevation Model |
| DGST | Department of Geospatial Sciences and Technology |
| EGM96 | Earth Gravity Model 1996 |
| SEM | Spectral Enhancement Method |
| SRTM15plus | Shuttle Radar Topography Mission DBM at 15 arc seconds resolution |
| TC | Terrain Correction |
| RTE | Residual Terrain Effects |
| RTM | Residual Terrain Model |
| TGF | Terrain Gravity Field software |
| WGS84 | World Geodetic System 1984 |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the Study

Gravity is the force of attraction between two bodies in the universe. It is the force that pulls objects towards each other and is the reason that objects fall to the ground when dropped. The strength of the gravitational force between two objects depends on their mass and the distance between them. The most well-known example of gravity is the Earth's gravity, which is what keeps us and all other objects on the planet from floating away into space. The concept of gravity was first introduced by Sir Isaac Newton in his law of universal gravitation, which states that every point's mass attracts every other point's mass by a force acting along the line intersecting both points. Gravity can be estimated and understood by using forward gravity modeling which helps us to know the effect of gravity. Forward gravity modeling uses the principle of gravity to estimate the gravitational field and its effect on the Earth's surface and subsurface (NOAA, 2021)

Forward gravity modeling refers to the method used to predict gravity anomalies in a specific location based on a set of known variables. It involves using computer algorithms to simulate the gravity field and predict the gravitational pull in a given area (Tziavos & Sideris, 2013). This method takes into account the density, thickness, and distribution of subsurface rocks and minerals to calculate the gravitational effect they have on the surface. Forward gravity modeling takes into account the short wave component when simulating the Earth's gravitational field. The models used in forward gravity modeling take into account the elevation, slope, and curvature of the Earth's surface, which affects the distribution of gravity on the Earth's surface and subsurface. The short wave component is an important factor in forward gravity modeling because it affects the accuracy of the modeled gravity field. The short wave component of gravity refers to the short-wavelength variations in the gravitational field, which are caused by localized subsurface structures such as mountains, valleys, and subsurface structures. These short-wavelength variations are typically in the range of a few kilometers to a few tens of kilometers and are more difficult to measure and interpret compared to the longer wavelength variations in the gravitational field (Forsberg, 1981). The short-wave component of gravity is important because it provides information on the subsurface structure, which can be used to infer the presence of mineral deposits and other subsurface resources. The interpretation of the short wave component of gravity is often combined with other geophysical data, such as seismic or magnetic data, to obtain a more complete picture of the subsurface structure.

In forward gravity modeling, the short wave component of gravity is typically modeled using numerical methods, which involve the use of computer algorithms to simulate the gravity field and predict the gravitational pull in a given area. This approach allows for the consideration of complex subsurface structures, such as subsurface mineral deposits, and provides a powerful tool for exploring and developing subsurface resources. Short wave component of gravity is the component with high frequency and whose degree and order are greater or equal to 2190 (El-Ashquer et al, 2020) and are computed from an accurate representation of the earth's topography. The topographic and bathymetric masses both create a gravity signal that strongly dominates the short-wavelength band of the gravity spectrum. The contribution of topography and bathymetry to gravity quantities such as gravity anomalies, gravity disturbance, geoid height, deflection of the vertical and gravity gradient are mainly due to strong correlation of short-wavelength of gravity with them, that is topography and bathymetry (Tziavos & Sideris, 2013). Digital Terrain Model and bathymetry models of high-resolution and accuracy can be used in computation of mass effects in gravity field modeling by using the available gravity reduction methods such as $2^{nd}$ Helmet's condensation, Bouguer plate (planar and spherical), Residual Terrain Model (RTM), and isostatic models. Most residual terrain modeling technique is used in the computation of residual terrain effects which yields short wavelength components.

The residual terrain effect (RTE) is a significant factor affecting the accuracy of geodetic measurements. It is defined as the deviation of the geoid surface from the reference ellipsoid and is primarily caused by variations in the Earth's gravity field due to topographical features on land and in the ocean (Watanabe et al, 2000) . Gravity data in Tanzania is characterized by significant gaps, particularly in game reserves, national parks, and areas where hydrocarbon products or valuable minerals remain undiscovered. However, along the Indian Ocean's coastline, stretching 50-150 kilometers inland from Dar es Salaam to Mtwara, including Zanzibar and Mafia islands, the central railway line, Northern Tanzania (with emphasis on the Shinyanga and Mwanza regions), and Western Tanzania (specifically in the Rukwa and Mbeya regions along Tanganyika and Nyasa), abundant gravity data can be found (Ulotu, 2009).The prediction of gravity at various geographical locations plays a crucial role in highlighting variations in the underlying rock density from one area to another. This enables geoscientists to effectively locate areas with potential mineral prospects and conduct investigations on Earth's gravitational field. Over the years, significant progress has been made in computing the residual terrain effect in Tanzania's mainland. Several authors, such as (Peter, 2018), (Busega & Kimboi, 2018), (Layda, 2020), and (Bundala, 2023), have contributed to this development. However, it is worth noting that most of the residual terrain effect computation has been focused on the mainland due to the limited availability of digital elevation models containing elevation/depth data of the oceans. As a result, no one has managed to compute the residual terrain effect in the oceanic areas. Fortunately, with the availability of bathymetry grids in SRTM15plus, providing depth information, there is now an opportunity to compute the residual terrain effect in the ocean area of Tanzania.

The computation of residual terrain effect in the ocean region of Tanzania involved utilizing the height information derived from the comprehensive dataset of SRTM15plus. This dataset includes both the topography grid and the bathymetric grid. However, in this specific research, the focus was on employing the bathymetric grid from SRTM15plus to ensure accurate computation of the residual terrain effect within the ocean area. By leveraging the bathymetric grid, valuable insights into the shape and depth of the ocean floor are obtained, facilitating precise determination of the residual terrain effect. The computation of the residual terrain effect using TGF allows for its subtraction from aerial gravity data within the same area of interest. This subtraction enables a more precise depiction of the short wave component of gravity in the ocean area. SRTM15plus assumes a crucial role in the computation of the residual terrain effect in water bodies, including ocean areas. It provides valuable information regarding the shape and depth of the ocean floor, facilitating accurate computation.

## 1.2 Statement of the Problem

In ocean areas, the residual terrain effect is mainly caused by the changes in the density of the ocean, as the ocean is composed of saltwater with a specific density that varies with temperature, salinity, and pressure. This variability in ocean density can cause significant differences in the residual terrain effect, which must be accurately modeled to accurately compute the residual terrain effect. Additionally, the topography of the ocean floor can also impact the residual terrain effect, as variations in the depth and shape of the ocean floor can cause changes in the residual terrain effect. Therefore, this study aims to compute the residual terrain effect in the ocean area of Tanzania while accounting for the density variation.

## 1.3 Research Objectives

### 1.3.1 Main Objective

The main objective of this research is to compute the residual terrain effect of the ocean area of Tanzania by using TGF software while accounting for the density variation.

### 1.3.2 Specific Objectives

I. Assessing the Extremely Short Wavelength Gravity Component computed from the TGF Software in the Area of Interest using Aerial Gravity Data.

## 1.4 Significance of the Study

The significance of this study lies in its ability to model the short-wavelength components of the gravity field and terrain correction over the Tanzania ocean area. This modeling provides valuable insights for geodesists and geophysicists, as accurate interpretations are crucial for their applications. Specifically, the results of this study can aid geodesists in the determination of gravimetric geoids using the Remove-Compute-Restore approach, as well as refine Bouguer anomalies during complete Bouguer reduction. Moreover, this study contributes to quantifying the characteristics of terrain effects over the computation area, particularly the Tanzania ocean area, which is valuable information for future research and practical applications in geodesy and geophysics.

## 1.5 Research Hypothesis

The use of TGF software, can significantly improve the accuracy of residual terrain effect computation in ocean areas.

## 1.6 Benefits of the Study

I. The study can aid in addressing the issue of sparse gravity data in specific regions by filling in the gaps with more detailed and comprehensive data. This can lead to a more accurate understanding of the underlying geological features and processes.

II. Additionally, the improved gravity data can be used for gravity prediction, which is critical for a wide range of applications, including mineral exploration, oil and gas exploration, and environmental monitoring. With more accurate gravity predictions, researchers can better assess the potential for natural resource deposits, monitor changes in subsurface geology, and identify areas of environmental concern.

## 1.7 Scope and Limitations of Research

The study is limited to the ocean area of Tanzania found between -2°S to -13°S latitude and 38.5°E to 44.5°E longitude (as shown in Figure 1.1) from which the residual terrain effect will be computed. This research will use SRTM15plus data, and varying densities of water, and the software that will be used is TGF.

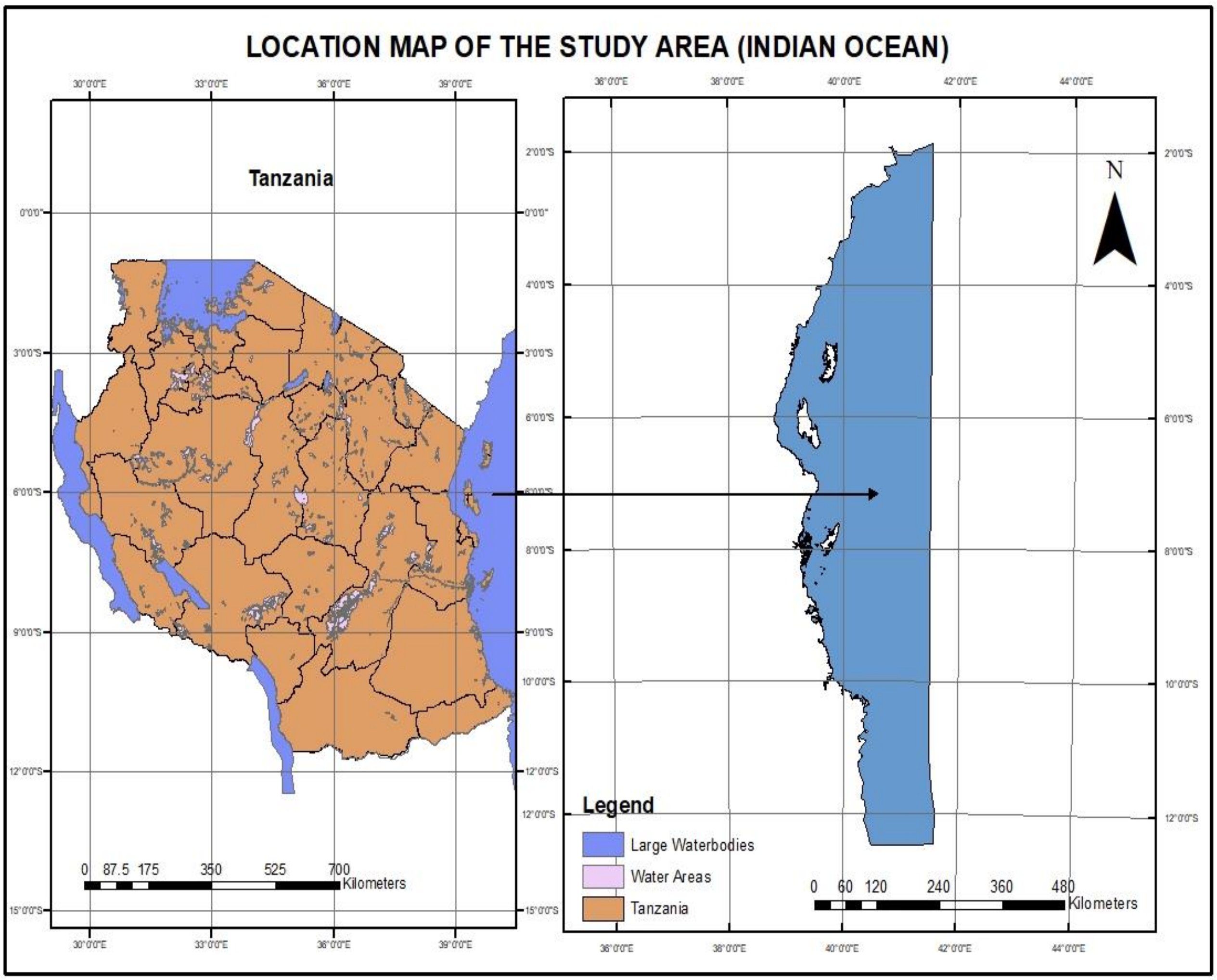


Figure 1.1: Location map of the study area

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Topographic Effect

In the field of gravity, the topographic effect refers to the influence of the Earth's topography on the measured gravity field. The topography of the Earth, which includes mountains, valleys, and other surface features, affects the distribution of mass in the Earth's crust, which in turn affects the strength and direction of the gravitational field at the Earth's surface. This effect is of particular importance in geodesy, which is the study of the Earth's shape, gravity field, and rotation (Kuhn & Featherstone, 2005). The topographic effect can be quantified using the Bouguer anomaly, which is defined as the difference between the observed gravity field and the gravity field that would be observed if the Earth's topography were removed. The Bouguer anomaly is calculated by subtracting the gravity contribution of the topography, which can be estimated using a digital elevation model (DEM), from the observed gravity field. One of the earliest studies on the topographic effect was conducted by Pierre Bouguer in the 18th century. Bouguer observed that the gravity field near the Andes Mountains in South America was weaker than what would be expected based on the mass of the mountains alone. This led him to hypothesize that the mass of the Earth's crust was not uniformly distributed and that the presence of the mountains was causing a reduction in the strength of the gravitational field (Bouguer, 1749). More recent studies have confirmed and refined Bouguer's findings. For example, the Gravity Recovery and Climate Experiment (GRACE) mission, which was launched in 2002, has provided high-precision measurements of the Earth's gravity field, including the topographic effect. The GRACE data have been used to study the mass balance of ice sheets, the dynamics of the Earth's mantle, and the distribution of groundwater resources. The topographic effect and the residual terrain effect can be understood in terms of the Bouguer plate model. The Bouguer plate model assumes that the Earth's crust is a thin, horizontal layer of uniform density that rests on a denser mantle. According to this model, the topographic effect can be calculated by assuming that the topography is a surface density anomaly that is added to the uniform density of the Earth's crust. However, in reality, the Earth's crust is not uniform in density, and the lateral variations in density beneath a topographic feature can cause additional gravity anomalies that contribute to the residual terrain effect.

### 2.1.1 Bouguer Plate.

The Bouguer plate is a model used to approximate the Earth's crust as a uniform, horizontal layer of constant density. The model was developed by Pierre Bouguer in the 18th century to explain the reduction in gravity observed near mountains and other topographic features. The Bouguer plate model is still widely used in geodesy and gravity field modeling today. In the Bouguer plate model, the Earth's crust is assumed to be a flat, horizontal plate of uniform density that extends infinitely in all directions. The model calculates the gravitational attraction between the Earth's crust and a point mass using the formula for the gravitational attraction between two parallel plates of infinite extent. The model can be used to calculate the gravity field at any point above the Earth's surface and is useful for studying the topographic effect on the gravity field. The Bouguer plate model is a simplification of the actual Earth, as the Earth's crust is not uniform in density, and its surface is not flat. However, the model is still useful because it provides a simple way to estimate the gravity field of the Earth's crust and quantify the topographic effect on the gravity field. The Bouguer plate model can be combined with other models, such as spherical harmonic expansions or finite element models, to improve the accuracy of gravity field modeling (Fosberg, 1984)

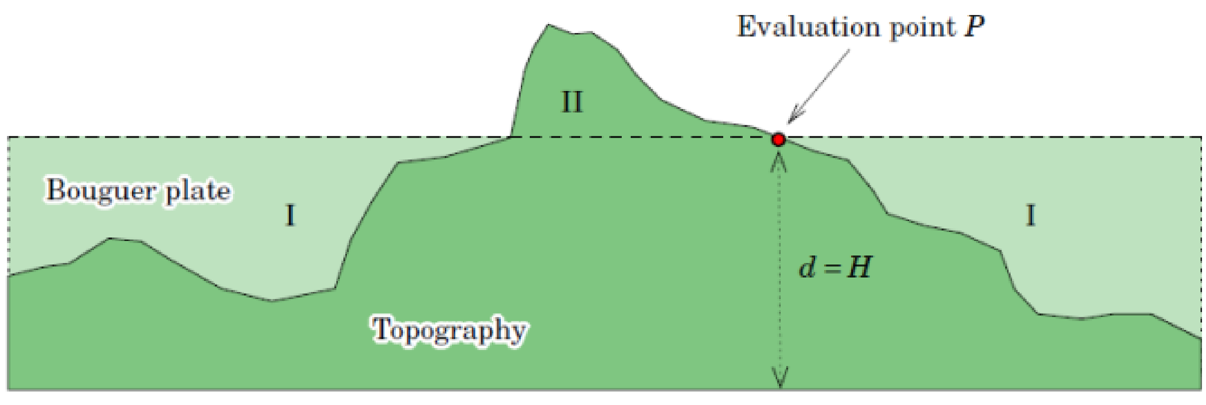


Figure 2.1: Bouguer plate as an approximation to the topography (Vermeer, 2018)

In the Bouguer reduction, all topographic points above the computation point are neglected and points below the computation point are overcompensated and the Bouguer reduction makes a systematic error (Vermeer, 2018).

In the ocean area, where the topography is dominated by the seafloor rather than land masses, the Bouguer plate model is also used to estimate the density distribution of the oceanic crust. The oceanic crust is generally thinner and denser than the continental crust, and its density distribution varies depending on factors such as age, spreading rate, and the presence of volcanic or hydrothermal activity. To estimate the density distribution of the oceanic crust, the Bouguer plate model is applied to gravity data collected by satellite altimetry and shipborne surveys. One of the challenges in applying the Bouguer plate model to the ocean area is that the water layer above the seafloor adds gravitational attraction that must be accounted for. This is done by using a modified version of the Bouguer plate formula, known as the Free-air anomaly formula, which subtracts the gravitational attraction of the water layer from the measured gravity field (Ravat et al, 2010).

The Free-air anomaly formula subtracts the gravitational attraction of the water layer from the measured gravity field to obtain a gravity anomaly that is due solely to the variations in the density of the seafloor. The formula is given by:

$$\Delta g_{fa} = \Delta g_{obs} - \gamma h \tag{2.1}$$

Where

$\Delta g_{fa}$ is the Free-air anomaly,

$\Delta g_{obs}$ is the observed gravity anomaly,

$\gamma$ is the gravitational acceleration, and

$h$ is the height of the water layer above the seafloor.

The Free-air anomaly formula assumes that the water layer is infinitely thin and that the density of the water is constant. These assumptions are generally valid for the ocean area, where the water layer is much thinner than the seafloor and the density of the water varies only slightly with depth. The Free-air anomaly formula is widely used in oceanography and geophysics to estimate the density structure of the oceanic crust. For example, a study by Sandwell and Smith (1997) used satellite altimetry data and the Free-air anomaly formula to estimate the density distribution of the seafloor in the Pacific Ocean. The study found that the seafloor density distribution was strongly influenced by the age and spreading rate of the seafloor. Another study by Brozena et al. (1996) used shipborne gravity data and the Free-air anomaly formula to investigate the density structure of the Juan de Fuca Ridge, a mid-ocean ridge located off the coast of western North America. The study found that the density of the seafloor increased with depth and was influenced by the presence of volcanic and hydrothermal activity.

### 2.1.2 Planar and Spherical Bouguer Effect

In the ocean area, the Bouguer plate model is used to estimate the density distribution of the oceanic crust, and the topographic effect is accounted for by using the Free-air anomaly formula. However, the Bouguer plate model assumes that the seafloor is a flat plate, which is not true for most of the oceanic crust. To account for the curvature of the Earth, two additional terms are added to the Bouguer plate formula, resulting in the planar and spherical Bouguer effect.

### 2.1.3 Planar Bouguer Effect

The planar Bouguer effect accounts for the curvature of the Earth assuming a flat seafloor. The formula for the planar Bouguer effect is given:

$$\Delta g_p = 2\pi G\rho h \tag{2.2}$$

Where

$\Delta g_p$ is the planar Bouguer anomaly,

$G$ is the gravitational constant,

$\rho$ is the density of the seafloor, and

$h$ is the height of the seafloor above a flat reference level

This formula assumes that the seafloor is a flat plate, and it is therefore only applicable to small areas with relatively flat seafloor topography.

### 2.1.4 Spherical Bouguer Effect

The spherical Bouguer effect, on the other hand, accounts for the curvature of the Earth and the curvature of the seafloor. The formula for the spherical Bouguer effect is given:

$$\Delta g_s = \frac{4}{3\pi G\rho R^2}\left(\frac{2}{3} - \frac{h}{R}\right) \tag{2.3}$$

Where

$\Delta g_s$ is the spherical Bouguer anomaly,

$R$ is the radius of the Earth, and

$h$ is the height of the seafloor above the geoid, which is a reference surface that approximates the mean sea level.

This formula is more accurate than the planar Bouguer formula and applies to larger areas with more complex seafloor topography.

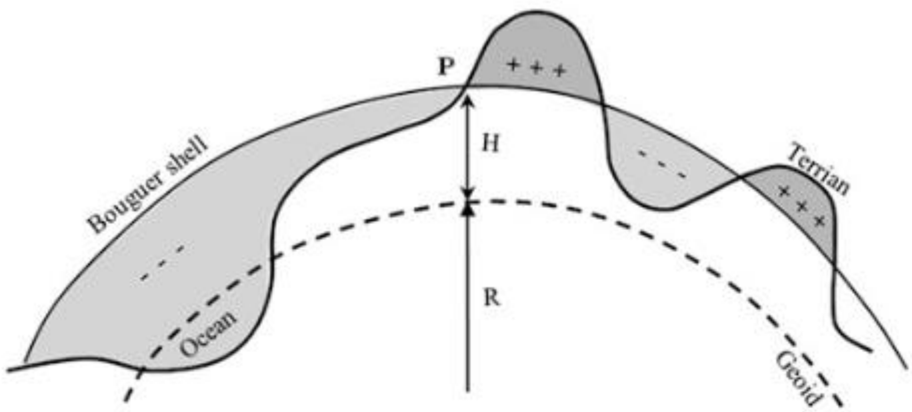


Figure 2.2: An approximation of how the Bouguer shell, ocean, terrain, and geoid physically exist

A study by Sandwell and Smith (2005) used satellite altimetry data and the spherical Bouguer formula to estimate the density structure of the oceanic crust. The study found that the seafloor density distribution was influenced by the spreading rate of the seafloor and by the presence of seamounts and other volcanic features. Another study by (Ravat et al, 2010) used shipborne gravity data and the planar Bouguer formula to investigate the gravity field of the Gulf of Mexico. The study found that the seafloor density distribution was influenced by the presence of salt domes and other sedimentary structures.

## 2.2 Residual Terrain Effect

The residual terrain effect (RTE) is a phenomenon in gravity measurements that arises due to variations in the topography of the Earth's surface. The RTE refers to the gravity signal that remains after the gravitational attraction of a homogeneous reference Earth model has been subtracted from the observed gravity data. This residual signal is caused by the density variations in the Earth's crust, which are influenced by the topography of the surface. The RTE can have a significant impact on gravity measurements, particularly in mountainous regions, where the topography varies greatly over short distances (Yahaya, 2018).

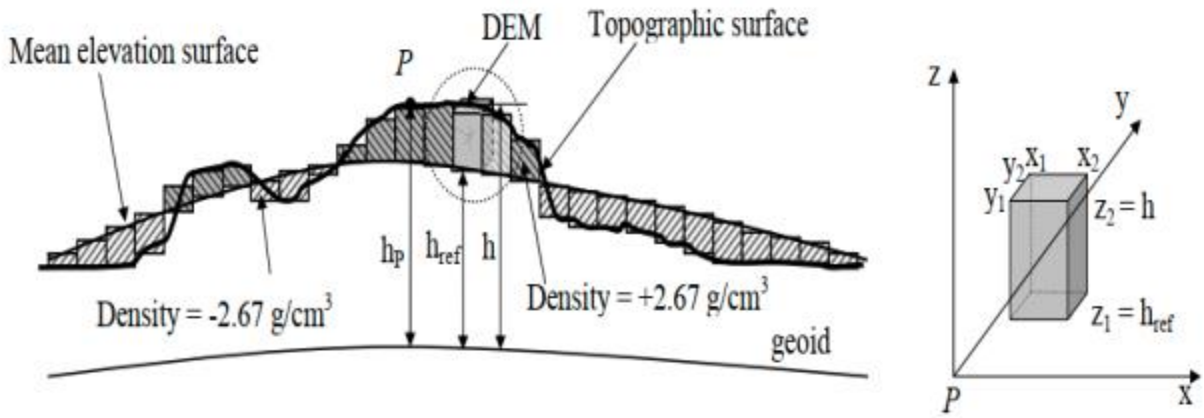


*Figure 2.3: Rectangular Prism for RTM (Dumrongchai, 2012)*

Several methods have been developed to account for the RTE and obtain accurate estimates of the Earth's gravity field. One such method is the Terrain-Enhanced Bouguer Anomaly (TEBA) technique, which was proposed by (Sampietro & Brovelli, 2009). The TEBA method involves the use of a Digital Elevation Model (DEM) to model the topography of the Earth's surface and to estimate the RTE. The TEBA method is effective in reducing the impact of the RTE on gravity measurements and improving the accuracy of gravity models. Another method for accounting for the RTE is the use of spectral methods, which involve the decomposition of the gravity signal into different frequency components. The low-frequency components of the gravity signal are attributed to the Earth's gravity field, while the high-frequency components are attributed to the RTE. The spectral methods are effective in separating the gravity signal from the RTE and improving the accuracy of gravity models (Tenzer *et al*, 2017).

### 2.2.1 Residual Terrain Model

A residual terrain model (RTM) is a mathematical model that predicts the residual gravity signal caused by the topographic and density variations of the Earth's crust. The RTM is an essential tool for studying the gravity field of the Earth's crust and for separating the gravity signal caused by the crustal density anomalies from other sources, such as the Earth's gravitational field and the topographic effect. The RTM is based on the principle of isostasy, which states that the Earth's crust floats on the denser mantle and that the topography of the Earth's surface is in equilibrium with the density structure of the underlying crust. The RTM predicts the gravity signal caused by the density variations of the crustal rocks, assuming a uniform density for the underlying mantle. One of the advantages of the RTM is that it can be used to separate the gravity signal caused by the density variations of the crustal rocks from the gravity signal caused by other sources such as the topography and the Earth's gravitational field. This is important for studying the Earth's crustal structure and for detecting mineral and hydrocarbon deposits.

The advantage of the RTM reduction is that the reduced gravity anomalies are mostly smoother than those following other reduction techniques. An extra advantage of the RTM reduction is that the quantity to be restored, in the restore step of the computation of height anomalies, is very small compared to the indirect effect on the geoid from other methods, and no assumption about isostatic compensation is needed as in the isostatic reductions. The disadvantage of the RTM method is that the gravity potential below the reference surface is not a harmonic function and therefore imposes a great theoretical problem in this method.

In the RTM approach, a smooth mean elevation surface also called the reference surface is chosen and the topographic masses above this 8 reference surface are removed and fill up the valleys below (Abulaitijiang, 2019).

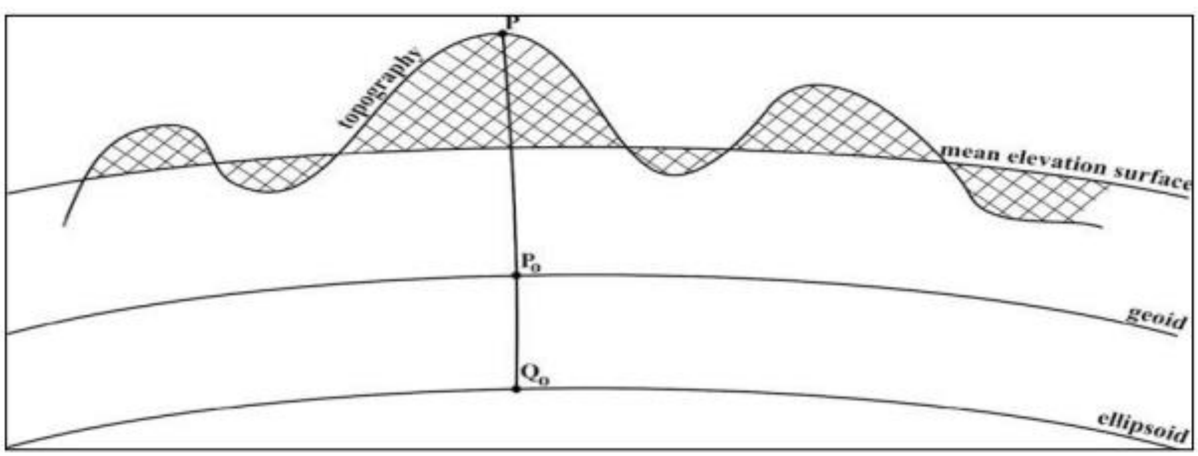


Figure 2.4: Residual Terrain Model (Sanso & Sideris, 2013)

The RTM technique relies on the assumption that the masses of the Earth's surface remain constant concerning their density. In this thesis, we will eliminate the short wavelengths from RTM and subsequently recover them through the Remove-Compute-Restore procedure. The direct topographical effect on gravity is given by the mathematical relation in the equation

$$\Delta g_T = 2\pi G\rho h_p - C_p \quad (2.4)$$

Where

$C_p$ Terrain correction

$G$ Newton's gravitational constant

$\rho$ Topographic density

$h_p$ Elevation at a point P

Then, due to the direct topographic effect the attraction change $\delta A_{RTE}$ can be obtained using equation

$$\delta A_{RTE} = G\rho \iint_{\_E} \int_{h_p}^{h} h_p - h/s^3 dxdydz \quad (2.5)$$

$h_p$ and $h$ are the height of the reference surface and topographic height respectively and $s$ is described

$$s = \sqrt{\left(x_p - x\right)^2} + \sqrt{\left(y_p - y\right)^2} + \sqrt{(h_p - h})\quad (2.6)$$

Using a rectangular prism for the computation of the direct residual terrain effect topographic effect at a computation point the following relationship can be used.

$$\delta A_{RTE} = G\rho \left|\left|\left| x\text{I}n(y+r) + y\text{I}n(x-r) - ztan^{-1}\frac{xy}{zr}\right|_{X_1}^{X_2}\right|_{Y_1}^{Y_2}\right|_{h_{ref}}^{h} \quad (2.7)$$

Where

x and y are horizontal coordinates, and z is the vertical coordinate (elevation in this case)

$\rho$ Is density

$G$ Is Newton's gravitation constant

$r$ Is the radial distance given by the equation

$$r = \sqrt{x^2 + y^2 + z^2} \tag{2.8}$$

### 2.2.2 Terrain Correction

Terrain correction is a method used in geophysics to account for the effect of the Earth's topography on gravity measurements. The Earth's topography, or terrain, can cause variations in the gravitational field due to the density differences in the underlying geological structures. These variations can be significant, and if not corrected for, can result in an inaccurate interpretation of the gravity data. The terrain correction involves calculating the gravity effect of the topography and subtracting it from the observed gravity data. The following equation is used in terrain correction computation at point P.

$$C_p = G\rho \iint_E \int_{h_p}^{h} \frac{h_p - h}{s^3\left(x_p - x, y_p - y, h_p - h\right)} dxdydz \tag{2.9}$$

Where,

$C_P$ Is the terrain correction

$s$ Is the distance between the running and computation point

$G$ Is Newton's gravitational constant

$E$ Is the integration area and the remaining symbols are defined as in the section

$h_p$ Is the height of the reference surface

$h$ Is the topographic height

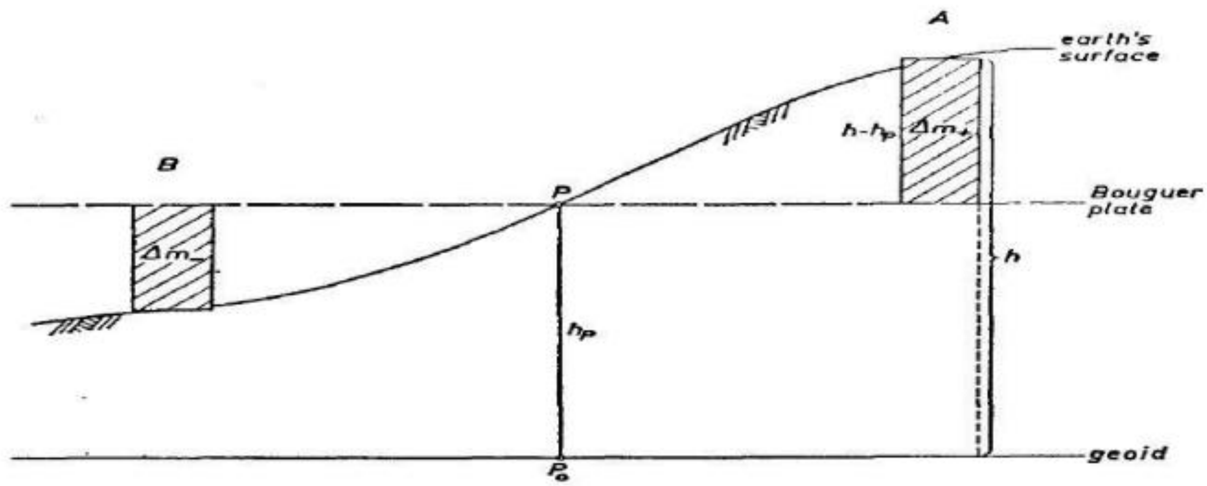


Figure 2.5: Terrain correction (Hieskanen & moritz, 1967)

In the ocean area, terrain correction is even more critical due to the presence of water, which has a different density than the Earth's crust. The density difference between water and rock can cause significant variations in the gravitational field, which must be corrected to obtain accurate gravity data. There are several methods for calculating the terrain correction, including the Bouguer correction, the free-air correction, and the topographic/isostatic correction.

The Bouguer correction was developed by Pierre Bouguer in the 18th century and is one of the oldest methods for terrain correction. The Bouguer correction assumes a constant density for the Earth's crust and subtracts the gravitational effect of a hypothetical infinite slab of material of equal thickness to the actual terrain. The Bouguer correction is still widely used in gravity surveys today, but it has limitations in areas with significant variations in crustal density or topography. The Bouguer correction in the ocean area involves subtracting the gravitational effect of the water column above the seafloor from the observed gravity data. The Bouguer correction assumes a constant density for the seawater and a constant thickness for the water column. However, the actual thickness of the water column can vary due to tides and currents, which can cause errors in the correction. The free-air correction is a modified version of the Bouguer correction that takes into account the additional gravitational attraction caused by the atmosphere. The free-air correction subtracts the gravitational effect of a hypothetical point mass located at the height of the observation point, assuming a constant atmospheric density. The free-air correction is less sensitive to variations in crustal density and topography compared to the Bouguer correction, but it can be affected by variations in atmospheric density. The free-air correction in the ocean area involves subtracting the gravitational effect of a hypothetical point mass located at the height of the observation point, assuming a constant density for the seawater and a constant atmospheric density. The free-air correction is less sensitive to variations in water depth and density compared to the Bouguer correction. The topographic/isostatic correction takes into account the actual topography and crustal density variations. The topographic/isostatic correction involves calculating the gravity effect of the topography using a digital elevation model (DEM) and subtracting it from the observed gravity data. The topographic/isostatic correction is the most accurate method for terrain correction, but it requires detailed information on the topography and crustal density variations (Bouguer, 1749).

In addition to the above corrections, a more accurate method for terrain correction in the ocean area is the use of a digital bathymetric model (DBM). The DBM takes into account the actual bathymetry and density variations of the seafloor, resulting in a more accurate terrain correction. The digital bathymetric model can be constructed using various data sources, such as satellite altimetry, ship-based sonar surveys, and gravity measurements. The accuracy of the model depends on the quality and resolution of the data used, and the interpolation and smoothing algorithms employed to generate the model.

## 2.3 TGF Software

TGF software is a new MATLAB-based program that has been developed to efficiently and accurately model the gravity field generated by an arbitrary topographic mass-density distribution. This software is based on the residual terrain modeling (RTM) technique that is widely used in geodesy and geophysics for determining high-frequency gravity field signals. One of the main challenges encountered in using an ultra-high-resolution digital elevation model (DEM) in Newtonian integration is computational efficiency. However, TGF software overcomes this challenge by using an adaptive algorithm that divides the integration masses into four zones and adaptively combines four types of geometries, namely polyhedron, prism, tesseroid, and point-mass, with different spatial resolutions. Moreover, TGF software allows users to calculate ten independent gravity field functions, supports two types of density inputs, namely constant density value and digital density map, and considers the curvature of the Earth by involving spherical approximation and ellipsoidal approximation. Additionally, it is capable of delivering the gravity field of full-scale topographic gravity field implied by masses between the Earth's surface and mean sea level (Yang, 2020)

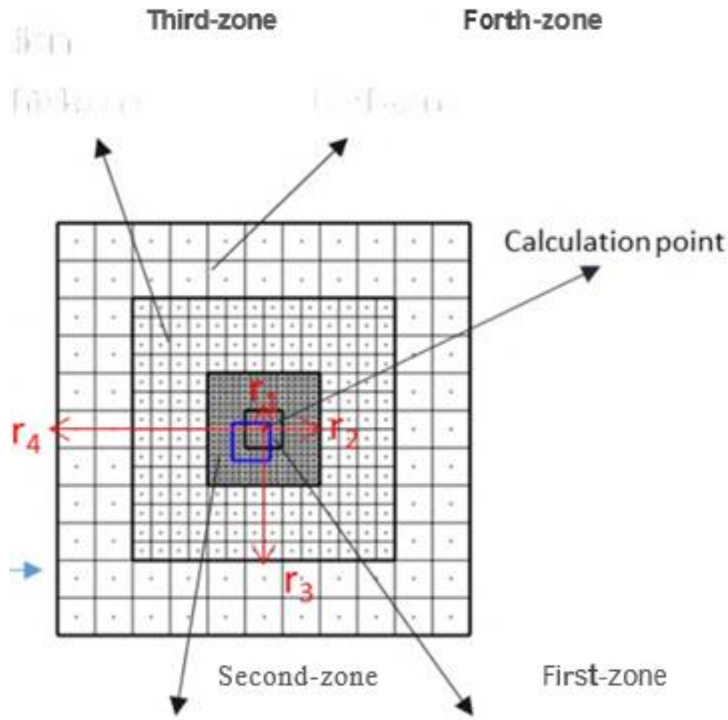


Figure 2.6: Distribution of zones about the computation point (Yang *et al*, 2020)

## 2.4 SRTM15plus

SRTM 15 Plus (Shuttle Radar Topography Mission 15 Plus) is a digital elevation model (DEM) dataset that provides detailed information about both the land surface topography and the seafloor bathymetry of the Earth. It is derived from the combination of NASA's Shuttle Radar Topography Mission (SRTM), elevation data, and additional bathymetric data sources. In the SRTM15Plus dataset, the horizontal datum used World Geodetic System 1984 (WGS84) and for the vertical datum, the SRTM15Plus dataset generally uses the EGM96 (Earth Gravitational Model 1996) geoid model. The dataset incorporates the SRTM15Plus, which is an enhanced version of the original SRTM dataset, with an improved spatial resolution of approximately 15 arc seconds. Each pixel in the dataset represents an area of approximately 15 arc seconds by 15 arc seconds on the Earth's surface. This higher resolution allows for more precise analysis and visualization of the Earth's topography, encompassing both land and ocean regions. The SRTM15Plus dataset combines the elevation data obtained from NASA's Shuttle Radar Topography Mission (SRTM) with additional bathymetric data sources. These sources include multibeam sonar measurements, satellite altimetry, and other marine geophysical surveys. By integrating these diverse data sources, the dataset provides a more complete representation of the Earth's surface, including its underwater features. The availability of both land topography and bathymetric information in a single dataset is valuable for a wide range of applications. It supports various scientific research endeavors, such as studying coastal processes, understanding oceanic features, and investigating tectonic activity. The dataset is also useful in marine navigation, coastal zone management, and the exploration and management of marine resources. The availability of a comprehensive dataset that integrates land topography and seafloor bathymetry at a high resolution contributes to a deeper understanding of the Earth's surface and enhances our ability to make informed decisions regarding various coastal and marine-related activities (Tazer & Sandwell, 2019).

## 2.5 LITHO 1.0 Global Crustal Density Model

The LITHO1.0 model represents a tessellated version of the Earth's crust and uppermost mantle, encompassing the lithospheric lid and the asthenosphere beneath it ( Pasyanos *et al*, 2014). It builds upon the CRUST1.0 model, incorporating additional types of newly accessible data. This model has been carefully parameterized both horizontally and vertically to facilitate geophysical computations on a spherical framework. The lateral parameterization utilizes a tessellation surface, while depth parameterization is achieved through layer thickness and associated parameters such as density (ibid). To ensure a more uniform sampling across the globe, the model adopts a lateral parameterization that employs a tessellated surface instead of a fixed latitude and longitude grid. This tessellation process involved constructing an initial regular polyhedron with 20 equilateral triangular faces, 30 edges, and 12 vertices that were approximately evenly spaced (ibid). Each triangle was then subdivided into four smaller triangles, progressively reducing the distance between nodes until the desired spacing was achieved. Through six subdivisions ($60^0 \rightarrow 30^0, 30^0 \rightarrow 15^0, 15^0 \rightarrow 8^0, 8^0 \rightarrow 4^0, 4^0 \rightarrow 2^0, 2^0 \rightarrow 1^0$ ), this process resulted in the creation of approximately 40,962 vertices and 81,920 triangles. In contrast, a regular grid based on latitude and longitude would yield a significantly higher number of points (64,800), but with closer sampling near the poles. The vertical parameterization of the model is structured into nine distinct sub-layers, each geographically identified. These sub-layers consist of (1) water, (2) ice, (3) upper sediments, (4) middle sediments, (5) lower sediments, (6) upper crust, (7) middle crust, (8) lower crust, and (9) lithospheric mantle (lid). Each layer possesses its own thickness and is characterized by associated parameters such as velocity ($V_P, V_S$ ), density, and seismic attenuation.

The model utilized CRUST1.0 bathymetry and topography data obtained from ETOPO1. The horizontal reference for the model is based on the WGS84 geographic datum, while the vertical reference is the sea level. To create the model, the topography, bathymetry, and ice thickness data from ETOPO1 were processed by grouping and averaging the information within 1-degree cells.

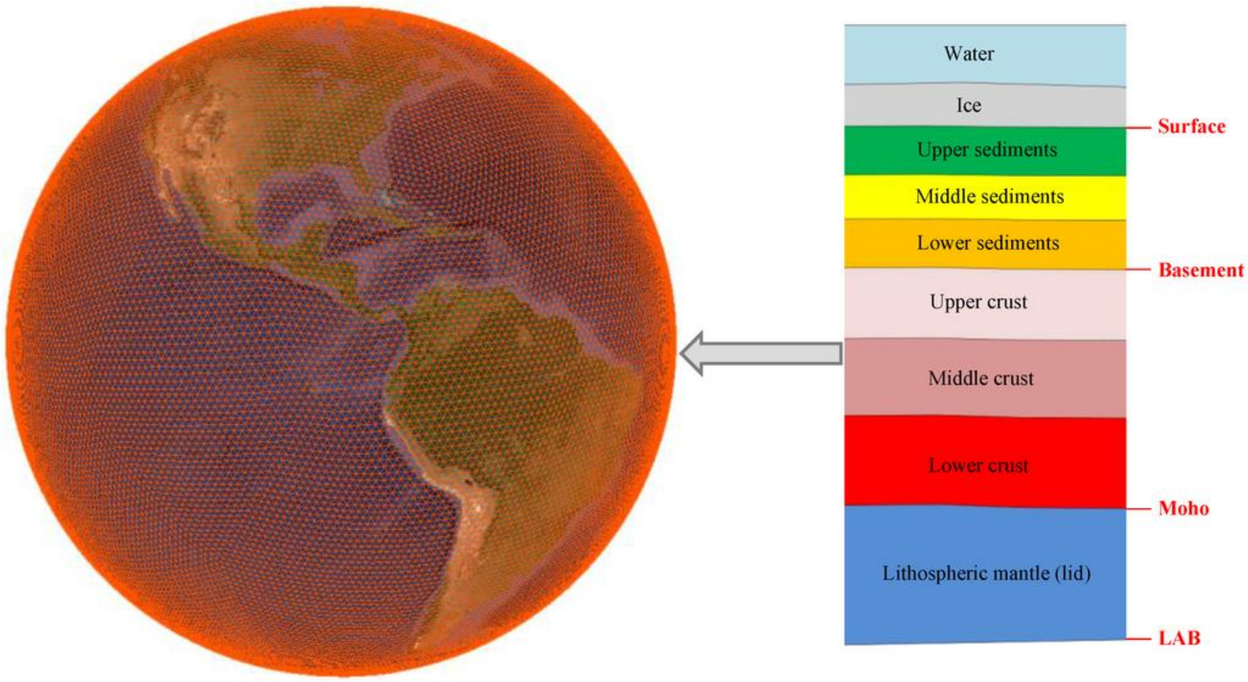


Figure 2.7: Lithospheric Structure representation implemented in the LITHO1.0 model

# CHAPTER THREE

# METHODOLOGY

In this chapter, a detailed explanation is presented for the approach used to calculate the Residual Terrain Effect (RTE) within the ocean region of Tanzania using SRTM15plus data. The evaluation of the RTE outcomes derived from this computation was discussed. The chapter offers a comprehensive overview of the methodology utilized to estimate the RTE and assess the resulting findings within the specified area of study.

## 3.1 Creation of a Regional Crustal Density Model

To develop a regional crustal density model for the area of interest (AOI) spanning from 4°N to 15°S latitude and 26°E to 44°E longitude, the following procedures were followed: Firstly, the global crustal density model (LITHO1.0) was extracted from its compressed format using WinRAR software. This extraction process resulted in two files: a README file containing instructions for accessing the data, and a LITHO1.0 directory containing two subdirectories named "progs" and "litho_model". The "progs" subdirectory houses C++ programming language programs designed to access the data stored in the "litho_model" subdirectory. Additionally, a "bin" subdirectory was created to store the executable files, complementing the existing subdirectories.

Next, the makefile located within the "progs" subdirectory was modified to ensure compatibility with the computer's working environment variables. Several key sections were edited, including:

1. BIN: The path to the previously created "bin" subdirectory was specified in order to set the appropriate location for storing compiled binaries.
2. CPP: The C++ compiler used for compiling the C++ codes was defined. In this particular case, the GNU G++ compiler was employed.
3. FLAGS: The directory path to the model file was established, ensuring that the necessary model information could be accessed during the compilation process.

Finally, $1^{o}$ x $1^{o}$ a grid of cells (nodes) was generated to cover the AOI, Subsequently, the density information was obtained for each grid cell by executing the "access_litho" program and inputting the latitude and longitude values specific to each cell. The extracted data for each cell was organized within Microsoft Excel software to facilitate convenient data processing.

Figure 3.1 presents an illustrative instance of density information obtained from a specific grid cell located at latitude -15°S and longitude 45°E. The extracted data includes compressional wave velocities $V_s$ and $V_{s2}$, shear wave velocities $Q_k$ and $Q_u$and seismic waves for the corresponding sublayers, as described by Pasyanos et al. (2014). Among the acquired data, the most pertinent information can be found in the first two columns, which provide the depth and density details of each respective sublayer.

gabriel_litho - Notepad

File Edit Format View Help

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 190091. | 3300.00 | 7899.27 | 4293.08 | 0.00 | 70.00 | 7899.27 | 4293.08 | 1.00000 | ASTHENO-TOP |
| 190091. | 3300.00 | 8060.48 | 4592.86 | 0.00 | 200.00 | 8060.48 | 4592.86 | 1.00000 | LID-BOTTOM |
| 26734. | 3300.00 | 8060.48 | 4592.86 | 0.00 | 200.00 | 8060.48 | 4592.86 | 1.00000 | LID-TOP |
| 26734. | 2936.40 | 6949.49 | 3964.15 | 0.00 | 600.00 | 6949.49 | 3964.15 | 1.00000 | CRUST3-BOTTOM |
| 18932. | 2936.40 | 6949.49 | 3964.15 | 0.00 | 600.00 | 6949.49 | 3964.15 | 1.00000 | CRUST3-TOP |
| 18932. | 2760.22 | 6362.21 | 3660.72 | 0.00 | 600.00 | 6362.21 | 3660.72 | 1.00000 | CRUST2-BOTTOM |
| 11130. | 2760.22 | 6362.21 | 3660.72 | 0.00 | 600.00 | 6362.21 | 3660.72 | 1.00000 | CRUST2-TOP |
| 11130. | 2662.34 | 6068.57 | 3464.96 | 0.00 | 600.00 | 6068.57 | 3464.96 | 1.00000 | CRUST1-BOTTOM |
| 3093. | 2662.34 | 6068.57 | 3464.96 | 0.00 | 600.00 | 6068.57 | 3464.96 | 1.00000 | CRUST1-TOP |
| 3093. | 2295.31 | 3419.05 | 1739.93 | 0.00 | 600.00 | 3419.05 | 1739.93 | 1.00000 | SEDS2-BOTTOM |
| 1533. | 2295.31 | 3419.05 | 1739.93 | 0.00 | 600.00 | 3419.05 | 1739.93 | 1.00000 | SEDS2-TOP |
| 1533. | 2051.91 | 2334.01 | 912.31 | 0.00 | 600.00 | 2334.01 | 912.31 | 1.00000 | SEDS1-BOTTOM |
| -297. | 2051.91 | 2334.01 | 912.31 | 0.00 | 600.00 | 2334.01 | 912.31 | 1.00000 | SEDS1-TOP |

Figure 3.1: Presents an image displaying the extracted data at specific latitude -15ºS and longitude 45ºE. The extracted data is organized in sequential order, starting with the depth (m) information, followed by the density (kg/m³), V_p (m/s), V_s (m/s), Q_k,Q_u

As the data extracted from each grid cell consisted of multiple sublayers with varying density values, it was necessary to calculate a weighted density that would represent the overall density of the grid cell. However, the primary focus was on obtaining the crustal density for the computation of RTE (Residual Terrain Effect). Consequently, only the densities of layers located above moho were taken into consideration. In this specific scenario, the density information for the region of interest was calculated from the sublayer known as crust 1-bottom (lower crust), which corresponds to the upper crust. This sublayer typically had a depth of 0 meters for most instances. The density computation started from the crust1-bottom layer and extended downward to the water sublayer, representing the density from the water surface up to the Moho discontinuity.

The weighted density was calculated by summing the product of the density of each sub-layer starting from the crust1-bottom (lower crust), layer and its corresponding depth, divided by the total depth of all sub-layers.

$$\delta_{wgt} = \sum(\delta_i \times d_i) \div \sum d_i \tag{3.1}$$

Where $\delta$ stands for density, $d$ stands for depth, $\sum$ stands for summation and $\delta_{wgt}$ is the density weight at each extracted grid cell. Subsequently, the weighted density for each grid cell was interpolated using the nearest neighbor gridding method in Golden Surfer software. This process resulted in the creation of a mass-density model, which was utilized in the calculations of the Residual terrain effect (RTE).

### 3.1.1 Computation of Residual Terrain Effect (RTE)

Residual terrain modeling (RTM) is employed to determine the residual terrain effect (RTE) by focusing on the high-frequency gravity field components within the specified area of interest (AOI). This involves utilizing knowledge about the geometry and density distribution of the ocean area's topography in Tanzania. In this study, TGF software is utilized for the computation of RTE.

The TGF software, equipped with a user-friendly graphical interface (GUI), is utilized for calculating RTE. The GUI consists of four sections: input of computation points, the definition of mass distributions, specification of functional and computation zones, and output files. Initially, the downloaded SRTM15Plus data is processed using Global Mapper software to generate three sets of DEMs at resolutions of 15" and 30", ensuring comprehensive coverage of the study area. The gridded DEMs are then imported into Golden Surfer software to create a square matrix. This is achieved by determining the number of nodes in the DEM, dividing it by the number of columns, subtracting one, and multiplying the result by the resolution of the DEM. The resulting values are added and subtracted from the latitude and longitude of the coverage area. The edited square matrix is exported as a Gravsoft grid (.gri) format using Global Mapper software. To meet the requirements of the TGF software, the Gravsoft grid (.gri) format is further processed in Golden Surfer software by editing the first and second columns of the file. Subsequently, the grid DEMs are converted to binary (.bin) format using the grid2bin program provided by the TGF software. This conversion is necessary as TGF software exclusively accepts datasets in binary format. During the grid2bin conversion process, essential inputs such as the minimum and maximum latitude values (minlat and maxlat), the minimum and maximum longitude values (minlon and maxlon), and the resolution (reslat and reslon) of the respective DEM are specified. Finally, the corresponding .grid DEM to be converted is selected, and the conversion is initiated by clicking the Grid_file button. Please refer to the accompanying figure for a visual representation of the steps involved.

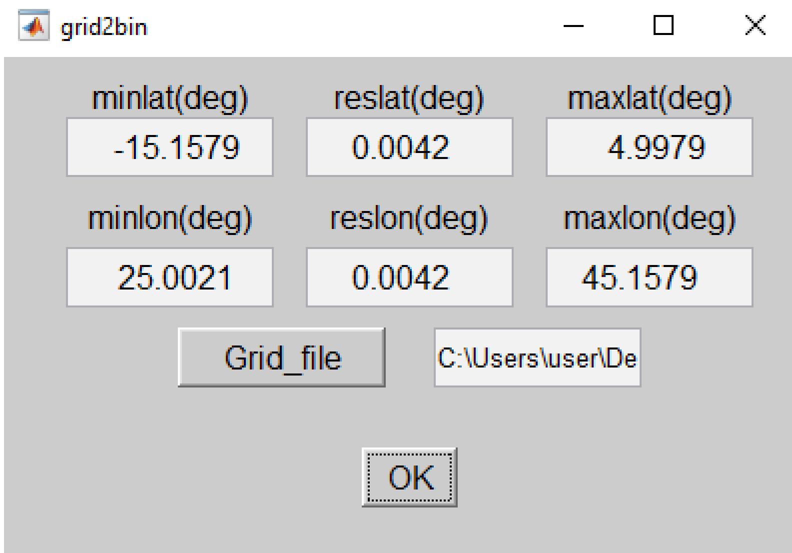


Figure 3.2: Showing the grid2bin file from a TGF software and the value indicated for the AOI

The dataset was divided into four distinct zones, with the first and second zones utilizing the same DetailedDEM. The third zone employed the TessDEM, while the CoarseDEM was utilized in the fourth zone. Table 1 provides a comprehensive overview of the specific DEMs assigned to each zone.

Table 3.1: Provides detailed specifications of the DEMs used in the TGF software for the computation of RTE. It outlines the specific characteristics and parameters of each DEM employed in the analysis.

| ZONE | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| NAME | DetailedDEM | DetailedDEM | TessDEM | CoarseDEM |
| GEOMETRY | Polyhedron | Prism | Tesseroid | Point mass |
| EXTENSION(º) | 0.03 | 0.03 | 0.15 | 0.80 |
| RESOLUTION | 15" | 15" | 15" | 30" |
| FORMAT | .bin | .bin | .bin | .bin |

### 3.1.2 Preparation of Density Map

In order to calculate the residual terrain effect in the ocean area of Tanzania using bathymetry data, a density map was generated using Surfer 15 software. To be more specific, for the ocean area, each grid cell was assigned a density value derived from the LITHO1.0 model's crustal density to represent the density of water. Additionally, the topography or seabed was assigned a specific crustal density from the LITHO1.0 model. This approach ensures that the density variations within the ocean area are accurately accounted for, taking into consideration both the properties of water and the characteristics of the seabed according to the LITHO1.0 model. This density map was created at the same resolution and size as the digital bathymetry model (DBM), ensuring that density information was available for each computation point. The resulting density map provides crucial data for accurately computing the residual terrain effect within the specified area of interest.

### 3.1.3 Mean Reference Surface.

A reference surface is a representation of the average elevation of a specific area of interest. In this study, the gridded DEM with resolutions of 15″ and 30″ was employed to generate three types of reference surfaces: DetailedREF, TessREF, and CoarseREF. To achieve this, the Moving Average technique was applied using Golden Surfer Software. According to Forsberg (1884), the Moving Average should be computed from a DEM model with spacing no greater than that of the desired smoothness level for the reference grid. Hence, in this research, the SRTM15plus-DEM was utilized at an equivalent resolution to generate the reference surface. The process was executed in Golden Surfer 15 software by applying a low-pass filter to the DEM using a 3x3 window. The resulting grid was then prepared following the aforementioned procedure to create a square matrix, which was subsequently converted to the .bin format using the grid2bin utility. This binary format can be recognized by the TGF software.

.Table 3.2: Presents a concise summary of the meticulously prepared reference surface, which is now in its optimal state for seamless integration into RTE computations within the TGF software

| ZONE | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| NAME | detailedREF | detailedREF | tessREF | courseREF |
| RESOLUTION | 15 | 15 | 15 | 30 |
| FORMAT | .bin | .bin | .bin | .bin |

The computation point preparation involved creating a 1' x 1' resolution using Global Mapper software. The resulting grid file was then imported into Golden Surfer software and converted into .dat format. Utilizing Excel software, the file was further organized to include point number, latitude, longitude, and height. To complement the computation points at 1' x 1' resolution, three datasets of DEM (Detailed Mass, Tesseroid Masses, and Coarse Masses) were prepared at 15" and 30" resolutions. The prepared files underwent conversion from Surfer grid files to a binary format compatible with TGF software using the "grid2bin" tool. The computation zones, consisting of polyhedron, prism, tesseroid, and point masses at 15" and 30" resolutions, were established, LITHO 1.0 crustal density model and specified radii. After a waiting period of a few hours, the data processing commenced. Subsequently, the obtained file was converted into the grid2bin format for further analysis.

Table 3.3: A sample of the computation point file used in the computation of RTE

| S/N | Latitude (°) | Longitude (°) | Height (m) |
|---|---|---|---|
| 1 | -6 | 41 | -2971 |
| 2 | -6 | 42 | -2981 |
| 3 | -6 | 42 | -2990 |
| 4 | -6 | 42 | -3000 |

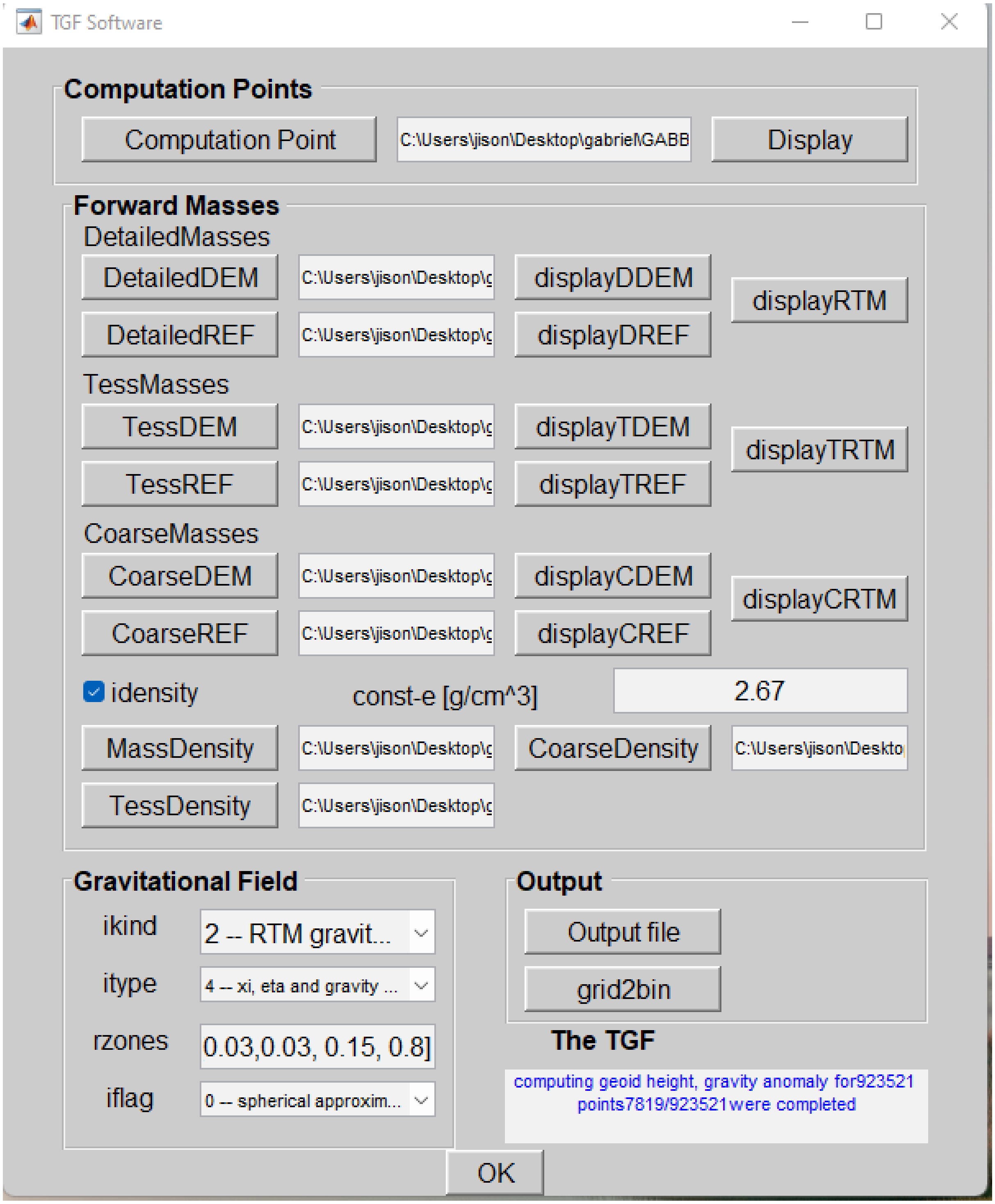


Figure 3.3: Graphical User Interface of a TGF Software

Finally, the collected data was imported into the TGF software using the designated buttons, as depicted in Figure (3.7). When computing RTE with constant density, the "idensity" button remained unchecked. However, for RTE calculations involving variable density, the "idensity" button was selected, and the respective density models were inputted accordingly. Within the Gravitational Field tab, the "RTM gravitational field" option was chosen in the "ikind" button. The "Itype" button, responsible for defining computation functions, was set to option 4, which computes gravity anomalies and vertical deflections. The "Rzones" button, determining the extent of each zone in degrees, was populated with values [0.03, 0.03, 0.15, 0.8], as suggested by Yang et al. (2020) as the minimum requirement for achieving an accuracy of 1mGal.

## 3.2 Required Data

SRTM15Plus, a comprehensive dataset known as the Global Bathymetry and Topography, offers valuable information on both underwater topography and land surface elevation. Bathymetry data provides essential details about the depth and structure of underwater terrains like seafloors, lakebeds, and riverbeds, including water depth distribution. Specialized tools such as sonar, echo sounders, and depth sounders are commonly utilized to collect this vital data. The significance of bathymetry data extends across various applications, including marine navigation, geological studies, oceanographic research, underwater resource exploration, and environmental monitoring. These datasets are typically presented through 2D or 3D maps or models, enabling effective visualization, analysis, and interpretation of underwater features and phenomena.

In this research, I make use of the SRTM15Plus dataset to access bathymetry data. This dataset is an invaluable resource that provides comprehensive information about the underwater topography of the Tanzania-Indian Ocean region. The dataset can be freely downloaded from https://portal.opentopography.org/raster?opentopoID=OTSRTM.122019.4326.1 and is available in GeoTiff format with a resolution of 15 arc minutes, which is roughly equivalent to 450 meters. Covering the entire Tanzania-Indian Ocean region, the SRTM15Plus dataset encompasses crucial information about the depth of the ocean floor, as well as the shape and characteristics of the seafloor terrain. The horizontal and vertical datums employed in the SRTM15Plus dataset are WGS84 and EGM96, respectively. To access and analyze the data, various software tools such as QGIS, ArcGIS, and Global Mapper can be utilized. The data is presented in a visually intuitive color-coded format, with different shades of blue representing varying depths of the ocean floor.

The SRTM15Plus dataset proves particularly valuable for oceanographic research, marine resource exploration, and environmental monitoring in the Tanzania-Indian Ocean region. It offers researchers and scientists invaluable insights into the underwater landscape, facilitating informed decision-making and sustainable management of marine environments.

### 3.2.1 Aerial Gravity

Aerial gravity data refers to measurements of gravity obtained from airborne surveys. These surveys involve flying specialized instruments, such as gravimeters, over a specific area to collect gravity readings. The instruments measure minute changes in gravitational force caused by variations in the density and mass distribution of the Earth's subsurface. In this research, the data used here is the one obtained or collected in the year 2013 when an aerial gravity survey was conducted in our country, Tanzania and a substantial amount of Aerial Gravity Data comprising approximately 15,112 data points specifically covering the Indian Ocean region of Tanzania. These data points were sourced from the Ardhi University gravity Database (ARUDB), a comprehensive collection of gravity information gathered from various sources, including measurements taken with airborne instruments. The Aerial Gravity Data served as a vital tool for validating the accuracy of the computed Residual Terrain Effect (RTE) obtained from the TGF software.

By comparing the computed RTE values with the Aerial Gravity Data, this research aimed to evaluate the reliability and precision of the RTE calculations. This validation process played a crucial role in ensuring the accuracy of the RTE results and assessing the performance of the TGF software in generating RTE values. The utilization of the extensive Aerial Gravity Data from the DGST and ARUDB enhanced the robustness and credibility of the validation process, contributing to the overall quality of the research findings

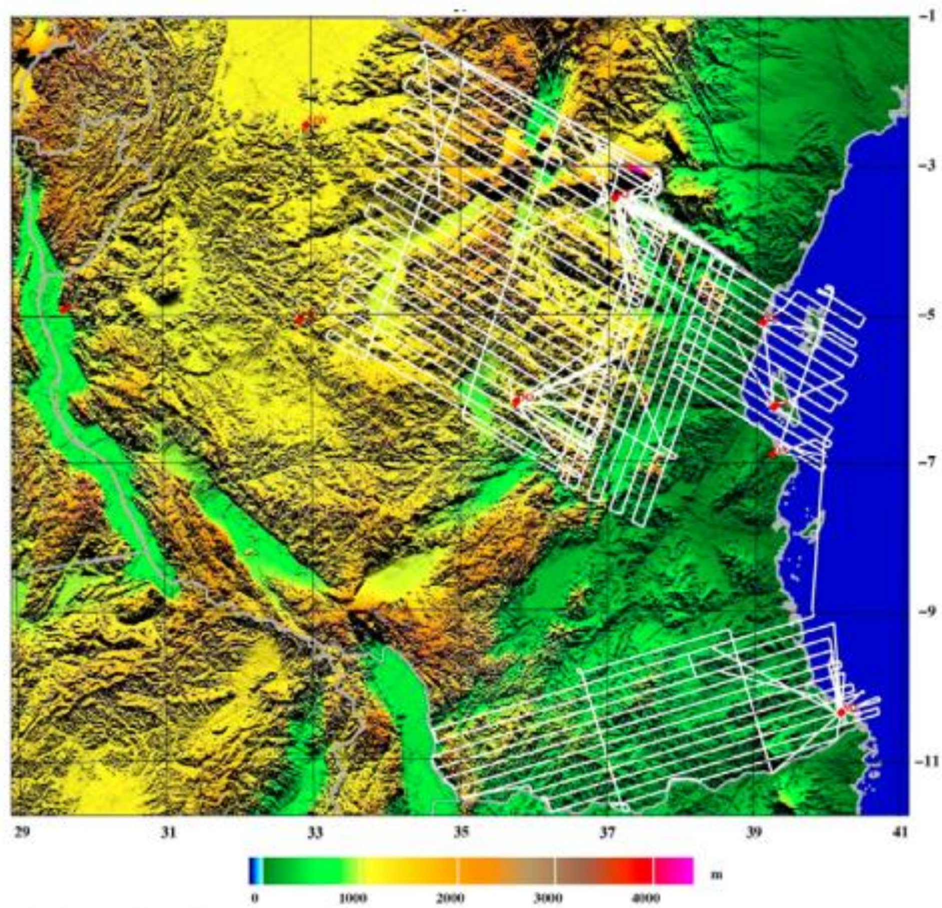


*Figure 3: Ground track pattern of aerial gravity data*

### 3.3 Validation of Results

To ensure the accuracy of computed Residual Terrain Effects (RTE), a critical step involves comparing them with RTE values derived from aerial gravity data. Subsequently, the airborne data is downward continued to the sea surface and cross-compared with the computed residual terrain effect from SRTM15plus. For this purpose, the (RCR) technique proves valuable, employing Global Geopotential Models (GGM) and topographical information to control low and high-frequency gravity variations. To refine the airborne gravity data, the combined satellite model EGM2008 up to degree 750 is used to remove-restore the long-wavelength information. Furthermore, the terrain correction (TC) effects in gravity signals are removed, focusing solely on the short-wavelength alterations. This is achieved through a process involving the determination of a smooth mean elevation surface, computational removal of masses above this surface, and filling in valleys. The result is the creation of the residual terrain model, utilizing prism integration to calculate the short wavelength in the TC effects, adopting a LITHO1.0 density for the ocean area.

To achieve this, we will employ the effective Spectral Enhancement Method (SEM). Illustrated in Figure 3.5, SEM empowers us to derive genuine RTE values based on the aerial gravity measurements obtained at the 15,112 points. By adopting this approach, we can ensure a reliable and accurate comparison between the computed RTE value from DEM and the one computed from aerial gravity data. This process enhances our understanding of the terrain effects and their impact on gravity anomalies, ultimately advancing our knowledge in this field.

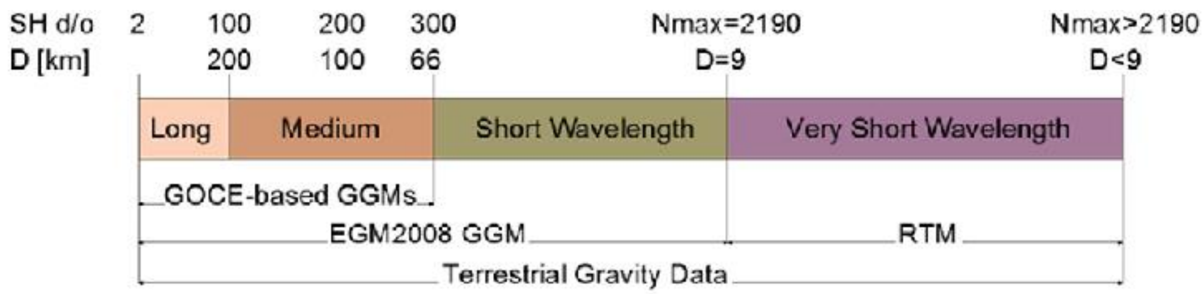


Figure 3.5: The spectral enhancement method *(El-Ashquer et al, 2020)*.

## 3.4 Software.

1. TGF Matlab software

   The TGF Matlab software played a crucial role in conducting the computations for the Residual Terrain Effect (RTE). It was utilized for computing RTE using the LITHO1.0 crustal density model.

2. Golden Surfer software (Surfer 15)

   The Golden Surfer software, specifically Surfer 15, was utilized for gridding and data preparation required in the computation of the RTE. This software facilitated the transformation and organization of the data to ensure it was suitable for further analysis.

3. Global mapper

   The Global mapper software was employed to convert data formats, specifically converting Surfer grid and GeoTiff formats to the Gravsoft grid format. This conversion process was essential for compatibility and seamless integration of the data in subsequent analysis.

4. Microsoft Excel

Microsoft Excel played a crucial role in arranging the exported data from the LITHO1.0 model. It provided a versatile platform for organizing and manipulating the data. Additionally, it assisted in the computation of the weighted density necessary for the analysis.

5. Microsoft Word

   Microsoft Word was used for report-writing purposes. It served as the primary tool for documenting the findings, analysis, and conclusions of the study. Microsoft Word's features and formatting capabilities enabled the creation of a professional and comprehensive report.

# CHAPTER FOUR

# RESULTS AND ANALYSIS

In this chapter, the procedures utilized for data processing were explored, the obtained results are presented, and a detailed discussion regarding those outcomes is conducted. The main emphasis of my computations and results revolves around the methodology and data outlined in Chapter 3. Through this exploration, my objective is to offer a comprehensive understanding of the data processing methods employed, the resulting findings, and a meticulous analysis and interpretation of those findings.

### 4.1.1 Developed Regional Crustal Density Model over the AOI

In Section 3.1, we begin by arranging the extracted data in a tabular format, as illustrated in Table 4.1. Moving forward, the weighted density was by computed using equation 3.1 and proceed to analyze its statistical properties, which are presented in Table 4.2. The density data extracted from the LITHO1.0 crustal density model was meticulously analyzed to derive the weight density of each grid point within the study area. The results are elegantly presented in a visually appealing blue color, showcased in the map below in Figure 4.1, effectively depicting the density variations across each grid location.

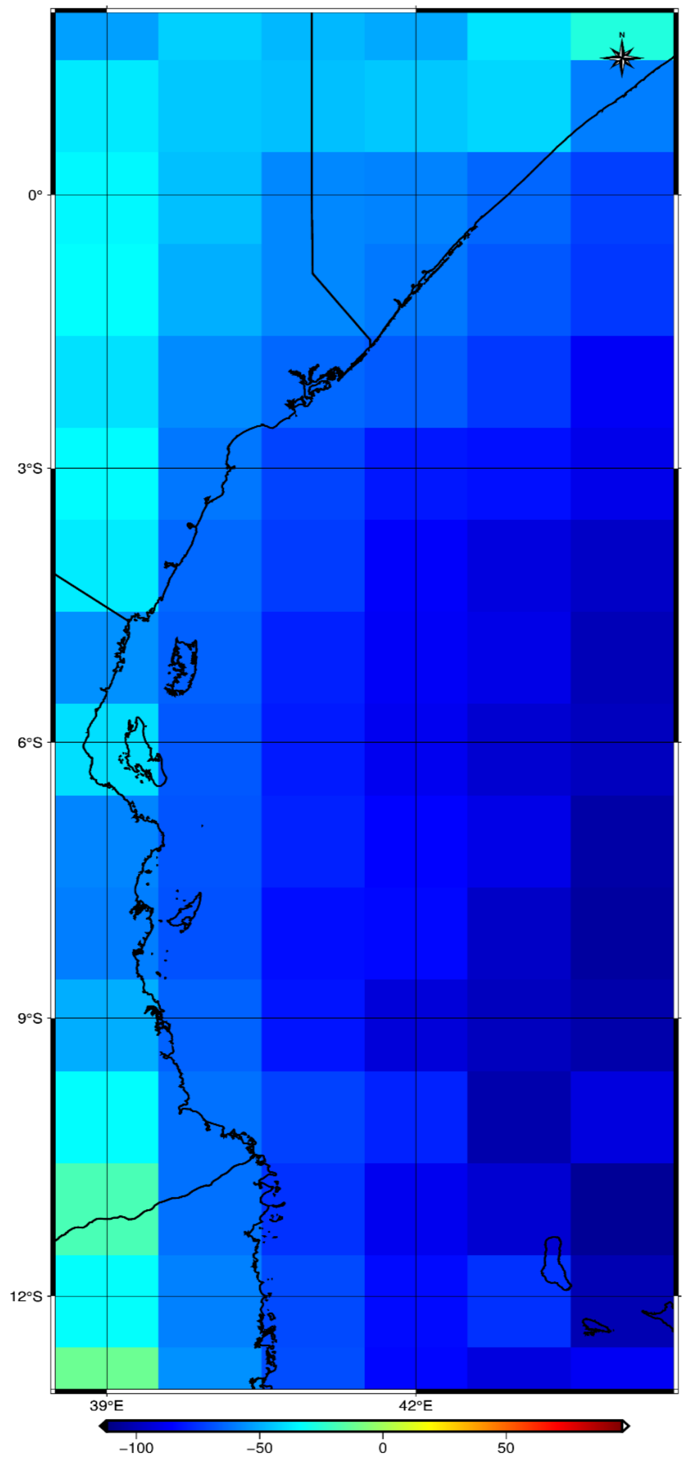


Figure 4.1: Distribution of crustal density over the AOI in g/cm$^3$

In Table 4.1 a sample of the data extracted from LITHO1.0, along with the corresponding computed weighted density at each given node. This table serves as a reference point for understanding the specific values and their associated weights in relation to the extracted data from LITHO1.0

Table 4.1: A sample of the data extracted from LITHO1.0, along with the corresponding computed weighted density at each given node.

| Latitude($\theta^0$) | Longitude($\lambda^0$) | Weight density($g/cm^3$) |
|---:|---:|---:|
| -1 | 31 | 2.7945 |
| -2 | 31 | 2.9495 |
| -3 | 31 | 3.0081 |
| -4 | 31 | 2.9543 |
| -5 | 31 | 2.7835 |

Where, $\theta$ is the geographic latitude ($^0$) and $\lambda$ is the geographic longitude ($^0$), and weight density ($g\ /\ cm^3$)

Table 4.2: Statistics of computed weight density at 199 nodes over the AOI.

| | |
|---|---:|
| Number of values | 199 |
| Sum($g\ /\ cm^3$ ) | 472.77 |
| Minimum ($g\ /\ cm^3$) | 2.0277 |
| Maximum ($g\ /\ cm^3$) | 3.2181 |
| Range($g\ /\ cm^3$ ) | 1.456 |
| Mean($g\ /\ cm^3$) | 2.6886 |
| Standard deviation ($g\ /\ cm^3$) | 0.2872 |

### 4.1.2 Mean Average Reference Surface

By following the outlined procedures in Section 3.2.1, successfully, a Mean Average reference surface was constructed that encompasses a specific geographical area defined by longitude 38.5$^0$ E to 45$^0$ E and latitude 2$^0$ N to -14 S. This reference surface serves as a representation of the elevation across the given region. Notably, the minimum elevation recorded within this area was -4615m, while the maximum elevation reached 2000m. Below, on the left, is a map displaying the contour distribution within the area of interest, while on the right, the surface map showcases the same area.

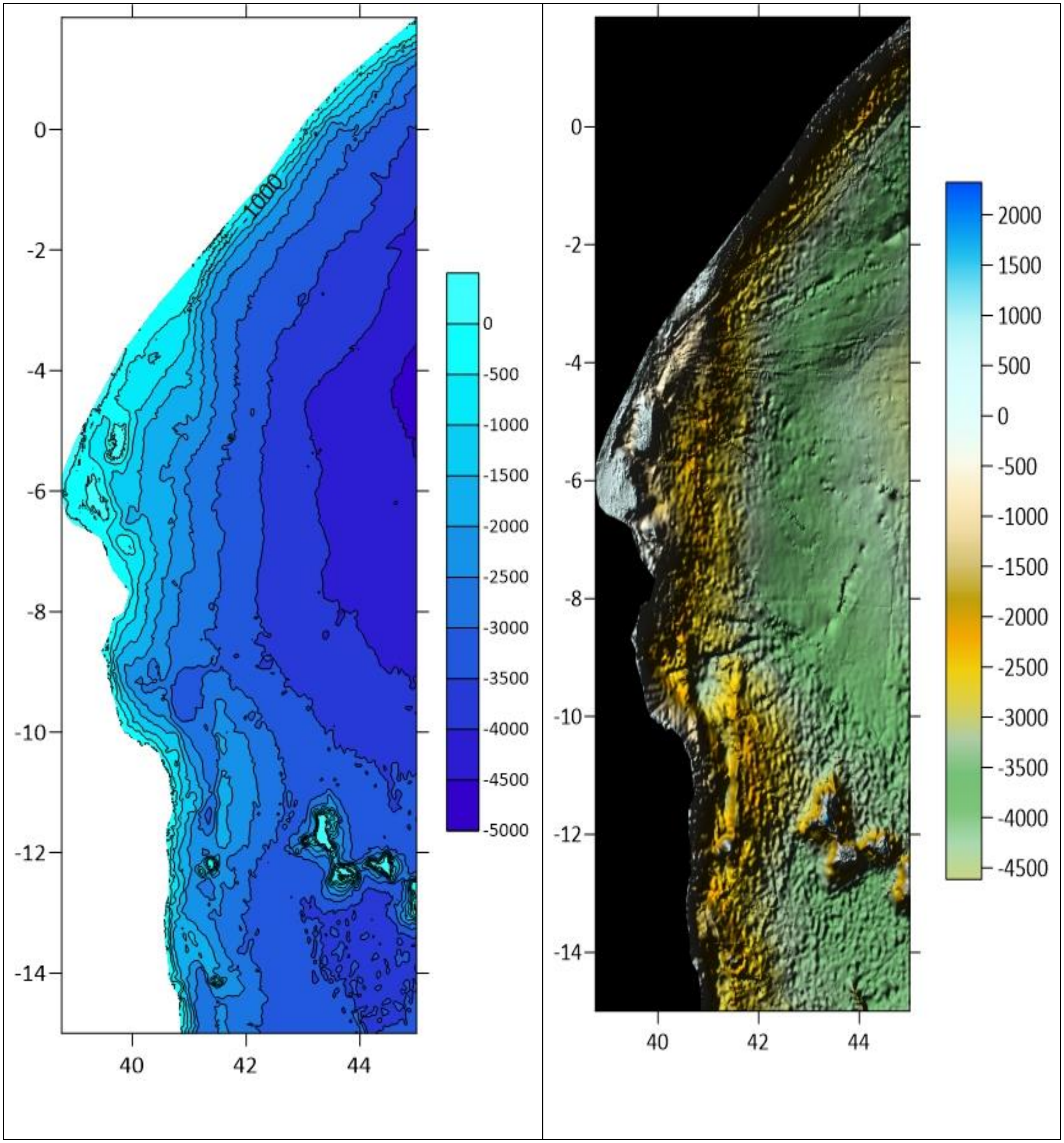


Figure 4.2: Contour and surface map of MA reference surface

### 4.1.3 Computations of $1' \times 1'$ RTE

The TGF software was utilized to calculate the short wavelength component of gravity on the area of interest. This process is described in section 3.6 of this document. The resulting Residual Terrain effect (RTE) values were computed and a sample of these values is provided in Table 4.3.

Table 4.3: Sample of computed RTE over area of interest

| Latitude(⁰) | Longitude(⁰) | RTE (mGal) |
|---:|---:|---:|
| -10.333 | 36.117 | -0.124 |
| -10.333 | 36.133 | -0.176 |
| -10.333 | 36.15 | -0.069 |
| -10.333 | 36.167 | 0.764 |
| -10.333 | 36.183 | -1.066 |
| -10.333 | 36.033 | -0.273 |

The computation of resulting Residual Terrain effect (RTE) values was analyzed using Surfer 15 software. The statistical analysis of the computed RTE values was conducted, and the results are presented in Table 4.4, displaying the relevant statistics.

Table 4.4: Statistics of computed Residual Terrain effect (RTE) over the area of interest.

| Minimum(mGal) | Maximum(mGal) | Mean (mGal) | STD (mGal) | RMS (mGal) |
|---|---|---|---|---|
| -19.134 | 3.033 | 1.155 | 0.364 | 1.211 |

The Residual Terrain Effect (RTE) grid file, which was generated, served as the foundation for producing a visualization of the computed RTE over the Area of Interest (AOI) using Generic Mapping Tools (GMT) software. This informative visualization is showcased in Figure 4.3, offering a clear depiction of the RTE values across the AOI. The computation was executed with a specific resolution of $1' \times 1'$.The resulting visualization is thoughtfully presented using a palette color map below, effectively highlighting the diverse variations in the residual terrain effect throughout the entire region.

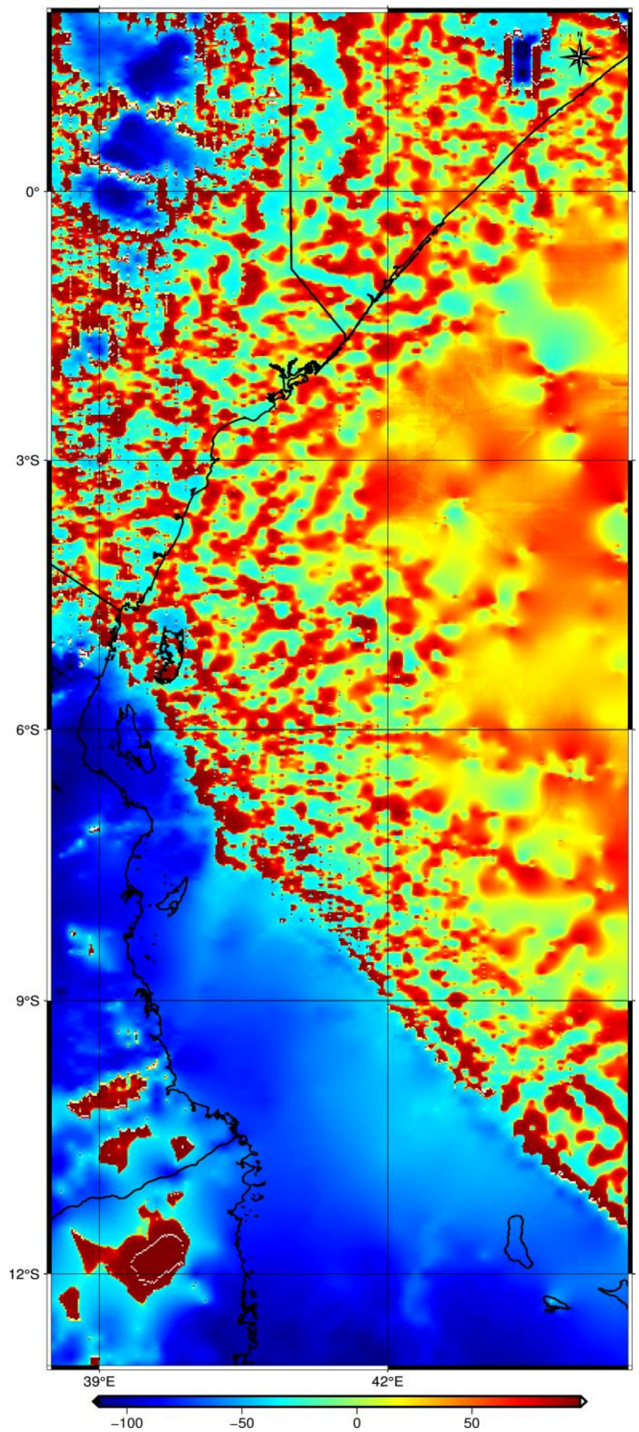


Figure 4.3: The computed RTE (mGal) values across the AOI.

## 4.2 Quality Assessment

### 4.2.1 Validation of the Computed $1' \times 1'$ RTE

In order to validate the RTE gravity anomalies, a comparison was conducted with computed RTE values obtained from aerial gravity data. The RTE values derived from aerial gravity involved the removal of long, medium, and short wavelength gravity components from the sea surface gravity anomalies measured at 15,112 aerial gravity points within the study area. This comparative analysis enabled an evaluation of the accuracy and dependability of the RTE gravity anomalies.

### 4.2.2 Comparison with Aerial Gravity Data

To ensure the accuracy of computed Residual Terrain Effects (RTE), a critical step involves comparing them with RTE values derived from aerial gravity data. Subsequently, the airborne data is downward continued to the sea surface and cross-compared with the computed residual terrain effect from SRTM15plus. For this purpose, the (RCR) technique proves valuable, employing Global Geopotential Models (GGM) and topographical information to control low and high-frequency gravity variations. To refine the airborne gravity data, the combined satellite model EGM2008 up to degree 750 is used to remove-restore the long-wavelength information. Furthermore, the terrain correction (TC) effects in gravity signals are removed, focusing solely on the short-wavelength alterations. This is achieved through a process involving the determination of a smooth mean elevation surface, computational removal of masses above this surface, and filling in valleys. The result is the creation of the residual terrain model, utilizing prism integration to calculate the short wavelength in the TC effects, adopting a litho1.0 density for the ocean area. The outcome of reducing the airborne gravity anomalies using EGM2008 and TC is well-documented in Table (4.5). Additionally, Figure (4.4) provides a visual representation of the residual gravity signals after the removal of EGM2008 and TC effects. Using a low-pass filter is crucial in reducing short-wavelength noise resulting from the Downward Continuation (DWC) operation. In this study, we opted for the Gaussian filter to smoothly process the downward-continued gravity signals. The Gaussian filter is widely preferred due to its several desirable properties. Notably, it exhibits acceptable spatial and frequency localization properties, making it the ideal choice as a low-pass filter. Moreover, the Gaussian filter maintains rotational constancy and analyzability. Its close connection to multi-resolution or multi-scale processing allows for the generation of input data with varying resolutions, ranging from coarse to fine.

In Table (4.5), is the sample of the residual airborne gravity anomalies that were continued to the sea surface altitude using FFT with the Gaussian filter.

Table 4.5: Presents some of the residual airborne gravity anomalies from aerial gravity data

| S/N | Latitude($^o$) | Longitude($^o$) | $\Delta g_{RTE}^{AERIAL}(mGal)$ |
|---|---|---|---|
| 1 | -9.05 | 39.75 | -6.962 |
| 2 | -7.75 | 40.4 | -1.1195 |
| 3 | -0.55 | 42.8 | 1.778 |
| 4 | -11.45 | 40.7 | 6.835 |
| 5 | -9.1 | 39.75 | -7.972 |

The grid file containing the residual terrain effect (RTE) data, generated from aerial gravity observations, played a crucial role in creating a comprehensive visualization of the computed RTE over the area of interest. Utilizing the powerful tools of Generic Mapping Tools (GMT), we produced an informative visualization, displayed in Figure 4.4 below, which provides a clear depiction of the RTE values across the designated area .The resulting visualization, thoughtfully presented using a color palette map below, and effectively accentuates the diverse variations in the residual terrain effect throughout the entire study area. This presentation significantly enriches our understanding of the RTE distribution and its spatial patterns across the study region.

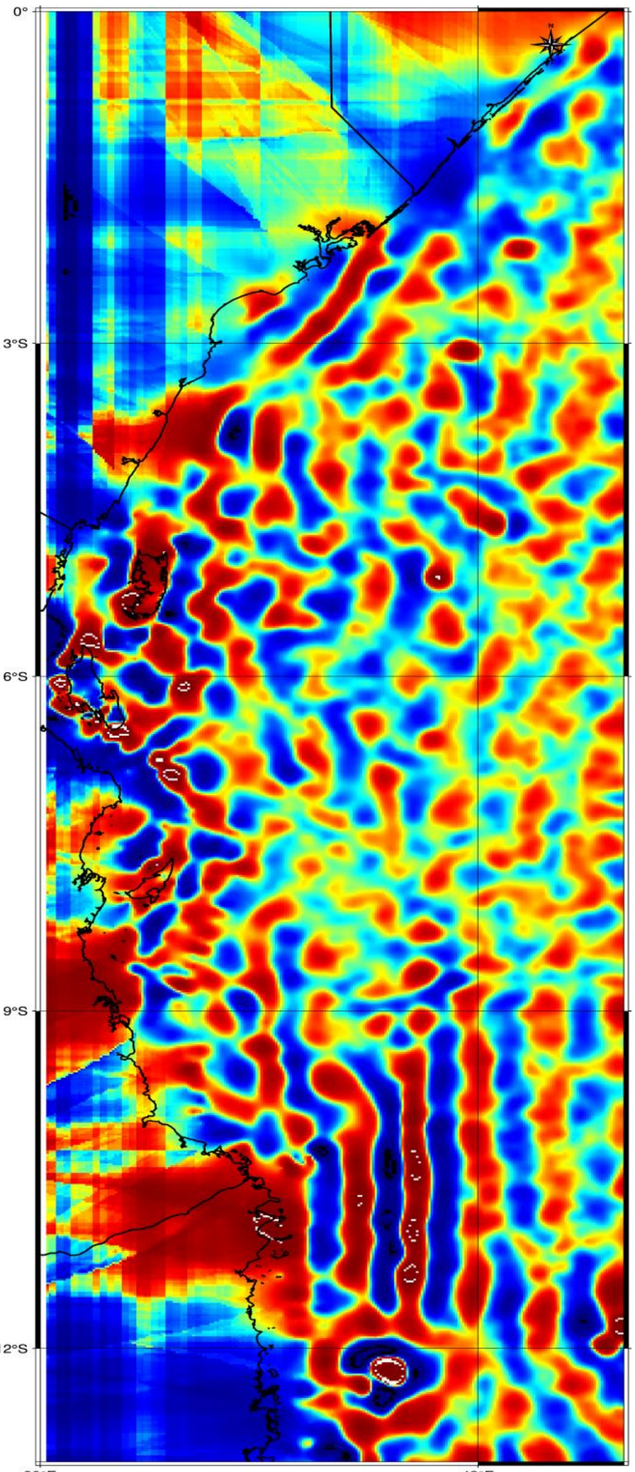

Figure 4.4: The computed RTE (mGal) values across the AOI from aerial gravity data.

Here are the computed Residual Terrain Effects (RTE) for the specified area of interest, obtained using the TGF software.

Table 4.6: Computed RTE by using TGF software

| S/N | Latitude(⁰) | Longitude(⁰) | $\Delta g_{RTE}^{TGF}(mGal)$ |
|---|---|---|---|
| 1 | -9.05 | 39.75 | -6.979 |
| 2 | -7.75 | 40.4 | -1.065 |
| 3 | -0.55 | 42.8 | 1.468 |
| 4 | -11.45 | 40.7 | 7.974 |
| 5 | -9.1 | 39.75 | -7.646 |

Table 4.7 displays the disparity between the computed (RTE) values from the digital elevation model and the actual sea surface RTE values from aerial gravity data. The table presents the differences between these two sets of RTE values, providing insight into the level of deviation or agreement between the computed RTE from the digital elevation model and the actual sea surface RTE values from aerial gravity data at the respective gravity stations.

Table 4.7: Difference between the computed RTE by using aerial gravity data and the one computed from TGF software.

| S/N | Latitude(⁰) | Longitude(⁰) | $\Delta g_{RTE}^{AERIAL} - \Delta g_{RTE}^{TGF}(mGal)$ |
|---|---|---|---|
| 1 | -9.05 | 39.75 | -0.017 |
| 2 | -7.75 | 40.4 | -0.055 |
| 3 | -0.55 | 42.8 | 0.31 |
| 4 | -11.45 | 40.7 | -1.139 |
| 5 | -9.1 | 39.75 | -0.326 |

## 4.3 Discussion of Results

The computed (RTE) values obtained through the TGF software have been accompanied by a comprehensive set of statistics, including the mean, standard deviation, root mean square, minimum, and maximum values, which are 1.155 mGal, 0.364 mGal, 1.211 mGal, -19.134 mGal, and 3.330 mGal, respectively. These statistics provide crucial insights into the gravity characteristics within the Area of Interest (AOI).The mean RTE value of 1.155 mGal represents the average gravity level across the AOI. Meanwhile, the standard deviation of 0.364 mGal indicates the amount of dispersion or variability around this mean value, which can be indicative of local geological structures or density variations affecting the gravity measurements. The root mean square (RMS) value of 1.211 mGal gives a measure of the overall strength of the gravity fluctuations, reflecting the spatial complexity of the gravity field. The computed RTE results also exhibit a wide range of gravity values within the AOI. The minimum value of -19.134 mGal and the maximum value of 3.330 mGal suggest the presence of significant gravity anomalies, potentially arising from subsurface geological features, mass distributions, or other geophysical processes. These extreme values underscore the need for further investigation to understand the underlying geological and geophysical factors contributing to such variations.

To ensure the credibility and confidence in the computed RTE results, a comprehensive validation was conducted using a substantial dataset of 15,112 aerial gravity points within the AOI. This validation process helps to verify the accuracy and reliability of the computed gravity values, especially when compared to ground-truth measurements obtained through aerial gravity data. Additionally, a statistical analysis was performed to compare the computed RTE values with the aerial gravity RTE for the same 15,112 aerial gravity points. The results of this analysis showed a mean difference of 2.990 mGal, indicating a consistent bias between the computed RTE and the actual aerial gravity RTE. The STD of 4.025 mGal signifies the spread of these differences around the bias, while the RMS value of 5.011 mGal represents the overall scatter between the computed and actual values. The minimum and maximum differences of -19.316 mGal and 12.040 mGal, respectively, highlight the significant range of variations encountered in the comparison. These findings suggest the presence of systematic discrepancies between the computed RTE values from the TGF software and the actual aerial gravity RTE. While the computed RTE values provide valuable insights into the gravity field in the AOI, it is crucial to recognize and consider these discrepancies when interpreting the results for geological modeling, resource exploration, or any other application relying on precise gravity data. This assessment emphasizes the importance of conducting thorough validation procedures to verify the accuracy and reliability of computed gravity values. The observed bias between computed RTE and actual aerial gravity RTE suggests that further refinement may be necessary to improve the precision of the computed RTE values.

Additionally, the wide range of variations encountered in the comparison indicates the need for careful consideration and interpretation of the results, particularly in geological modeling and resource exploration applications that rely on precise gravity data. Despite these challenges, the computed RTE values provide valuable insights into the gravity field within the AOI, contributing to the understanding of its geology and geophysical processes. Moving forward, addressing the identified biases and variations will be critical to enhancing the utility of the computed RTE values for gravity-related studies in the area.

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

This study successfully accomplished its primary objective, which was to compute the residual terrain effect (RTE) in the ocean area of Tanzania by considering density variations and validating it against aerial gravity data. The computed RTE values were accompanied by a comprehensive set of statistical measures, including mean, standard deviation, root mean square, maximum, and minimum values, which were found to be 1.155 mGal, 0.364 mGal, 1.211 mGal, -19.134 mGal, and 3.330 mGal, respectively. These results were particularly evident when Mean Average reference surfaces were utilized. The findings of this research clearly demonstrate that the computed RTE closely aligns with the aerial gravity data, indicating the success of the research objectives. The validation process, which involved comparing the computed RTE values with a substantial dataset of 15,112 aerial gravity data within the area of interest, confirmed the accuracy and reliability of the computed gravity values. The statistical analysis further supported the validity of the results, showing a mean difference of 2.990 mGal between the computed RTE and the actual aerial gravity RTE. The spread of differences around this bias was represented by the STD of 4.025 mGal, while the RMS value of 5.011 mGal highlighted the overall scatter between the computed and actual values. The minimum and maximum differences of -19.316 mGal and 12.040 mGal, respectively, underscored the significant range of variations encountered in the comparison.

With the successful validation and rigorous statistical analysis, the study establishes that the computed RTE can be effectively employed in the R-C-R approach, leading to enhanced gravity data within the specified area of interest. This technique allows for the densification of gravity measurements, resulting in a more comprehensive dataset, which can be valuable for various applications, including geodetic and geomatics studies. Moreover, the computed RTE holds significant potential for broader implications beyond the scope of this study, suggesting its usefulness in diverse fields. In conclusion, this research demonstrates the effectiveness and reliability of the computed residual terrain effect in the ocean area of Tanzania. The close agreement between the computed RTE and aerial gravity data validates the accuracy of the results, highlighting the success in achieving the research objectives. By employing the R-C-R approach and conducting rigorous statistical analysis, this study has provided valuable insights and a solid foundation for further gravity-related studies and applications within the area of interest and beyond.

## 5.2 Recommendation

Following the successful completion of this research, the following suggestions are proposed to enhance the accuracy and efficiency of RTE computations:

In this study, the RTE computations were conducted using TGF software. It is advised that future researchers consider making modifications to the TC program from GRAVSOFT in order to incorporate the density of both the topography and water when computing RTE. This enhancement would enable a more comprehensive and accurate calculation of RTE by accounting for the varying densities of the topography and water.

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