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VERTICAL ASSESSMENT OF DEMs DERIVED FROM ALOSv3.2-1″, TANDEM-X-3″DSMs AND NEW GEDI, OLD GEDI CHMs USING GGCPs IN TANZANIA

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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 dissertation titled "**Vertical Assessment of DEMs Derived from ALOSv3.2-1″, TANDEM-X-3″ DSMs and New GEDI, Old GEDI CHMs Using GGCPs in Tanzania**" in partial fulfillment of the requirements for the award of degree of Bachelor of Science in Geomatics at Ardhi University.

…………………………………

Ms. Regina V Peter

(Supervisor)

Date ………………………

DECLARATION AND COPYRIGHT

I, MRAMBA, BENEDICT F. 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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DEDICATION

I dedicate this dissertation to my beloved family; my parents Mr. & Mrs. Mramba, my brothers Bazil, Joseph and Emmanuel Mramba through their patience, understanding, prayers, love, support and encouragement on my academic journey.

ABSTRACT

The vertical assessment of newly released Global Digital Elevation Models (GDEMs) in developing countries like Tanzania is still very essential because of costs and difficulty reliable in creating a digital elevation database covering the whole country. The release of New GEDI CHM from GEDI and ESA and the use of Old GEDI CHM create an opportunity for deriving DEMs by subtracting the Two GEDI LiDAR CHMs from ALOSv3.2-1″ and TanDEM-X-3″ public available DSMs. This study aims to take the advantage of availability of the Two GEDI LiDAR CHMs and public DSMs to determine a better DEM than the current public available DEMs from different providers. The selected study area is Tanzania mainland 1˚N to 12˚S and 29˚E to 41˚E in which the vertical assessment of four derived DEMs is done using a total of 574 GGCPs scattered all over the country. The method used is statistical assessment of height differences between derived DEMs and GGCPs relative to EGM96 geoid model. The minimum SD and RMS were the basis of the vertical assessment in this dissertation as it involves the comparison of the four derived DEMs with public available NASA DEM and MERIT DEM countrywide and in selected 12 land covers, vertical assessment using GGCPs countrywide and in selected 12 land covers.

At 95% confidence level statistics reveals that MERIT public available DEM shows better results countrywide over all four derived DEMs and NASA available DEM based on vertical assessment using GGCPs in terms of both SD and RMS with SD of 3.56m and RMS of 3.61m while derived DEM using New GEDI CHM results are seen not to be good, TanDEM-X-3″ derived DEM being the lowest with SD 4.05m and RMS of 5.44m. In the twelve selected land covers the assessment using GGCPs results vary from one place to another with no systematic trend but MERIT DEM shows the best results in most land covers with RMs between 2.43m and 4.59m including flat and bare terrain, flat and plain terrain, barely flat and forested coastal terrain, slightly mountainous and forested terrain, forested and fairly flat terrain and lastly flat and forested coastal terrain. ALOSv3.2-1″ derived DEM using New GEDI CHM is superior to all the derived and available DEMs validated in this study only in the Eastern branch of the Great Rift Valley. TanDEM-X-3″ derived DEM using New GEDI CHM is superior to available public DEMs validated in this study only in highland and forested terrain and the western branch of the Great Rift Valley but it is inferior to derived DEMs using Old GEDI CHM.

Keywords: GEDI, DEM, DSM, GGCPs, LiDAR CHM, SD, RMS

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ABBREVIATIONS

ALOS	Advance Land Observing Satellite
AOI	Area Of Interest
ARD	Analysis Ready Data
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
CHM	Canopy Height Model
CNN	Convolutional Neural Networks
DED	Digital Elevation Data
DTED	Digital Terrain Elevation Data
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESA	European Space Agency
EGM96	Earth Gravitational Model of 1996
ESRI	Environmental Systems Research Institute
GDEMs	Global Digital Elevation Models
GEDI	Global Ecosystem Dynamics Investigation
GeoTIFF	Geographic Tagged Image File Format
GGCPs	GPS Ground Control Points
GLAD	Global Land Analysis and Discovery
GLAS	Geoscience Laser Altimeter System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICESat	Ice, Cloud and land Elevation Satellite

InSAR	Interferometric Synthetic Aperture Radar
JAXA	Japan Aerospace Exploration Agency
LiDAR	Light Detection and Ranging
MERIT	Multi Error Removed Improved Terrain
NASA	National Aeronautics and Space Administrations
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
RH	Relative Height metric
SAR	Synthetic Aperture Radar
SFM	Structure From Motion
SRTM	Shuttle Radar Topography Mission
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurements
TAREF11	Tanzania Reference Frame 2011
WGS84	World Geodetic System 1984

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The Digital Elevation Model (DEM) is a regularly-spaced bare-earth raster grid referenced to a common vertical datum without the above ground features. In some countries, a DEM is termed as a Digital Terrain Model (DTM). But in some countries a DTM is a DEM with additional data about natural features such as ridges and break-lines (Ulotu, 2017). DEMs can be created from ground surveys, digitizing existing hardcopy topographic maps or by remote sensing technique which includes photogrammetry, airborne and space borne Interferometry Synthetic Aperture Radar (InSAR) and Light Detection and Ranging (LIDAR) (Athmania & Achour, 2014). Because of the high cost of producing digital elevation models by conventional ground surveys and inaccessibility of some places due to roughness of the terrain, it has become necessary to research on the less expensive and safer digital elevation models (Alwan et al., 2020). DEMs are now predominantly created using remote sensing techniques with observing the benefits that a large spatial area can be mapped by few people at a lower cost (Smith & Clark, 2005).

Digital Surface Models (DSMs) are the basic component for 3D presentation of the bare-earth surface, vegetation, forest and human made structures such as buildings above bare topography (Sefercik et al., 2012). The most common techniques for DSM generation from satellite imagery are optical stereoscopy and Interferometric Synthetic Aperture Radar (InSAR) (Sefercik et al., 2012). For DSM from optical stereoscopy, it uses image parallax and obtain coordinate differences between conjugate points in the pair of overlapping images and basing on their geometry, extraction of elevation information is achieved. On the other side DSM from InSAR, uses two acquired SAR images which are accurately registered and resampled. Several DSM have been released to the public like SRTMv3-1″, ALOSv3.2-1″, ASTERv3-1″, TanDEM-X-3″, SRTM3″-original, ASTERv2-1″ and ALOSv2-1″ where by their quality vary in different area. Available public DSMs and DEMs used in this study are well described from previous studies as follows, NASA DEM has been explained by (Mavunde, 2021) page 18. Also ALOSv3.2-1″, TanDEM-X-3″ and MERIT DEM have been well explained by (Mbago, 2022) page 25-31. The selected public DSMs in this proposal, TanDEM-X-3″ is generated using InSAR (Leonardo et al., 2020) and ALOSv3.2-1″ is generated using optical stereoscopy (Takaku et al., 2016).

The DSM models the top surface of the land cover, such as forest canopy, whereas DEM models the bare terrain ground after removing the land cover, such as trees (Balenovic et al., 2015). Therefore, we can derive a DEM (DTM) if we have a Canopy Height Model (CHM) by subtracting the CHM from the available public DSM. A previous study on derivation of DEMs from DSMs using the Old GEDI CHM have been explained by (Siles, 2021).The DEMs to be generated in this research will require the use of the above selected DSMs intergraded together with Old and New GEDI CHMs of which are briefly described in the next paragraph. Figure 1-1 below shows the relationship between DSM, DEM (DTM) and CHM.

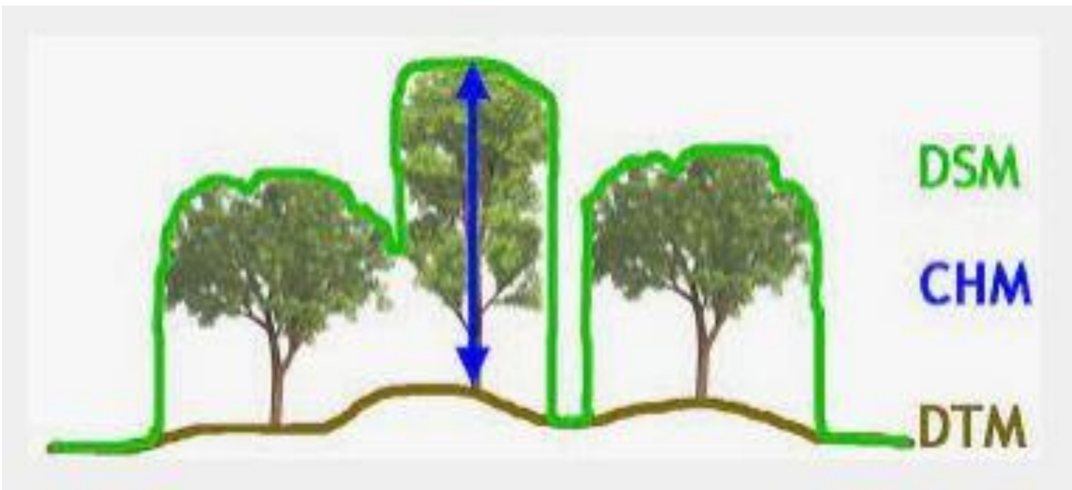

Figure 1-1: Relationship between DSM, DEM (DTM) and CHM.
Source: (https://www.researchgate.net) (April 2011)

Given forests' central relevance to life on our planet, several new space missions have been developed to measure vegetation structure and biomass, such mission include Global Ecosystem Dynamics Investigation (GEDI) which is a full wave LiDAR instrument which takes detailed Earth's surface 3D structure measurements by processing the waveforms and obtain forest canopy heights from their returns for each footprint. A key mission is NASA's GEDI campaign, which has been collecting full-waveform LiDAR data explicitly for the purpose of measuring vertical forest structure globally, between 51.6˚ north and south (Dubayah et al., 2020). However, estimating forest characteristics like canopy height or biomass from optical images is a challenging task (Gibbs et al., 2007), as the physical relationships between spectral signatures and vertical forest structure are complex and not well understood (Rodriguez-Veiga et al.,2017).

The Old GEDI CHM is the LiDAR CHM -1″ with 30-m spatial resolution and Relative Height metric 95% (RH95) from GEDI LiDAR forest structure measurements and Landsat analysis-ready data time series which was extrapolated beyond the Global Land Analysis and Discovery (GLAD) data of forest height globally (52˚N and 52˚S). The New GEDI CHM is the fused GEDI LiDAR with Sentinel-2 CHM estimated from NASA's GEDI full waveform LiDAR (Lang et al., 2022). It has Relative Height metric 98% (RH98) ensemble with Convolutional Neural Networks (CNN) and has a 10-m spatial resolution globally (51.6˚N and 51.6˚S).

Different studies on DEMs determination using CHMs have been done by many scholars. Among of them include; (Hopkinson & Chasmer, 2009) proposed using a combination of airborne LiDAR data and different processing techniques to derive a DSM and a CHM. The CHM is then subtracted from the DSM to estimate forest canopy height and terrain relief. The authors suggested this approach as an accurate method for estimating terrain relief, particularly in areas with dense vegetation. (Kandare et al., 2015) proposed using Structure From Motion (SFM) techniques on Unmanned Aerial Vehicle (UAV) imagery to generate a DSM. They subtract a CHM from the DSM for flood modeling purposes and recommend the method as an effective approach for generating high-resolution DSMs from UAV imagery and subsequently deriving flood-relevant information by subtracting the CHM. (Carleer et al., 2013) compared the use of CHMs derived from SRTM and ASTER GDEM data for floodplain mapping. The CHMs are subtracted from the respective DEMs and suggested using CHMs derived from high-resolution LiDAR data instead of global DEMs for accurate floodplain mapping due to their improved quality and spatial resolution.

The advancement of technology in remote sensing techniques for creating DEMs has influenced highly developed countries to create a reliable DEM covering the whole country. In most developing countries including Tanzania still face challenges in creating a reliable DEM covering the whole nation. These challenges are due to the high cost and technical capabilities of the high quality remote sensing instruments as they perform on a wide coverage in short time (Johnson et al., 2021). GEDI provides data based on accurate measurements of the forest canopy heights using LiDAR full waveforms to generate a CHM in a global coverage to be used for various applications (Silva et al., 2018). The high resolution of the New GEDI CHM (10m) led to the improvement of accuracy in capturing the vertical structure of the canopy, the enhanced accuracy can contribute to generating more precise DEMs. In addition the model is trained with CNN which models unknown effects such as atmospheric noise and learns to robust waveform features that generalize to unseen geographical regions (Lang et al., 2022), thus can contribute to generating more precise DEMs after removing the above ground features. This study intend to take the availability of the Old and New GEDI CHMs to obtain best derived DEMs from various DSMs by subtracting Old and New GEDI CHMs from the DSMs i.e. (DEM=DSM−CHM). Therefore, TanDEM-X-3″ and ALOSv3.2-1″ DSMs are used in determination of the DEMs and conduct their vertical assessment in different land covers in Tanzania using GGCPs mostly from TAREF11. Later on, the derived DEMs are compared to public available NASA and MERIT DEMs in Tanzania.

1.2 Statement of Research Problem

Previous studies on assessment of public GDEMs in Tanzania indicated low accuracy and poor performance in various slightly mountainous and forested terrains and Western part of Arusha. The use of Old and New GEDI LiDAR CHMs with the ability to robust features in unseen geographical regions such as dense forested areas may give the opportunity to generate more reliable Digital Elevation Model (DEM) in Tanzania to be applied in various fields. This research deals with vertical assessment of derived DEMs from TanDEM-X-3″ and ALOSv3.2-1″ DSMs using the New and Old GEDI CHMs.

1.3 Objectives

1.3.1 Main Objective

The main objective of the study is to take advantage of the availability of Old and New GEDI CHMs, public DSMs to determine a better DEM than the current public available DEMs from different providers for Tanzania mainland.

1.3.2 Specific Objectives

i. Generation of DEMs from DSMs using New and Old GEDI CHMs
ii. Comparison of derived DEMs with available DEMs
iii. Assessment of the available and derived DEMs using GGCPs in Tanzania

1.4 Hypothesis

The derived DEMs from public available DSMs using the New GEDI CHM shows better vertical assessment results than the derived DEMs from available public DSMs using the Old GEDI CHM and current available public DEMs in Tanzania.

1.5 Significance of the Research

This research will present the bare terrain more accurately for Tanzania mainland from both old and new GEDI CHMs derived DEMs, hence obtain precise terrain height data for different required fieldworks which may require the use of DEMs as an alternative approach in completing the works. Thus become cost effective since it consumes less time and uses less manpower.

1.6 Beneficiaries

The beneficiaries of this research include; geomaticians, geodesists, natural resource managers, ecologists, environmentalists, cartographers, GIS and Remote Sensing, geo-hazards managers, engineers and generally all Earth Sciences fields.

1.7 Scope and Limitation

This study deals with the assessment of derived DEMs from TanDEM-X-3″ and ALOSv3.2-1″ DSMs only which are the selected public DSMs used in this study on different land covers found within 1˚N to 12˚S and 29˚E to 41˚E Tanzania mainland. The vertical assessment in the study uses GGCPs, as it focus only on the places where these GGCPs are located as it includes Lake Zone areas, western part of Arusha, flat and bare areas, mountainous and forested terrains. Both old and new GEDI CHMs will be used to derive DEMs from above selected public DSMs. All the two CHMs are trained with sparse supervision, using reference heights at globally distributed GEDI footprints, with full waveform LiDAR which is large to detect the ground on all terrains accurately. Figure 1-2 below shows the AOI and available GGCPs for vertical assessment

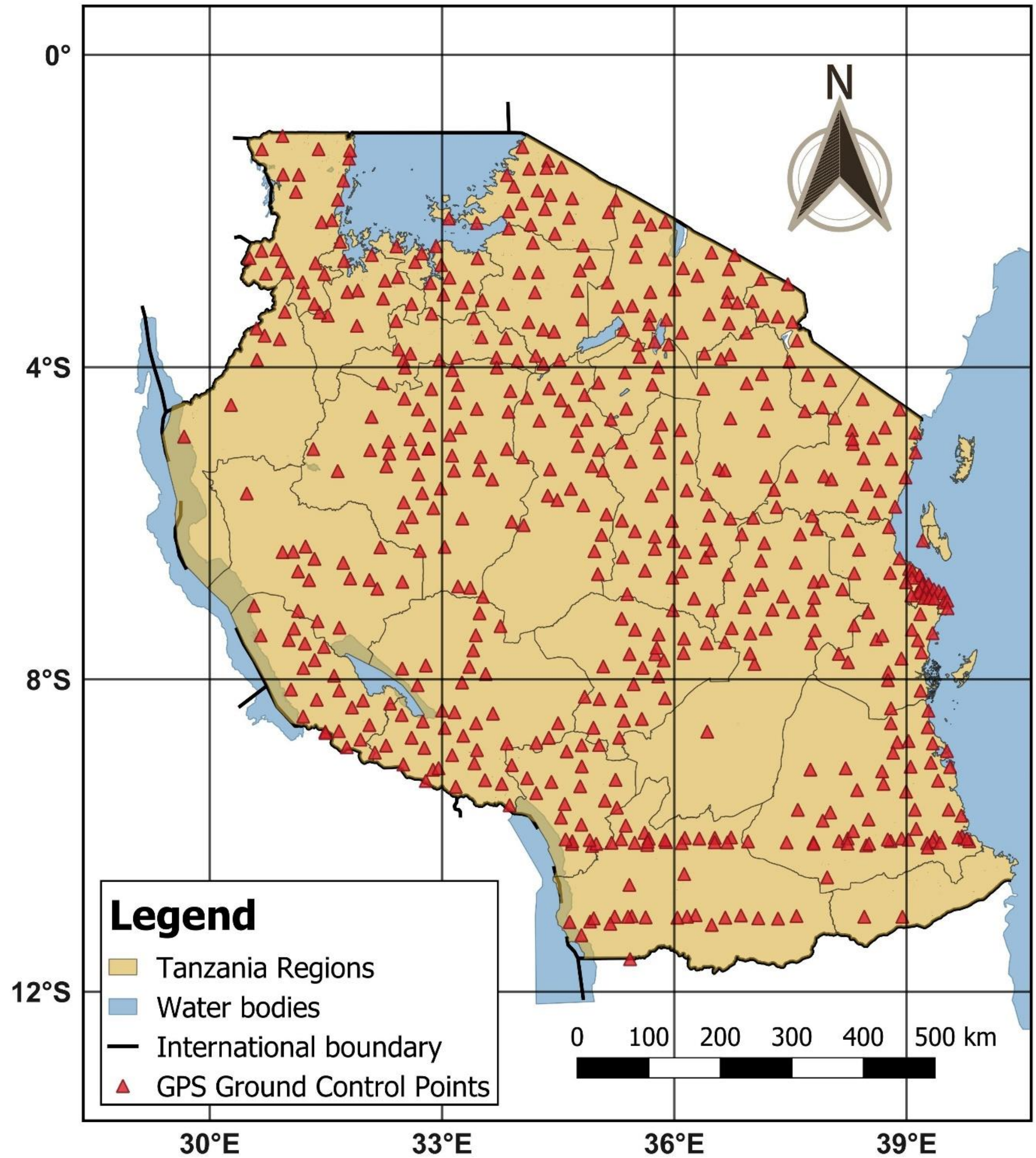

Figure 1-2: AOI and available GGCPs for vertical assessment

1.8 Structure and Organization of Dissertation

This dissertation is structured into five chapters, the contents for each chapter are as follows;

a) Chapter One

Chapter One introduces the study by explaining the background of the study, statement of the problem, main objective of the research, specific objectives of the research, hypothesis, scope and its limitation, significance of the research and beneficiaries of the research.

b) Chapter Two

Chapter Two in this research consist of literature review, DEMs generation methods, methods for DEMs vertical assessment, applications of DEMs, DSMs and CHMs, methods of analysis of results and method selected for this dissertation.

c) Chapter Three

Chapter Three explains the Methodology, data requirement and preparation and data description.

d) Chapter Four

Chapter Four presents the results obtained after Data processing according to methodology and Analysis of the results.

e) Chapter Five

Chapter Five consists of Conclusion drawn from this study and recommendations for the future related researches.

CHAPTER TWO

LITERATURE REVIEW

The development of science and technology in modern world has emphasized the experts in GIS and remote sensing to develop space missions such as NASA and JAXA and hence release Digital Elevation Data (DED) to be used in various applications. These DED includes the DSMs, DEMs and DTMs of which some are kept public and others are commercially available, referenced to a common vertical datum. The DSM models the top surface of the land cover, such as forest canopy, whereas DEM models the bare terrain ground after removing the land cover, such as trees (Balenovic et al., 2015). In analyzing GDEMs, important aspects to consider include acquisition of data, data modeling, data management, accuracy and application development (Lakshmi & Yarrakula, 2018). Since the remote sensing raw data provides a DSM at first, and then the DEM and the DTM are derived from it, then the quality of a DEM is also a function of how reliably the above ground features have been estimated and removed from the respective DSM (Ulotu, 2017). A DEM and a DSM may be used to determine a CHM. Canopy Height Model (CHM) refers to the mean height of the top surface of a forest's canopy derived by subtracting the DEM from the DSM (Ahmad et al., 2017). The CHM is not an elevation value, rather it is the height or distance between the ground and the top of the trees (Wasser, 2020). The GEDI mission from NASA which uses waveform LiDAR to generate LiDAR CHM can be used to derive DEMs from the DSMs by subtracting the LiDAR CHM from the DSMs.

2.1 DEMs Generation Methods

The following are some of the methods used to generate Digital Elevation Models with their respective interpolation, suitability and limitation.

i. Ground surveys

The DEMs generated from the ground surveys uses the ground elevation points as the data format and uses TIN to perform interpolation. The availability of ground surveys is suitable for small areas while it is expensive and time consuming to collect data for large areas. This method has a limitation of GPS does not provide reliable height under canopy (Alkema et al., 2016).

ii. Airborne photogrammetric surveys

The airborne photogrammetric surveys basically require aerial photography for generating a DEM. This method consists of manual and automatic interpolation methods of which they both use kriging interpolation. The manual method data format comprises of contours and measured point while the automatic method uses correlated points as the data format. The method is limited to some areas since it normally face problems with vegetation and measurement frequency (Alkema et al., 2016).

iii. Existing topographic map data

The existing topographic maps which are stored in softcopies can be used to generate a DEM by initially extracting the maps data. The data format used in topographic maps is primary contours and interpolation is done by kriging interpolation. The data can be readily available and can be done relatively cheap. This method has problems with vegetation and adds errors with digitizing (Alkema et al., 2016).

iv. Airborne laser scanning

The airborne laser scanning method generates a DEM basically by airborne instrument which is composed of laser scanner used to scan the features on the surface of the Earth. The data format is point data and the interpolation used is inverse distance weights. It is available at a lower cost and high resolution DEM, DSM and DTM are requested as products. In this method problems may occur with steep slopes and heavy vegetation areas (Alkema et al., 2016).

v. Radar based satellite imagery

The satellite imagery produced from radar technique can be used to generate a DEM in a given geographical area. A raster DEM is taken as its data format and there are no interpolation used during generation of a DEM. It costs lower than photogrammetry and a high resolution is possible but lower than LiDAR. The method faces problems with vegetation and steep slopes (Alkema et al., 2016).

vi. LIDAR based satellite imagery

The satellite imagery obtained from Light Detection and Ranging (LiDAR) technique is used to generate a DEM in a given area. The data format is usually in LASer (LAS) point values and uses kriging interpolation. It is available at low cost than photogrammetry methods and provides a high resolution DEM with a good accuracy as its covers a large area. The method suffers from an inability to penetrate in dense canopy and also faces difficulties in interpretation and processing of large datasets (Alkema et al., 2016).

2.2 Methods for DEMs Vertical Assessment

The vertical accuracy of a DEM means the accuracy in the elevation obtained at any location in the DEM. When talking about the accuracy of a DEM, two types of accuracies can be distinguished, absolute and relative vertical accuracies. The absolute vertical accuracy is the vertical accuracy with respect to a Geodetic-Cartographic Reference System where an official altitude Datum has been adopted (Mesa-Mingorance & Ariza-López, 2020). On the other hand, the relative vertical accuracy refers to the measure of point to point vertical accuracy within a specific dataset (Luebke, 2019). Determination of the quality of a DEM is done by assessing the absolute and relative accuracy. The accuracy assessment of DEM requires a large number of checkpoints with high accuracy at least three times more accurate than DEM elevations so as to obtain reliable measures (Athmania & Achour, 2014).

There are various methods used to assess the accuracy of DEMs elevation data in different parts of the world. The following are among the methods for DEMs vertical assessment;

i. DEM Vertical Assessment using GGCPs

The DEM elevations have to be assessed using the GGCPs heights which have to be converted to Orthometric height by subtracting geoid height from the GNSS points. Orthometric heights are subtracted from the corresponding DEM. Positive difference mean the interpolated DEM elevation is below the GGCPs elevation and negative errors denote the location where the DEM elevation was above GGCPs elevation (Luana et al., 2015). In the assessment the statistical parameters such as mean, RMS, SD and minimum and maximum values are necessary to be calculated and the results with smaller values generally indicates high vertical accuracy of a DEM. Advantage of this method is that independent reference geodetic control points are stable so has high accuracy which increase the spatial accuracy of the data. Disadvantage of GGCPs are not accessible in areas where there is dense forest, areas with rough/mountainous due to difficult of provision (Ulotu, 2017).

ii. DEM Vertical Assessment using Heights from Topographical maps

The vertical accuracy of the DEM can be assessed by use of topographical maps. These maps are digitized to obtain JPEG file format and later extract the useful details (elevation points and contour lines). Furthermore, georeferencing and projection of the horizontal positions is done when required so as to match with the DEM to be assessed. The spot levels from the topographical map are collected simply as reference elevation in ArcGIS (El-Quilish et al., 2018). The interpolation method for producing DEM which will be used in the vertical accuracy assessment by subtracting the topographic map height values from DEM elevation values to create residual surfaces (Ravibabu & Jain, 2008). The statistical results with smaller RMS, SD and minimum and maximum values indicates high vertical accuracy of the given DEM. When the maps are processed efficiently, the assessment will give reliable results. The method face the challenge of deficiencies in the course of contours on the topographic map especially in urban regions with compact buildings (Szypula, 2019).

iii. DEM Vertical Assessment using ICESAT/GLAS

The measurements of ice-sheet topography and atmospheric properties, clouds and associated temporal changes are taken by Geoscience Laser Altimeter System (GLAS) instrument. The Ice, Cloud and land Elevation Satellite (ICESAT) elevation data is referenced to the TOPEX/Poseidon-Jason ellipsoid (Beaulieu & Clavet, 2009). The elevation differences of DEM and ICESAT elevation data are to be calculated and statistical measures such as SD, mean, RMS, minimum and maximum value with smaller value point out a more accurate DEM. The assessment of DEM vertical accuracy using ICESAT land elevation data is essential specifically for geographical areas which have limited ground control points. In the comparison of DEM created from air photo with recent ICESAT data leads to a vertical shift due to the temporal gap obtained and may result to accuracy assessment problems (Beaulieu & Clavet, 2009).

iv. DEM Vertical Assessment using Another DEM

The vertical assessment of a DEM can also be performed using another available more accurate DEM but under the condition that both should be in the same horizontal and vertical datum. The resampling DEMs data to have a common resolution (higher to lower spatial resolution) is necessary. At a common grid intersection the difference in elevation between the two DEMs is calculated. The statistical results of the DEM such as with smaller SD and RMS generally indicates good performance. Comparing every grid of the DEM with those of more accurate DEM will deliver a very reliable assessment of accuracy (Ravibabu & Jain, 2008). The method encounter presence of excessively large discrepancies (outliers) between the elevation data of the DEMs and in general, would correspond to the existence of peaks or wells (Ariza-López & Reinoso-Gordo, 2021).

2.3 Applications of GDEMs and CHMs

The ability of GDEMs to derive actual ground height and height above ground has extensive practical and analytical applications. Depending on data capture GDEMs can be inform of DEMs or DSMs. Below is a summary of some of the applications of DEMs and DSMs starting with application of DEMs as discussed by (Balasubramanian, 2017) and (Croneborg et al., 2015).

i. Water resource management (WRM)

The shape of the terrain determines the flow of water and therefore a DEM is a critical component since it provides the shape of the terrain. WRM encompasses the hydrological and bathymetric modeling and analysis, which includes flow channel characterization, water catchment mapping, water supply and sanitation, flood plain management etc.

ii. Geological applications

DEMs are used in geology, geomorphology, and geophysics for example, in landform and geo-hazard mapping, subsidence or fault mapping based on shaded relief maps. To monitor seismic fault zones high resolution and accuracy DEMs are needed. Assessing damages after disasters such as earthquakes and volcanoes, comparing the DEMs before and after the event is useful.

iii. Coastal monitoring

DEMs are used in coastal areas to monitor and asses the impacts caused by climate change in coastal areas. This includes monitoring sea level rise, mapping coastal inundation, seafloor morphology etc.

iv. Infrastructures

DEMs are used to plan, map and asses different engineering infrastructures such as road infrastructure whereby DEMs are used to plan, map and constructing roads, as well as optimizing construction vehicle roads and ensuring safer working environment.

v. Agricultural sector

DEMs are used in agricultural sector to inform on planting and irrigation strategies, to avoid waterlogged crops, water-stressed crops in various terrains In addition, DEMs are used to develop contour-farming strategies to reduce soil erosion and crop nutrients loss along slope directions.

Applications of DSMs

i. Aviation

During construction of a runway or its maintenance, a DSM is used to assess encroachment along the runway approach zone and all obstruction present.

ii. Telecommunication

It is used in 3D modeling during design of a transmission line to manage vegetation along the line. The design of the site area is drawn using GIS or engineering software by considering the DSM map which shows vegetation coverage of the area.

iii. Urban planning

DEMs, DSMs and their derivatives are widely used in urban environmental planning and infrastructure assessment. Applications include checking how the proposed building would affect the view shed of residents, identifying building construction sites, assessing drainage structures and patterns.

iv. Commercial forestry

DEMs and DSMs are used in deriving value added CHM, which are in turn used to assess tree biomass, classify strand structure, plan harvest schedules, road planning and mapping.

There are numerous applications of Global Digital Elevation Models, the few described above are given to help users in different fields of study to understand clearly how they are utilized in various sectors.

Applications of CHMs

Applications of CHMs as discussed by (Nash, 2022) include the assessment of vegetation risk to power lines and other utility infrastructure, forest fuel load and fire risk, habitat suitability for wildlife, accurate visibility in forested regions from ground surface points. Also CHMs are used in creating and analyzing forest inventory, evaluating the condition of forests in recreational and protected areas, monitoring logging and forest recovery and modelling of forest metrics like tree size class, basal area and volume.

2.4 Methods of Analysis of Results

There are various methods of results analysis which includes visualization, statistical analysis and geostatistics. Statistical analysis was the method of results analysis used in this study.

Statistical Analysis

This is the method used to analyze the results in order to obtain the output of the research. The parameters which are usually used in the analysis are mean, Root Mean Squire (RMS) and Standard Deviation (SD). Mean is the measure of average value from the total and number of all available values in a set. RMS usually measures the difference s between values predicted by model or an estimator and the values observed. RMS has the ability to encompass all the random and systematic errors and also measure surface quality and give insight into the distribution of deviation on either side of the mean value. SD is the measure of amount dispersion of a set of values where by, high SD shows that the values are spread out over a wide range while low SD shows that the values tend to be close to the mean of the set. The researches which have been mostly conducted using the RMS and SD as their basis of comparison, the RMS and SD with smaller value is taken to be the superior in the analysis of the results.

2.5 Method selected for this Dissertation

In this Dissertation, four derived DEMs are compared with the available DEMs at their common grid intersection in the area of interest mainly to check for their agreement or disagreement and their conformity among the four derived DEMs. Furthermore, the assessment of the four derived DEMs using GGCPs is done because the points have significant high accuracy and cover large part over AOI. GGCPs ellipsoidal heights are converted to Orthometric heights using EGM96 geoid model so as to be compatible with the four derived DEMs from the GEDI CHMs and TanDEM-X-3″and ALOSv3.2-1″DSMs.

CHAPTER THREE

METHODOLOGY

In this part the methods, data availability and software used are well explained. Hence in the process of achieving the objective of this study, the procedures followed include; conversion of GGCPs ellipsoidal heights to Orthometric heights using EGM96, conversion of DSMs to EGM96 Orthometric heights so as to be compatible with the derived and available DEMs datum, generation of derived DEMs from selected DSMs and GEDI CHMs, computation of height differences between derived DEMs and GGCPs, comparison of derived DEMs at common grid intersection over the area of interest and finally the statistical analysis of the results, in which the height differences, mean, SD and RMS were calculated.

3.1 Conversion of GGCPs Ellipsoidal Height to EGM96 Orthometric Height

The ellipsoidal heights of the GPS ground control points were converted to Orthometric heights because they are physical and widely used in the world. The process of conversion was done by subtracting the geoid height of EGM96 geoid model from the GGCPs ellipsoidal height as shown in equation 3.1 below

$$H_{EGM96}^{GGCPs} = h_{GGCPs} - N_{EGM96} \quad (3.1)$$

3.2 Conversion of DSMs and GEDI CHMs to EGM96 Orthometric Heights

TanDEM-X-3″ DSM was converted to EGM96 Orthometric heights by using equation 3.2 below. ALOSv3.2-1″ DSM has EGM96 Orthometric height hence need no conversion. For the case of the two GEDI CHMs, since they are not referenced to a vertical datum hence the GEDI CHMs also need no conversion.

$$H_{EGM96}^{GDEM} = h_{GDEM} - N_{EGM96} \quad (3.2)$$

3.3 Generation of LiDAR DEMs from selected DSMs Using GEDI CHMs

The four derived DEMs were obtained where by, the first two derived DEMs by subtracting Old GEDI CHM from TanDEM-X-3″ and ALOSv3.2-1″ DSMs and other two derived DEMs by subtracting the New GEDI CHM from TanDEM-X-3″ and ALOSv3.2-1″ DSMs as shown in equations 3.3, 3.4, 3.5 and 3.6 below

$$H_{DEM1} = H_{DSM1} - LiDAR^{OLD}_{CHM} \quad (3.3)$$

$$H_{DEM2} = H_{DSM1} - LiDAR^{NEW}_{CHM} \quad (3.4)$$

$$H_{DEM3} = H_{DSM2} - LiDAR^{OLD}_{CHM} \quad (3.5)$$

$$H_{DEM4} = H_{DSM2} - LiDAR^{NEW}_{CHM} \quad (3.6)$$

Whereby;

H_{DEM} is Derived DEM

H_{DSM1} is ALOSv3.2-1″ public available Digital surface model

H_{DSM2} is TanDEM-X-3″ public available Digital surface model

$LiDAR^{OLD}_{CHM}$ is Old Canopy height model from GEDI

$LiDAR^{NEW}_{CHM}$ is New Canopy height model from GEDI

3.4 Height differences between Derived DEMs and GGCPs

The differences in height between the derived DEMs and GGCPs as shown below in equation 3.7 were computed and hence used in validating the results.

$$\Delta H^{GGCPs,DEM} = H^{GGCPs}_{EGM96} - H^{DEM}_{EGM96} \quad (3.7)$$

3.5 Comparison of Derived DEMs with Available DEMs at Common Grid Intersection Over the AOI

The four derived DEMs were compared with the available MERIT DEM and NASA DEM in terms of their height differences at common grid intersection over AOI using equation 3.8 below.

$$\Delta H^{DEM1,DEM2} = H^{DEM1}_{EGM96} - H^{DEM2}_{EGM96} \quad (3.8)$$

Whereby;

$\Delta H^{DEM1,DEM2}$ is height difference between a derived DEM and available DEM

3.6 Statistical Analysis

After the derivation of DEMs from selected DSMs and GEDI CHMs, in their vertical assessment using GCCPs the statistical analysis was performed by computing the Mean, Root Mean Square and Standard Deviation as shown in equations 3.9, 3.10, 3.11 respectively.

i. Mean of height differences between GGCPs and derived DEMs

$$\text{ME} = \frac{1}{n}\sum_{i=1}^{n}\Delta H^{GGCPs,DEM} \tag{3.9}$$

Whereby;

ME is mean,

n is number of GGCPs

$\Delta H^{GGCPs,DEM}$ is height difference between GGCPs and derived DEM

ii. Root mean square

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta H^{GGCPs,DEM})^{2}} \tag{3.10}$$

Whereby;

RMS is Root Mean Square

iii. Standard deviation

$$\text{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\Delta H^{GGCPs,DEM} - ME)^{2}} \tag{3.11}$$

Whereby;

SD is Standard deviation

The same procedures were followed for statistical assessment of height differences between derived DEMs and available DEMs.

3.7 Data Requirements, Description and Preparation

This research require six different types of data which are from selected DSMs Old and New GEDI CHMs, GGCPs and public DEMs all over Tanzania mainland. All the downloaded data consists of basic elevation information and can be obtained from their respective achieves which are described on the Table 3-1 below. Also in Table 3-2 below is a short summary of data used based on owners, released date, spatial resolution and their vertical and horizontal Datum.

Table 3-1: Achieves for the Data source

NO	Data	Website
1	TanDEM-X-3″	https://geoservice.dlr.de/web/dataguide/tdm90
2	MERIT DEM	https://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/index.html
3	NASA DEM	https://Ipdaac.usgs.gov/tools/earthdata
4	OLD GEDI CHM	https://gedi.umd.edu/data/download
5	NEW GEDI CHM	https://langnico.github.io/globalcanopyheight
6	ALOSv3.2-1″	https://www.eorc.jaxa.jp
7	EGM96	https://earthinfo.nga.mil/GandG/wgs84/gravitymod/index.html

Table 3-2: Summary of the Data to be used

No	Name	Owner	Date	Resolution	Datum	
					Hz	Vt
1	TanDEM-X-3″	DLR-German	March 2018	90m	WGS84	WGS84
2	ALOSv3.2-1″	JAXA-Japan	Jan 2021	30m	WGS84	EGM96
3	OLD GEDI CHM	NASA and University of Maryland	Jan 2020	30m	WGS84	No datum
4	NEW GEDI CHM	NASA, ETH Zurich, University of Zurich and Yale University	April 2022	10m	WGS84	No datum
5	MERIT DEM	Tokyo University	Oct 2018	90m	WGS84	EGM96
6	NASA DEM	NASA	Jan 2020	30m	WSG84	EGM96

3.7.1 TanDEM-X-3″ DSM

TanDEM-X is an Earth observation radar mission that consists of a SAR interferometer built by two almost identical satellites flying in close formation. TanDEM-X-3″ is a global 90m DSM with reduced pixel spacing of 90m, accessible without quota limitations and free of charge for scientific use. The dataset is referenced to both horizontal and vertical WGS84 datum. TanDEM-X-3″ DSM is downloaded from its respective archives as described in Table 3-1 above in a compressed ZIP (* zip) format which is well explained by (Mapunda, 2019). The processing of the DSM after being downloaded was done in Surfer v15 which included merging of the GeoTIFF tiles to a single tile in AOI, converting the single tile to grid format, converting the ellipsoidal heights to EGM96 Orthometric heights and finally derivation of DEMs after subtracting GEDI CHMs from its gridded data at common grid point intersection.

3.7.2 ALOSv3.2-1″ DSM

ALOSv3.2-1″ is a freely available global DSM dataset collected by JAXA with a horizontal resolution of approximately 30 m. The DSM is derived from satellite based stereo-photography which is generated from images collected using PRISM. The dataset is referenced to horizontal datum WGS84 and vertical datum EGM96. The data is downloaded freely over AOI in Open Topography website as explained by (Mbago, 2022). After downloading the data, the GeoTIFF tiles were merged and resampled to 3 arc seconds to accommodate common grid point intersection during derivation of DEMs and their comparison using Surfer v15.

3.7.3 Old GEDI CHM

The model is from GEDI NASA mission in which a full-waveform LIDAR was attached to the International Space Station to provide the first global, high-resolution observations of forest vertical structure data product. Lower level data products (L1 & L2) are available from the NASA LPDAAC and the higher level products (L3 & L4) from the ORNL DAAC. The CHM has Spatial resolution of 30-m and spatial coverage within a global extent of 52˚N and 52˚S. The model is based on WGS84 reference system for horizontal positioning and it is not based on any vertical datum. The data was downloaded as a single GeoTIFF tile, clipped in AOI, converted to DTED, gridded and resampled to 3 arc seconds to accommodate common grid point intersection during derivation of DEMs from selected DSMs using Surfer v15.

3.7.8 New GEDI CHM

The model describes a deep framework to map canopy top height with high spatial resolution of 10m globally 51.6˚ N and 51.6˚ S, using publicly available optical satellite images as input. This CHM is constructed based on data from Copernicus Sentinel-2 mission with multispectral sensor delivers optical images covering the global landmass operated by the ESA and NASA's GEDI ongoing space missions, hence the model was developed by fusion of GEDI LiDAR with Sentinel-2. The model is based on WGS84 reference system for horizontal positioning and it is not based on any vertical datum. The data was downloaded in GeoTIFF tiles, converted to DTED, merged, gridded and resampled to 3 arc seconds to accommodate common grid point intersection during the derivation of DEMs from selected DSMs using Surfer v15.

3.7.5 NASA DEM

NASA DEM is a reprocessing of STRM data, with improved accuracy by incorporating auxiliary data from ASTER GDEM, ICESat GLAS, and PRISM datasets. The most significant processing improvements of the DEM involve void reduction through improved phase unwrapping and using ICESAT GLAS data for control hence improvements in height accuracy and data coverage as well as providing additional SRTM radar-related data products. The dataset is referenced to horizontal datum WGS84 and vertical datum EGM96. The data are in 1 arc second and was downloaded as well explained by (Mbago, 2022), merged, gridded and resampled to 3 arc seconds to accommodate common grid point intersection during comparison with derived DEMs using Surfer v15.

3.7.6 MERIT DEM

MERIT is an improved terrain DEM which separates absolute bias, stripe noise, speckle noise and tree height bias using multiple satellite datasets and filtering techniques. The DEM file is named according to the intervals of latitudes and longitudes of a given coverage area. MERIT DEM is referenced to WGS84 as horizontal datum and the EGM96 as vertical datum. In order to read the files directly from the GDEM you must know the exact format of the entire file format. The downloaded MERIT DEM files elaborated by (Mbago, 2022) contains elevation values which are in 3 arc seconds was merged then converted to grid and DAT format for further processing in Surfer v15.

3.7.7 GGCPs

The GPS ground control points can be obtained from the Ministry of Lands Housing and Human Settlement Development (MLHHSD) under the Surveys and Mapping Division (SMD). The given GGCPs heights are ellipsoidal heights and they cover large part of Tanzania with exception of areas with dense forest. It includes CORS, zero order, first order and second order points.

3.7.8 Software Packages

The following are the selected software used in this study.

- ❖ Golden surfer v15

It is used to convert all the data from their formats GeoTIFF to grid format and from grid to DAT format for elevation extraction, to merge the individual tiles of the downloaded GDEMs to a single tile covering AOI, to resample the data to have common grid intersection, to compute Orthometric height differences between derived DEMs and selected public available DEMs and between derived DEMs and GGCPs. Also it is used to prepare Derived DEMs surface maps and calculate the Mean, SD and RMS of the computed height differences.

- ❖ ArcGIS

The ArcGIS software is used in conversion of GEDI CHMs GeoTIFF tiles to be readable as DTED and prepare AOI map in this study.

- ❖ Microsoft package

The Microsoft Excel is used in the arrangement of the results and Microsoft Word for report preparation and organization.

CHAPTER FOUR

RESULTS AND ANALYSIS OF RESULTS

In this part the results obtained are clearly presented after following all the systematic procedures of data processing from the selected methods in chapter three. The analysis of results are later discussed using the selected statistical approaches.

4.1 Results

The results include four derived DEMs from TanDEM-X-3″ and ALOSv3.2-1″ public selected DSMs and GEDI CHMs (Old and New GEDI CHMs), statistics of height differences between the derived DEMs and public available MERIT DEM and NASA DEM countrywide and in twelve selected land covers. On the other hand, the vertical assessment of derived DEMs using GGCPs countrywide and in twelve selected land covers at 95% confidence level is presented in this chapter. The statistics of height differences include number of values, maximum value (MAX), minimum value (MIN), mean, Standard Deviation (SD) and Root Mean Squire (RMS). The data of all the four derived DEMs obtained in this study have a spatial resolution of 90m (3 arc seconds).

In this study four DEMs have been generated over the area of interest that is Tanzania mainland from the Old GEDI and New GEDI CHMs and TanDEM-X-3″ and ALOSv3.2-1″ public selected DSMs. Figure 4-1 to Figure 4-4 below shows the four derived DEMs in surface map generated over AOI using the Old GEDI and New GEDI CHM.

The four derived DEMs presented in this chapter which are used in the vertical assessment are denoted as follows;

DEM 1 is ALOSv3.2-1″ derived DEM using the Old GEDI CHM

DEM 2 is ALOSv3.2-1″ derived DEM using the New GEDI CHM

DEM 3 is TanDEM-X-3″ derived DEM using the Old GEDI CHM

DEM 4 is TanDEM-X-3″ derived DEM using the New GEDI CHM

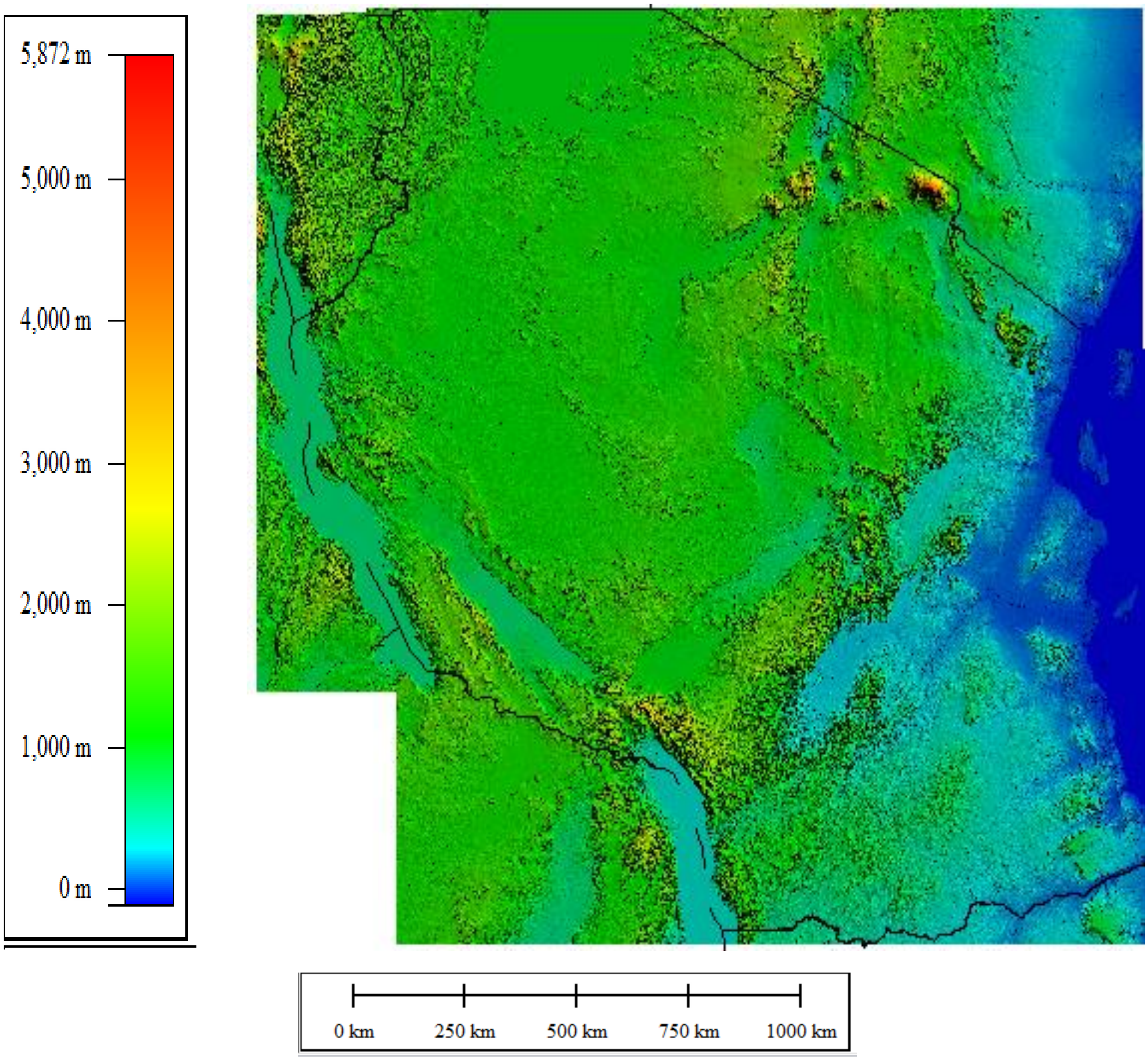

Figure 4-1: ALOSv3.2-1″ derived DEM surface map generated using Old GEDI CHM

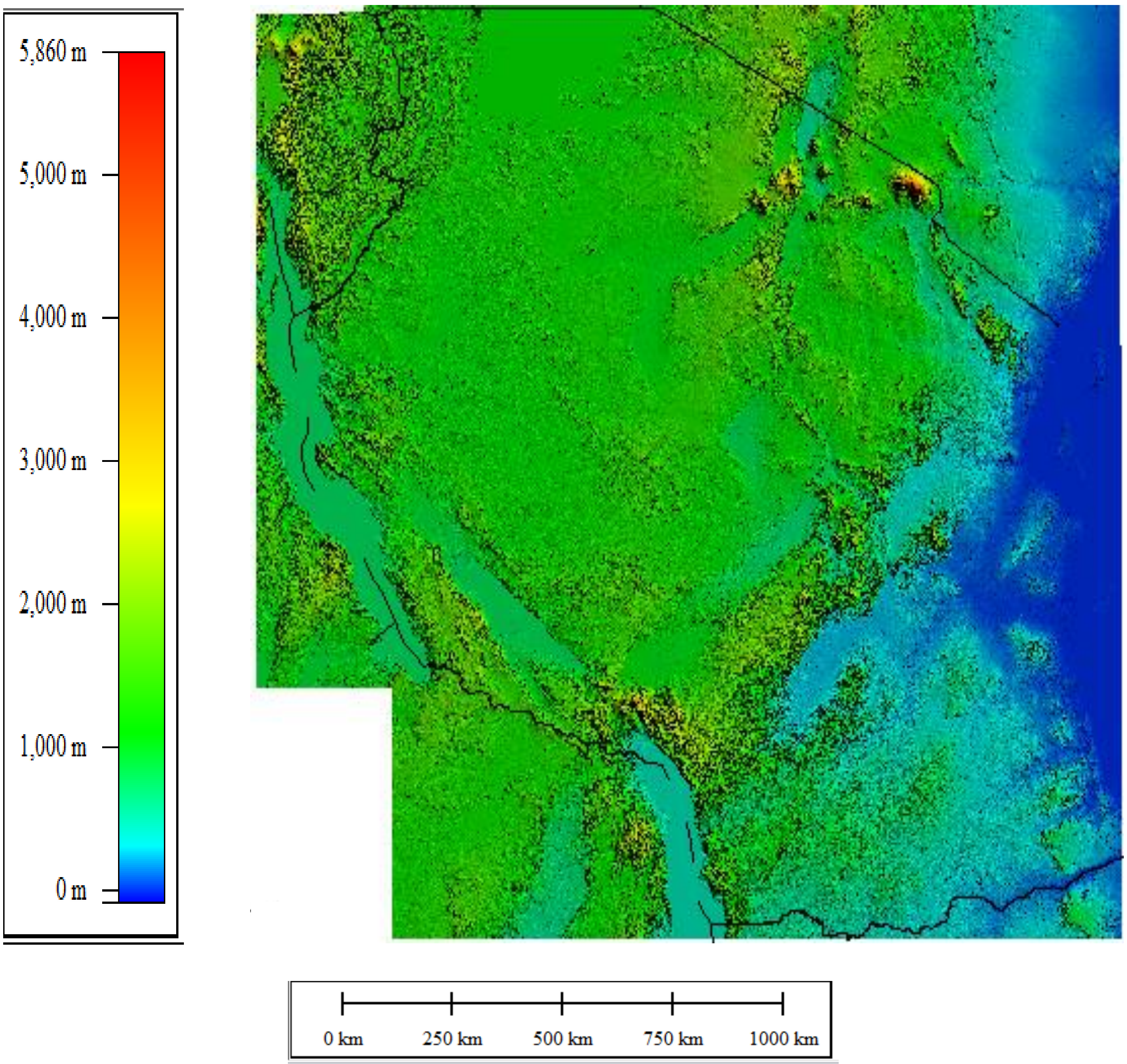

Figure 4-2: ALOSv3.2-1″ derived DEM surface map generated using New GEDI CHM

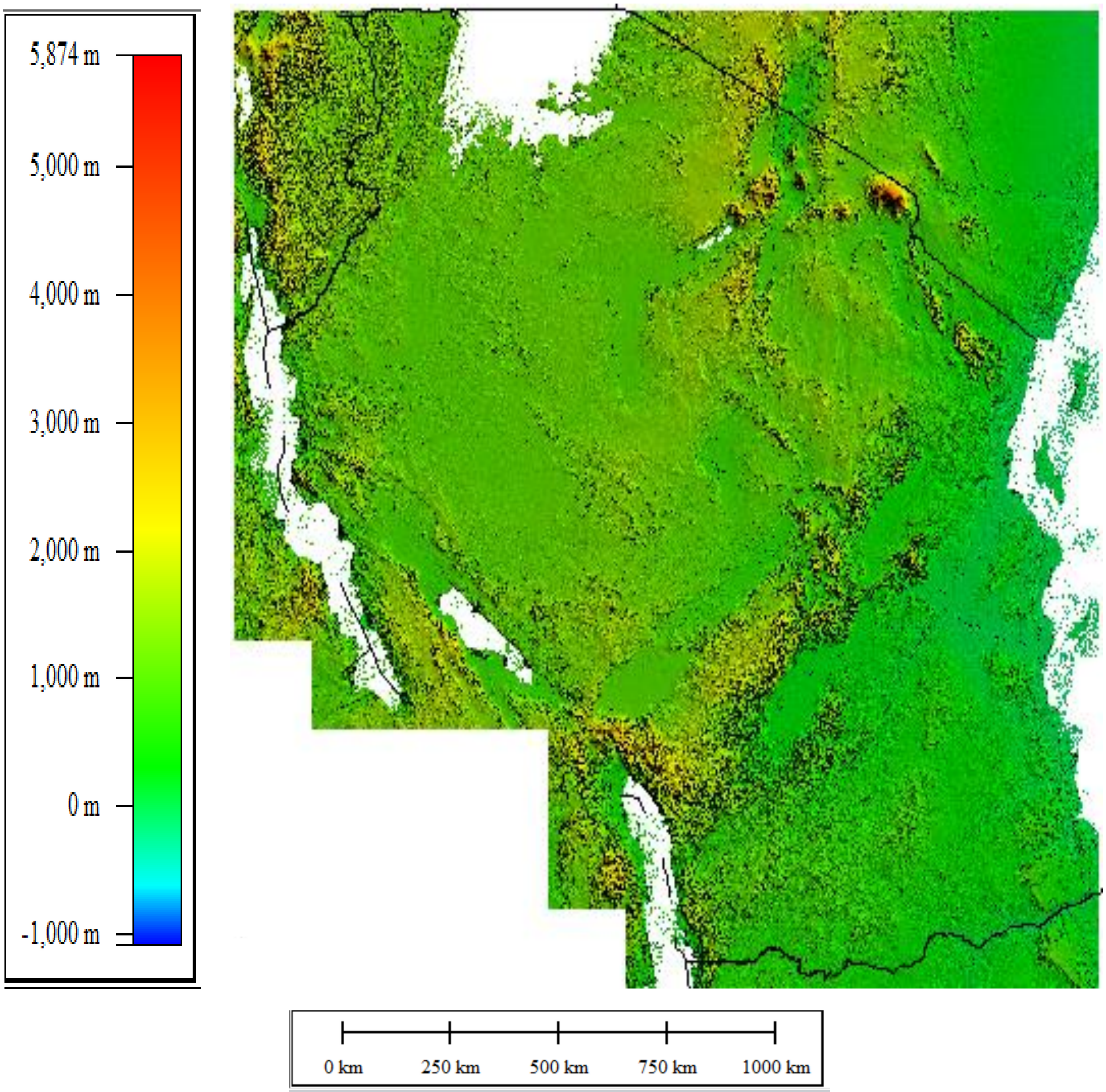

Figure 4-3: TanDEM-X-3″ derived DEM surface map generated using Old GEDI CHM

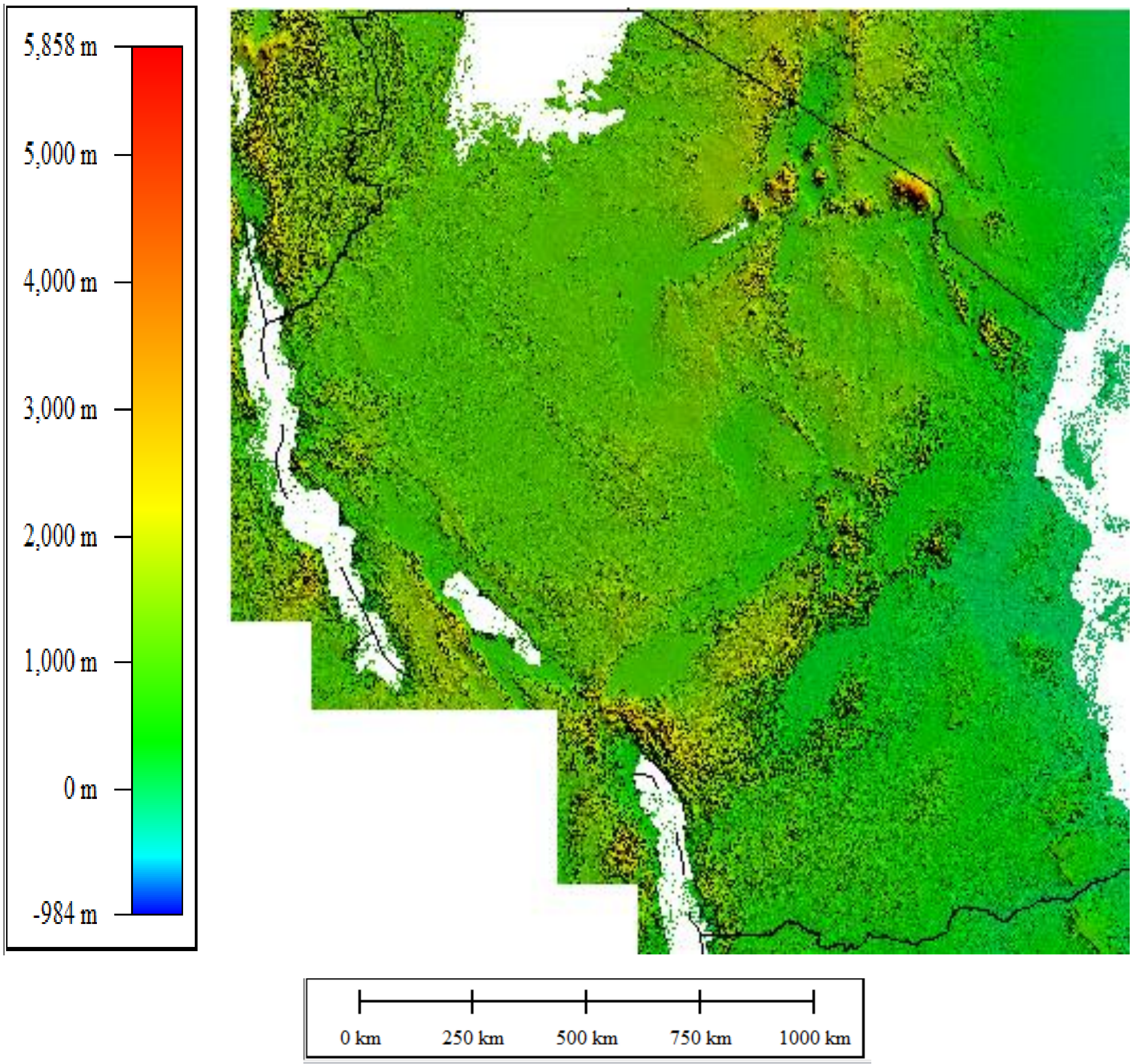

Figure 4-4: TanDEM-X-3″ derived DEM surface map generated using New GEDI CHM

4.1.1 Comparison between Derived DEMs with NASA DEM Countrywide

The comparison was done using mathematical relations presented in chapter three that is equations (3.8, 3.9, 3.10 and 3.11). The results are presented in Table 4-1 below.

Table 4-1: Statistics of height differences between derived DEM with NASA DEM Countrywide

HEIGHT DIFFERENCE	NO OF VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
NASA DEM – DEM 1	129582409	-1049.63	432.81	2.18	6.26	6.63
NASA DEM – DEM 2	143881596	-1054.11	450.03	3.95	7.19	8.20
NASA DEM – DEM 3	128110264	-1811.00	1851	3.30	8.48	9.10
NASA DEM – DEM 4	129920587	-1912.00	1750	5.57	9.08	10.65

4.1.2 Comparison between Derived DEMs with MERIT DEM Countrywide

The comparison was done using mathematical relations presented in chapter three that is equations (3.8, 3.9, 3.10 and 3.11). The results are presented in Table 4-2 below.

Table 4-2: Statistics of height differences between derived DEM with MERIT DEM Countrywide

HEIGHT DIFFERENCE	NO OF VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
MERIT DEM – DEM 1	146404527	-1096.24	612.48	2.06	5.13	5.53
MERIT DEM – DEM 2	155167012	-1100.72	642.42	3.86	5.72	6.90
MERIT DEM – DEM 3	137784640	-1809.98	1852.05	3.07	7.73	8.32
MERIT DEM – DEM 4	139341930	-1910.98	1751.05	5.37	8.37	9.94

4.1.3 Statistics of Height Differences between the Derived DEMs with NASA DEM and MERIT DEM in the Selected Land Covers

From 12 selected land covers as seen in Table 4-3 below, this selection is referred to previous studies on validation of DEMs in Tanzania by (Augustino, 2020). The results for statistics of height differences between derived DEMs with NASA DEM and MERIT DEM presented from Table 4-4 to Table 4-11 below

Table 4-3: List of selected land covers for the vertical assessment

Symbol	Relief Area	Regions
T1	Flat and bare terrain	Dodoma
T2	Mountainous and forested terrain	Kilimanjaro and Arusha
T3	Flat and plain Terrain	Tabora
T4	Barely flat and forested coastal terrain	Mtwara
T5	Slightly mountainous and forested terrain	Morogoro
T6	Forested and fairly flat terrain	Tanga
T7	Highlands and forested terrain	Mbeya
T8	Flat and forested coastal terrain	Lindi
T9	Western part of Arusha	Ngorongoro
T10	Western branch of great rift valley	Tanganyika
T11	Lake zone areas (Victoria)	Mwanza, Kagera, Geita and Mara
T12	Eastern branch of great rift valley	Natron

Table 4-4: Statistic of height differences between NASA DEM and DEM 1 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4001290	-63.85	140.77	0.83	5.21	5.28
T2	6214199	-298.98	386.40	0.96	5.44	5.52
T3	12945163	-59.40	214.49	2.14	5.32	5.73

T4	5014534	-120.15	115.47	3.03	5.60	6.37
T5	9732917	-305.75	153.53	2.70	6.95	7.46
T6	2735590	-1018.07	389.00	2.53	6.74	7.20
T7	3730763	-63.48	112.63	2.64	4.47	5.19
T8	11602116	-249.89	133.73	2.40	5.99	6.45
T9	1353493	-77.10	123.95	3.12	7.45	8.08
T10	7476683	-172.49	199.08	3.95	7.17	8.19
T11	8927096	-95.93	207.40	1.11	6.62	6.71
T12	1586016	-98.09	142.08	2.01	7.75	8.01

Table 4-5: Statistic of height differences between NASA DEM and DEM 2 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4203118	-67.89	157.13	2.67	6.60	7.12
T2	6231522	-290.81	409.27	2.60	6.89	7.36
T3	12967172	-76.20	128.55	4.14	6.98	8.11
T4	5037270	-127.41	85.04	4.58	5.72	7.33
T5	9773524	-297.43	170.04	6.91	8.65	11.07
T6	2949740	-1020.00	406.13	5.96	7.20	9.35
T7	3731027	-59.99	132.03	4.74	6.49	8.04
T8	12967140	-253.89	127.02	6.56	6.79	9.44
T9	856576	-71.42	150.63	5.01	8.02	9.46
T10	9885760	-180.10	199.50	3.65	7.33	8.19
T11	12679339	-101.16	121.38	1.26	4.97	5.13
T12	1643701	-86.53	150.63	2.83	7.10	7.64

Table 4-6: Statistic of height differences between NASA DEM and DEM 3 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4200878	-112.63	168.85	1.47	7.73	7.87
T2	173756116	-511.57	1069.12	1.33	7.11	7.23
T3	12943076	-58.22	247.67	3.20	4.67	5.66
T4	5320218	-94.95	207.42	4.31	5.66	7.11
T5	173557693	-554.20	238.00	4.85	10.26	11.34
T6	2733834	-266.20	389.60	3.74	9.77	10.46
T7	3730885	-200.34	159.06	2.99	6.32	6.99
T8	11617891	-1067.75	215.01	4.98	6.23	7.98
T9	2423691	-518.84	371.23	1.89	8.97	9.17
T10	7209703	-1289.20	1839.74	4.61	10.13	11.13
T11	8945987	-548.07	1138.54	2.30	8.24	8.55
T12	1586470	-518.84	293.30	2.13	10.40	10.62

Table 4-7: Statistic of height differences between NASA DEM and DEM 4 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4202576	-100.30	181.60	3.32	8.66	9.27
T2	6226769	-489.40	957.15	2.91	8.07	8.58
T3	12967031	-115.57	146.67	5.22	6.39	8.25
T4	5330689	-90.24	209.31	5.77	6.10	8.40
T5	174219038	-655.20	209.53	3.01	11.30	11.69
T6	159015423	-282.02	441.93	7.53	9.82	12.37
T7	3730681	-184.84	140.26	5.08	7.69	9.22
T8	11722266	-1168.75	203.01	9.75	6.97	11.98
T9	1382083	-242.90	282.71	3.91	9.30	10.09

T10	7296202	-1390.20	1748.74	5.65	10.54	11.96
T11	9144845	-649.07	1037.54	3.97	7.15	8.18
T12	1641218	-528.19	258.84	3.02	9.76	10.22

Table 4-8: Statistic of height differences between MERIT DEM and DEM 1 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4200897	-113.91	127.30	1.33	4.51	4.70
T2	6210618	-399.11	326.79	2.12	4.48	4.96
T3	12940878	-73.91	225.48	1.37	4.37	4.58
T4	5007128	-128.80	111.48	1.46	4.59	4.82
T5	9730004	-325.46	145.59	2.26	5.76	6.18
T6	2788025	-1096.20	199.31	2.05	5.84	6.19
T7	3730679	-75.99	113.18	2.90	4.08	5.01
T8	11584901	-271.17	154.69	0.75	4.82	4.88
T9	1350598	-108.09	284.89	2.91	5.86	6.54
T10	8213681	-197.06	178.34	3.86	6.12	7.24
T11	8903938	-107.64	220.75	1.62	4.89	5.15
T12	1581845	-149.32	284.89	2.35	6.29	6.71

Table 4-9: Statistic of height differences between MERIT DEM and DEM 2 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4153062	110.64	141.05	2.93	4.84	5.66
T2	6081977	-407.22	353.41	3.27	4.65	5.68
T3	12931985	-80.11	132.28	3.35	6.29	7.13
T4	4998801	-135.80	116.24	3.07	5.88	6.63

T5	9504666	-316.80	164.12	6.02	6.37	8.76
T6	2693593	-1100.70	229.69	5.36	4.65	7.09
T7	3694360	-69.95	133.28	4.80	5.75	7.49
T8	11611304	-272.77	175.43	5.77	6.31	8.55
T9	1377064	-92.73	297.85	3.71	4.94	6.18
T10	11086440	-206.36	194.99	3.33	5.95	6.82
T11	12650122	-119.89	134.59	2.62	4.18	4.93
T12	1607036	-147.67	297.85	3.13	5.07	5.96

Table 4-10: Statistic of height differences between MERIT DEM and DEM 3 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4200730	-120.24	223.55	1.98	7.40	7.66
T2	6211589	-512.07	1125.31	2.50	6.74	7.19
T3	12941602	-89.52	252.61	2.44	3.92	4.62
T4	5736172	-109.70	247.61	2.83	5.30	6.01
T5	9732931	-505.50	238.77	3.41	9.92	10.49
T6	2786541	-280.29	287.35	3.29	9.25	9.82
T7	3730813	-198.69	170.51	3.24	6.17	6.97
T8	11584643	-109.70	229.52	3.26	4.93	5.91
T9	1341027	-293.42	389.94	2.42	9.14	9.45
T10	7660293	-1810	1852.03	4.52	9.93	10.91
T11	8936495	-573.91	1150.50	2.92	7.72	8.25
T12	1585236	-554.35	297.07	2.63	10.50	10.82

Table 4-11: Statistic of height differences between MERIT DEM and DEM 4 in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	4202553	-113.01	228.21	3.83	7.85	8.76
T2	6225368	-503.74	1142.98	4.11	7.44	8.50
T3	12966978	-120.81	151.61	4.48	5.80	7.33
T4	5742782	-99.70	250.61	4.04	6.54	7.69
T5	9771377	-606.49	202.37	7.63	10.38	12.88
T6	2787387	-278.29	295.35	7.24	9.26	11.75
T7	3730654	-198.69	135.33	5.34	7.40	9.13
T8	11608536	-152.77	241.19	8.29	6.34	10.44
T9	1382230	-284.76	295.68	3.88	8.85	9.66
T10	7845123	-1911	1751.03	5.54	10.32	11.71
T11	9188250	-674.91	1049.50	4.72	7.01	8.45
T12	1640768	-554.35	292.74	3.68	9.63	10.31

4.1.4 Statistics of Vertical Assessment of DEMs Using GGCPs Countrywide.

This comparison was done using the mathematical relations presented in chapter three that is equations (3.7, 3.9, 3.10 and 3.11). The statistical results are presented in Table 4-12 below

Table 4-12: Statistics of height differences between DEMs and GGCPs Countrywide

HEIGHT DIFFERENCES	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
GGCPs – MERIT DEM	573	-10.24	6.69	-0.60	3.56	3.61
GGCPs – NASA DEM	574	-9.65	7.43	0.22	3.71	3.72
GGCPs – DEM 3	570	-8.38	8.74	1.01	3.59	3.73
GGCPs – DEM 1	573	-9.88	7.35	-0.54	3.69	3.73
GGCPs – DEM 2	574	-6.98	10.03	1.88	4.12	4.53
GGCPs – DEM 4	570	-5.27	11.66	3.64	4.05	5.44

4.1.5 Vertical Assessment of DEMs Using GGCPs in the selected Land Covers.

The results for the statistics of vertical assessment of DEMs in the 12 selected land covers using the mathematical relationship from chapter three in equations (3.7, 3.9, 3.10 and 3.11) are well presented in this section from Table 4-13 to Table 4-18.

Table 4-13: Statistics of height differences between DEM 1 and GGCPs in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	19	-9.88	5.79	-0.57	4.41	4.45
T2	18	-4.64	3.28	-0.50	2.04	2.10
T3	52	-7.05	6.94	-0.57	3.06	3.11
T4	5	-4.78	5.59	-1.08	4.76	4.88
T5	27	-9.88	7.35	0.05	4.55	4.55
T6	9	-1.79	7.32	2.00	3.59	4.10
T7	14	-8.22	5.93	-0.85	3.56	3.66
T8	30	-9.39	4.34	-3.15	3.63	4.81
T9	6	-2.48	5.70	2.19	3.07	3.77
T10	8	-5.64	3.70	-1.42	3.34	3.63
T11	46	-9.38	6.98	-0.24	3.88	3.89
T12	5	-8.18	4.55	-1.20	4.67	4.82

Table 4-14: Statistics of height differences between DEM 2 and GGCPs in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	19	-4.82	9.20	3.59	3.71	5.16
T2	19	-2.20	10.03	2.46	4.03	4.72
T3	50	-6.64	7.66	0.33	3.20	3.22

T4	6	-6.38	8.39	3.03	5.55	6.32
T5	24	-5.79	8.94	2.31	4.06	4.67
T6	9	-0.21	9.58	5.27	3.88	6.54
T7	12	-4.72	8.64	1.55	4.30	4.57
T8	31	-6.47	9.09	1.39	4.15	4.38
T9	6	-2.04	10.03	4.41	4.18	6.08
T10	8	-5.35	6.50	-0.02	4.03	4.03
T11	46	-6.82	9.57	2.43	4.51	5.12
T12	5	-4.15	3.96	0.38	3.10	3.12

Table 4-15: Statistics of height differences between DEM 3 and GGCPs in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	22	-7.70	8.07	0.53	4.78	4.81
T2	18	-4.31	7.88	1.11	3.17	3.36
T3	51	-6.08	7.51	0.92	2.61	2.77
T4	6	-8.38	6.13	-0.32	5.39	5.40
T5	29	-7.42	8.07	1.91	3.98	4.41
T6	8	-1.76	7.13	2.83	3.09	4.19
T7	15	-7.90	7.11	-0.48	4.39	4.47
T8	31	-8.38	7.45	0.79	3.95	4.03
T9	6	-1.92	4.78	1.05	2.46	2.67
T10	8	-4.82	2.32	-0.80	2.28	2.42
T11	47	-8.21	8.69	0.73	3.48	3.56
T12	4	-8.13	1.55	-2.88	4.26	5.14

Table 4-16: Statistics of height differences between DEM 4 and GGCPs in the 12 selected land covers in Tanzania

RELIEF AREA	NO VALUES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
T1	19	-2.45	10.46	4.89	3.70	6.13
T2	18	-2.67	9.98	3.38	3.99	5.23
T3	51	-2.51	11.3	2.51	3.22	4.08
T4	5	-4.51	11.29	4.12	5.93	7.22
T5	25	-2.45	11.47	3.96	3.59	5.35
T6	9	2.44	11.61	7.25	3.27	7.95
T7	12	-5.03	7.07	1.18	3.68	3.86
T8	29	-3.03	11.29	4.89	3.74	6.16
T9	7	-1.44	11.41	4.49	4.73	6.52
T10	8	-3.46	5.6	0.66	3.11	3.18
T11	48	-3.45	11.42	4.06	4.23	5.86
T12	5	-4.31	10.96	1.58	5.98	6.19

4.2 Analysis of Results

4.2.1 General Vertical Assessment of Derived DEMs and Available DEMs Countrywide

MERIT DEM shows better vertical assessment results using GGCPs countrywide with SD of 3.56m and RMS of 3.61m at 95% confidence level over all derived DEMs (DEM 1, DEM 2, DEM 3 and DEM 4) and available public DEMs validated in this study. It is then followed by NASA DEM with SD of 3.71m and RMS of 3.72m, DEM 3 with SD of 3.59m and RMS of 3.73, DEM 1 with SD of 3.69m and RMS of 3.73m (approximately the same RMS as DEM 3), DEM 2 with SD of 4.12m and RMS of 4.53m and lastly DEM 4 with SD of 4.05m and RMS of 5.44m. Generally, the results of derived DEMs entails that the derived DEMs using Old GEDI CHM are very close to NASA DEM in terms of RMS (lower by 1cm) while, derived DEMs using New GEDI CHM are seen to be not better overall derived and available DEMs validated in this study.

In comparison with previous studies on GDEMs vertical assessment using GGCPs countrywide, the derived DEMs using Old GEDI CHM are better than ALOSv3.2-1″ DSM. The derived DEMs using New GEDI CHM results are not better maybe due to the following reasons below;

i. The quality of a DEM is also a function of how reliably the above ground features have been estimated and removed from the respective DSM (Ulotu, 2017). DEM 2 and DEM 4 utilize a combination of GEDI LiDAR and Sentinel 2 datasets ensemble with a Convolutional Neural Network (CNN) for DEM derivation. If the CNN is not well-trained or lacks the necessary complexity to handle the data characteristics effectively, it may have resulted lower vertical accuracy in the DEM generation process compared to the other DEMs. While these datasets and methods have their benefits and differ in their vertical accuracies, they may have introduced additional uncertainties or errors in the DEM generation process for Tanzania mainland compared to DEM 1 and DEM 3, which rely on GEDI LiDAR and Landsat ARD time series.
ii. Since all the four derived DEMs were resampled from their original spatial resolution to 90m spatial resolution. According (Mesa-Mingorance & Ariza-López, 2020) the higher the resolution, the greater the expected accuracy, and vice versa. The use of a higher resolution New GEDI CHM (10m) in DEM 2 and DEM 4 might have introduced more interpolation errors, particularly if the original data is not well-suited for the new resolution during the resampling process. In the case of DEM 2 and DEM 4, resampling the New GEDI CHM from 10m to a 90m resolution might have led to loss of detail and accuracy, affecting the overall quality of DEM 2 and DEM 4.

4.2.2 Vertical Assessment of DEMs in selected Land Covers Using GGCPs

- **Flat and bare terrain (Dodoma)-T1**

Table 4-177: Summary of vertical assessment of DEMs in Flat and bare terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	3.53	3.54	• MERIT DEM shows better vertical results in both SD and RMs overall DEMs in this land cover, this is due to its good ability to represent elevation of flat and bare land. • DEM 1 shows better vertical result in terms of RMS approximately by 1cm only compared to NASA DEM, followed by DEM 3. • DEM 2 and DEM 4 both derived from the two selected public DSMs using New GEDI CHM shows worse vertical results in terms of their RMS.
DEM 1	4.41	4.45	
NASA DEM	4.41	4.46	
DEM 3	4.78	4.81	
DEM 2	3.71	5.16	
DEM 4	3.70	6.13	

- **Mountainous and forested terrain (Kilimanjaro and Arusha)-T2**

Table 4-18: Summary of vertical assessment of DEMs in Mountainous and forested terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
DEM 1	2.04	2.10	• DEM 1 fits best GGCPs compared to all DEMs in this land cover. This is due to the capability of its DSM and Old GEDI CHM to well represent this terrain. • DEM 3 is superior to NASA DEM in both SD and RMS. • DEM 4 shows worse vertical results in terms of RMS overall DEMs. This may be due to the capability of its DSM and New GEDI CHM to poor represent mountainous and forested terrain.
MERIT DEM	3.09	3.19	
DEM 3	3.17	3.36	
NASA DEM	3.34	3.51	
DEM 2	4.03	4.72	
DEM 4	3.99	5.23	

- **Flat and Plain terrain (Tabora)-T3**

Table 4-19: Summary of vertical assessment of DEMs in Flat and plain terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	2.39	2.43	• MERIT DEM shows better vertical results in both SD and RMs over all DEMs, this is due to its good ability to represent elevation of flat and plain land. • DEM 3 is superior to NASA DEM in both SD and RMS. • DEM 1is very close to NASA DEM in terms of RMS while DEM 2 deviates more from NASA DEM. • DEM 4 shows worse vertical results in terms of RMS.
DEM 3	2.61	2.77	
NASA DEM	2.92	3.10	
DEM 1	3.06	3.11	
DEM 2	3.20	3.22	
DEM 4	3.22	4.08	

- **Barely flat and forested coastal terrain (Mtwara)-T4**

Table 4-20: Summary of vertical assessment of DEMs in Barely flat and forested coastal terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	4.06	4.59	• MERIT DEM followed by DEM 1 showed better vertical results compared to other DEMs but generally all the results are not good in this terrain. • DEM 4 and NASA DEM shows worst vertical results. This may be due to the poor ability to well represent flat and forested coastal areas.
DEM 1	4.76	4.88	
DEM 3	5.39	5.40	
DEM 2	5.55	6.32	
DEM 4	5.93	7.22	
NASA DEM	7.09	7.43	

- **Slightly mountainous and forested terrain (Morogoro)-T5**

Table 4-21: Summary of vertical assessment of DEMs in Slightly mountainous and forested terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	2.98	3.00	• MERIT followed by NASA DEMs showed better vertical results in both SD and RMS. • All the derived DEMs here are inferior to the two available DEMs in both SD and RMS, DEM 4 showing worse results. This may be due to the poor ability of their DSMs and CHMs to well represent slightly mountainous and forested terrain. • DEM 4 shows worse vertical results in terms of RMS.
NASA DEM	3.45	3.71	
DEM 3	3.98	4.41	
DEM 1	4.55	4.55	
DEM 2	4.06	4.67	
DEM 4	3.59	5.35	

- **Forested and fairly flat terrain (Tanga)-T6**

Table 4-22: Summary of vertical assessment of DEMs in Forested and fairly flat terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	2.48	2.66	• MERIT DEM shows better vertical results in both SD and RMs over all DEMs, this is due to its good ability to represent elevation of flat areas. • DEM 1 and DEM 3 are superior to NASA DEM in terms of both SD and RMS. • DEM 2 and DEM 4 shows worst vertical results in terms of RMS. This may be due to the poor ability of their DSMs and CHMs to well represent this area.
DEM 1	3.59	4.10	
DEM 3	3.09	4.19	
NASA DEM	3.63	4.61	
DEM 2	3.88	6.54	
DEM 4	3.27	7.95	

❖ **Highlands and forested terrain (Mbeya)-T7**

Table 4-23: Summary of vertical assessment of DEMs in Highlands and forested terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
DEM 1	3.56	3.66	• DEM 1 followed by DEM 4 shows better vertical results in both SD and RMS over all DEMs. A good result is due to its DSM and CHM to well represent this terrain. • DEM 3 is inferior to NASA DEM but superior to MERIT DEM in terms of RMS. • DEM 2 shows worse vertical results in terms of both SD and RMS over all DEMs in this terrain.
DEM 4	3.68	3.86	
NASA DEM	4.18	4.35	
DEM 3	4.39	4.47	
MERIT DEM	4.29	4.49	
DEM 2	4.30	4.57	

❖ **Flat and forested coastal terrain (Lindi)-T8**

Table 4-24: Summary of vertical assessment of DEMs in Flat and forested coastal terrain using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
MERIT DEM	3.53	3.88	• MERIT DEM shows better vertical results in both SD and RMs over all DEMs, this is due to its good ability to represent elevation of this terrain. • DEM 3 is superior to NASA DEM in both SD and RMS. • DEM 4 shows worse vertical results over all DEMs in terms of RMS, this may be due to the poor ability of its DSM and CHM to well represent this land cover.
DEM 3	3.95	4.03	
NASA DEM	3.99	4.15	
DEM 2	4.15	4.38	
DEM 1	3.63	4.81	
DEM 4	3.74	6.16	

❖ **Western part of Arusha (Ngorongoro)-T9**

Table 4-25: Summary of vertical assessment of DEMs in Western part of Arusha using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
NASA DEM	1.93	2.28	• NASA DEM shows better vertical results in both SD and RMS over all DEMs, this is due to its good ability to represent elevation of this area. • DEM 3 is superior to MERIT DEM in both SD and RMS. • DEM 2 and DEM 4 shows worst vertical results in both SD and RMS. This may be due to the poor ability of their DSMs and CHMs to well represent this area.
DEM 3	2.46	2.67	
MERIT DEM	2.91	3.03	
DEM 1	3.07	3.77	
DEM 2	4.18	6.08	
DEM 4	4.73	6.52	

❖ **Western branch of Great Rift Valley (Tanganyika)-T10**

Table 4-26: Summary of vertical assessment of DEMs in Western branch of Great Rift Valley using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
DEM 3	2.28	2.42	• DEM 3 shows better vertical results in both SD and RMS over all DEMs, this is due to its good ability to represent elevation of this area. • DEM 4 and DEM are superior to all the two available DEMs in both SD and RMS. • DEM 2 is inferior to MERIT DEM but superior to NASA DEM in terms of RMS.
DEM 4	3.11	3.18	
DEM 1	3.34	3.63	
MERIT DEM	3.32	3.98	
DEM 2	4.03	4.03	
NASA DEM	3.99	4.15	

❖ **Lake zone areas (Victoria)-T11**

Table 4-27: Summary of vertical assessment of DEMs in Lake Zone areas using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
DEM 3	3.48	3.56	• DEM 3 shows better vertical results in both SD and RMS over all DEMs, this is due to its good ability to represent elevation compared to others DEMs in this land cover. • DEM 1 is superior to all the two available DEMs in both SD and RMS. • DEM 2 and DEM 4 shows worse vertical results in terms of RMS. This may be due to the poor ability of their DSMs and CHMs to well represent this area.
DEM 1	3.88	3.89	
NASA DEM	4.06	4.06	
MERIT DEM	4.06	4.21	
DEM 2	4.51	5.12	
DEM 4	4.23	5.86	

❖ **Eastern branch of Great Rift Valley (Natron)-T12**

Table 4-28: Summary of vertical assessment of DEMs in Eastern branch of Great Rift Valley using GGCPs

DEM	SD (m)	RMS (m)	REMARKS
DEM 2	3.10	3.12	• DEM 2 shows better vertical results in both SD and RMS over all DEMs, this is due to its good ability to represent elevation of this area. • DEM 1, DEM 3 and DEM 4 are inferior to the two available DEMs in terms of RMS. • DEM 4 shows worse vertical results in both SD and RMS. This may be due to the poor ability of its DSM and CHM to well represent this terrain.
MERIT DEM	4.07	4.42	
NASA DEM	4.50	4.73	
DEM 1	4.67	4.82	
DEM 3	4.26	5.14	
DEM 4	5.98	6.19	

4.2.3 Comparison between Derived DEMs with NASA DEM in Selected Land Covers

The results of fitting NASA DEM to DEM 1, DEM 2, DEM 3 and DEM 4 DEMs determined in this study in different 12 land covers is discussed in this section.

- **Flat and bare terrain (Dodoma)-T1**

DEM 1 with SD of 5.21m and RMS of 5.28m is much closer to NASA DEM followed by DEM 2 with SD of 6.6m and RMS of 7.12m, DEM 3 with SD of 7.73m and RMS of 7.87m and lastly DEM 4 with SD of 8.66m and RMS of 9.27m.

- **Mountainous and forested terrain (Kilimanjaro and Arusha)-T2**

DEM 1 with SD of 5.44m and RMS of 5.52m is much closer to NASA DEM followed by DEM 3 with SD of 7.11m and RMS of 7.23m, DEM 2 with SD of 6.89m and RMS of 7.36m and lastly DEM 4 with SD of 8.07m and RMS of 8.58m.

- **Flat and Plain terrain (Tabora)-T3**

DEM 3 with SD of 4.67m and RMS of 5.66m is much closer to NASA DEM followed by DEM 1 with SD of 5.32m and RMS of 5.73m, DEM 2 with SD of 6.98m and RMS of 8.11m and lastly DEM 4 with SD of 6.39m and RMS of 8.25m.

- **Barely flat and forested coastal terrain (Mtwara)-T4**

DEM 1 with SD of 5.6m and RMS of 6.37m is much closer to NASA DEM followed by DEM 3 with SD of 5.66m and RMS of 7.11m, DEM 2 with SD of 5.72m and RMS of 7.33m and lastly DEM 4 with SD of 6.1m and RMS of 8.4m.

- **Slightly mountainous and forested terrain (Morogoro)-T5**

The results are not good at all, but compared to all derived DEMs, DEM 1 with SD of 6.95m and RMS of 7.46m is close to NASA DEM. The remaining DEM 2 with SD of 8.65m and RMS of 11.07m, DEM 3 with SD of 10.26m and RMS of 11.34m and lastly DEM 4 with SD of 11.3m and RMS of 11.69m shows statistical disagreement with NASA DEM in this land cover.

- **Forested and fairly flat terrain (Tanga)-T6**

The results are not good at all, but compared to all derived DEMs, DEM 1 with SD of 6.74m and RMS of 7.2m is close to NASA DEM. The remaining DEM 2 with SD of 7.2m and RMS of 9.35m, DEM 3 with SD of 9.77m and RMS of 10.46m and lastly DEM 4 with SD of 9.82m and RMS of 12.37m shows statistical disagreement with NASA DEM in this land cover.

- ❖ **Highlands and forested terrain (Mbeya)-T7**

DEM 1 with SD of 4.47m and RMS of 5.19m is much closer to NASA DEM followed by DEM 3 with SD of 6.32m and RMS of 6.99m, DEM 2 with SD of 6.49m and RMS of 8.04m and lastly DEM 4 with SD of 7.69m and RMS of 9.22m.

- ❖ **Flat and forested coastal terrain (Lindi)-T8**

DEM 1 with SD of 5.99m and RMS of 6.45m is much closer to NASA DEM followed by DEM 3 with SD of 6.23m and RMS of 7.98m, DEM 2 with SD of 6.79m and RMS of 9.44m. DEM 4 with SD of 6.97m and RMS of 11.98m shows statistical disagreement with NASA DEM in this land cover.

- ❖ **Western part of Arusha (Ngorongoro)-T9**

DEM 1 with SD of 7.45m and RMS of 8.08m is closer to NASA DEM followed by DEM 3 with SD of 8.97m and RMS of 9.17m, DEM 2 with SD of 8.02m and RMS of 9.46m and lastly DEM 4 with SD of 9.3m and RMS of 10.09m.

- ❖ **Western branch of great rift valley (Tanganyika)-T10**

DEM 1 with SD of 7.17m and RMS of 8.19m is closer to NASA DEM followed by DEM 2 with SD of 7.33m and RMS of 8.19m. The remaining DEM 3 with SD of 10.13m and RMS of 11.13m and DEM 4 with SD of 10.54m and RMS of 11.96m shows statistical disagreement with the available NASA DEM in this land cover.

- ❖ **Lake zone areas (Victoria)-T11**

DEM 2 with SD of 4.97m and RMS of 5.13m is closer to NASA DEM followed by DEM 1 with SD of 6.62m and RMS of 6.71m, DEM 4 with SD of 7.15m and RMS of 8.18m and lastly DEM 3 with SD of 8.24m and RMS of 8.55m.

- ❖ **Eastern branch of great rift valley (Natron)-T12**

DEM 2 with SD of 7.1m and RMS of 7.64m is closer to NASA DEM followed by DEM 1 with SD of 7.75m and RMS of 8.01m, DEM 4 with SD of 9.76m and RMS of 10.22m and lastly DEM 3 with SD of 10.4m and RMS of 10.62m.

4.2.4 Comparison between Derived DEMs with MERIT DEM in Selected Land Covers

The results of fitting MERIT DEM to DEM 1, DEM 2, DEM 3 and DEM 4 DEMs determined in this study in different 12 land covers is discussed in this section.

- **Flat and bare terrain (Dodoma)-T1**

DEM 1 with SD of 4.51m and RMS of 4.7m is much closer to MERIT DEM followed by DEM 2 with SD of 4.84m and RMS of 5.66m, DEM 3 with SD of 7.4m and RMS of 7.66m and lastly DEM 4 with SD of 7.85m and RMS of 8.76m.

- **Mountainous and forested terrain (Kilimanjaro and Arusha)-T2**

DEM 1 with SD of 4.48m and RMS of 4.96m is much closer to MERIT DEM followed by DEM 2 with SD of 4.65m and RMS of 5.68m, DEM 3 with SD of 6.74m and RMS of 7.19m and lastly DEM 4 with SD of 7.44m and RMS of 8.5m.

- **Flat and Plain terrain (Tabora)-T3**

DEM 1 with SD of 4.37m and RMS of 4.58m is much closer to MERIT DEM followed by DEM 3 with SD of 3.92m and RMS of 4.62m, DEM 2 with SD of 6.29m and RMS of 7.13m and lastly DEM 4 with SD of 5.8m and RMS of 7.33m.

- **Barely flat and forested coastal terrain (Mtwara)-T4**

DEM 1 with SD of 4.59m and RMS of 4.82m is much closer to MERIT DEM followed by DEM 3 with SD of 5.3m and RMS of 6.01m, DEM 2 with SD of 5.88m and RMS of 6.63m and lastly DEM 4 with SD of 6.54m and RMS of 7.69m.

- **Slightly mountainous and forested terrain (Morogoro)-T5**

DEM 1 with SD of 5.76m and RMS of 6.18m is close to MERIT DEM followed by DEM 2 with SD of 6.37m and RMS of 8.76m. The remaining DEM 3 with SD of 9.92m and RMS of 10.49m and DEM 4 with SD of 10.38m and RMS of 12.88m shows statistical disagreement with MERIT DEM in this land cover.

- **Forested and fairly flat terrain (Tanga)-T6**

DEM 1 with SD of 5.84m and RMS of 6.19m is closer to MERIT DEM followed by DEM 2 with SD of 4.65m and RMS of 7.09m, DEM 3 with SD of 9.25m and RMS of 9.82m. DEM 4 with SD of 9.26m and RMS of 11.75m shows statistical disagreement with MERIT DEM.

- **Highlands and forested terrain (Mbeya)-T7**

DEM 1 with SD of 4.08m and RMS of 5.01m is much closer to MERIT DEM followed by DEM 3 with SD of 6.17m and RMS of 6.97m, DEM 2 with SD of 5.75m and RMS of 7.49m and lastly DEM 4 with SD of 7.4m and RMS of 9.13m.

- **Flat and forested coastal terrain (Lindi)-T8**

DEM 1 with SD of 4.82m and RMS of 4.88m is much closer to MERIT DEM followed by DEM 3 with SD of 4.93m and RMS of 5.91m, DEM 2 with SD of 6.31m and RMS of 8.55m and lastly DEM 4 with SD of 6.34m and RMS of 10.44m.

- **Western part of Arusha (Ngorongoro)-T9**

DEM 2 with SD of 4.94m and RMS of 6.18m is closer to MERIT DEM followed by DEM 1 with SD of 5.86m and RMS of 6.54m, DEM 3 with SD of 9.14m and RMS of 9.45m and lastly DEM 4 with SD of 8.85m and RMS of 9.66m.

- **Western branch of great rift valley (Tanganyika)-T10**

DEM 2 with SD of 5.95m and RMS of 6.82m is closer to MERIT DEM followed by DEM 1 with SD of 7.33m and RMS of 8.19m. The remaining DEM 3 with SD of 9.93m and RMS of 10.91m and DEM 4 with SD of 10.32m and RMS of 11.71m shows statistical disagreement with MERIT DEM in this land cover.

- **Lake zone areas (Victoria)-T11**

DEM 2 with SD of 4.18m and RMS of 4.93m is much closer to MERIT DEM followed by DEM 1 with SD of 4.89m and RMS of 5.15m, DEM 3 with SD of 7.72m and RMS of 8.25m and lastly DEM 4 with SD of 7.01m and RMS of 8.45m.

- **Eastern branch of great rift valley (Natron)-T12**

DEM 2 with SD of 5.07m and RMS of 5.96m is much closer to MERIT DEM followed by DEM 1 with SD of 6.29m and RMS of 6.71m, DEM 4 with SD of 9.63m and RMS of 10.31m and lastly DEM 4 with SD of 10.5m and RMS of 10.82m.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The aim of this dissertation was to take advantage of the availability of Old and New GEDI LiDAR CHMs and public DSMs to determine a better DEM than the current public available DEMs from different providers for Tanzania mainland, with the hypothesis that DEMs derived from available public DSMs using the New GEDI CHM shows better vertical assessment results than the DEMs derived from available public DSMs using the Old GEDI CHM and current available public DEMs in Tanzania. The statistical outcomes of this dissertation clearly indicated that the objectives have been greatly achieved but the hypothesis have been achieved only to a very small extent specifically in the selected land covers.

From the analysis of the results of this research the following conclusion has been made;

i. In the vertical assessment using GGCPs countrywide, the results show that at 95% confidence level MERIT DEM public available DEM is superior compared to all derived and available DEMs validated in this study in terms of both SD and RMS with SD of 3.56m and RMS of 3.61m, followed by NASA public available DEM, DEM 3, DEM 1, DEM 2 and lastly DEM 4 with 4.05m of and RMS of 5.44m which shows lowest results.

ii. In the twelve selected land covers the vertical assessment using GGCPs results vary from one place to another with no any systematic trend where by, DEM 2 is superior compared to the derived DEMs using Old GEDI CHM and available public DEMs validated in this study only in Eastern branch of Great Rift Valley. DEM 4 is superior compared to the available public DEMs validated in this study only in highland and forested terrain and Western branch of the Great Rift Valley but it is inferior to derived DEMs using Old GEDI CHM. The derived DEMs using Old GEDI CHM in most land covers are seen to be better to the ones using New GEDI CHM. Generally, MERIT DEM public available DEM show best results in most land covers with RMs between 2.43m and 4.59m includes flat and bare terrain, flat and plain terrain, barely flat and forested coastal terrain, slightly mountainous and forested terrain, forested and fairly flat terrain and lastly flat and forested coastal terrain.

iii. For the overall fitting of the four derived DEMs to NASA DEM and MERIT DEM selected public available DEMs in this study, the trend is generally not good but ALOSv3.2-1″ derived DEMs using Old and New GEDI CHMs (DEM 1 and DEM 2) slightly fits NASA DEM with RMS of 6.63m and 8.20m respectively. Similarly ALOSv3.2-1″ derived DEMs using Old and New GEDI CHMs (DEM 1 and DEM 2) slightly fits MERIT DEM with RMS of 5.53m and 6.90m respectively.

5.2 Recommendation

i. Since newer DEMs are continually being released, and MERIT DEM public available DEM has the best vertical accuracy results in Tanzania as validated in this study compared to NASA DEM and the four derived DEMs obtained in this study therefore, it is recommended that further research should be carried out so as to identify and assess the vertical accuracy of MERIT DEM against newer released GDEM in different land covers for the determination of the best GDEM for Tanzania in all land covers in future.

ii. New GEDI LiDAR CHM used in this Dissertation from fused GEDI with Sentinel-2 optical satellite images since its release on 13^{th} April, 2022 has not yet been validated in Tanzania, thus it is recommended that the next researcher should validate it with in-situ forest canopy height data which cover Tanzania mainly with terrain and land cover characteristics for wider coverage other than ones used by (Mbago, 2022) and compare with Old GEDI CHM and other non-LiDAR derived CHMs.

iii. Since GEDI is two years mission, hence on release of updated GEDI LiDAR CHM the next researcher may use the opportunity to derive best DEM in Tanzania from newer released public available DSMs such as ALOSv4.0-1″ released on 7^{th} April, 2023 other than derived DEMs used in this study and by (Siles, 2021).

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APPENDICES

Appendix I

Sample of GGCPs used for the vertical assessment

LONGITUDE (dd)	LATITUDE (dd)	h (m)	N_EGM96 (m)	H_EGM96 (m)
32.8254551	-5.040146003	1204.8500	-19	1223.8500
37.3371030	-3.349947108	840.6029	-17	857.6029
39.2079256	-6.765585222	70.4607	-28	98.4607
39.2971815	-6.817814342	22.3957	-28	50.3957
39.2107164	-6.218534344	-3.9758	-28	24.0242
35.7483040	-6.169643667	1099.9710	-20	1119.9710
34.8002773	-11.27367291	523.3506	-18	541.3506
37.3405287	-11.06259767	672.8775	-23	695.8775
35.7531567	-7.675926314	1411.3400	-17	1428.3400
31.6057151	-7.951186911	1791.2130	-11	1802.2130
39.1166297	-5.087755350	-15.9371	-28	12.0629
32.8254633	-5.040230144	1201.5000	-19	1220.5000
29.6683633	-4.886717589	808.0352	-15	823.0352
31.7992248	-1.325546939	1237.5960	-15	1252.5960
32.9225184	-2.446997372	1127.8710	-18	1145.8710
33.8379494	-1.537530333	1167.9890	-18	1185.9890
37.8049290	-6.748471417	480.3136	-23	503.3136
31.1505425	-1.531897620	1635.7900	-13	1648.7900
34.6816347	-1.834966040	1599.8000	-18	1617.8000
30.6694232	-2.506661890	1776.2300	-11	1787.2300
31.3657688	-2.664346750	1424.5900	-14	1438.5900
34.8197577	-2.436597240	1486.400	-17	1503.400
35.5451276	-2.067269020	2007.7600	-17	2024.7600
36.7040963	-2.742595100	1312.0800	-17	1329.0800
39.1373580	-6.894069800	116.4669	-27	143.4669
39.1661490	-6.876714400	60.0960	-28	88.0960

39.2563860	-6.864194600	25.9569	-28	53.9569
39.2803540	-6.943122600	15.5828	-28	43.5828
39.3533000	-6.845500300	-12.2723	-28	15.7277
39.4164990	-6.866625000	24.6628	-29	53.6628
39.4802200	-6.892843400	-14.7713	-29	14.2287
39.2279360	-6.952074200	34.3978	-28	62.3978
39.2978180	-6.955225600	34.6742	-28	62.6742
39.3603920	-6.962594100	101.1131	-28	129.1131
39.4851410	-7.010491000	25.3099	-29	54.3099
39.5272370	-6.987390600	-6.1885	-29	22.8115
30.6734113	-1.205801529	1649.6147	-11	1660.6147
30.9399043	-1.037301251	1235.6645	-12	1247.6645
31.4053573	-1.204689154	1143.0717	-13	1156.0717
31.8127186	-1.221719012	1211.8907	-14	1225.8907
30.9468135	-1.529348109	1440.9719	-12	1452.9719
31.7258398	-1.607506062	1313.9074	-15	1328.9074
31.1125665	-1.751691235	1551.3343	-13	1564.3343
31.6548146	-1.851174838	1275.4246	-15	1290.4246
33.0899011	-2.092851368	1169.1616	-18	1187.1616
33.4497865	-2.149592810	1136.4600	-18	1154.4600
33.8602760	-2.000974618	1225.4622	-18	1243.4622
33.9243681	-1.682146367	1347.4380	-18	1365.4380
34.0389053	-1.178223532	1178.9762	-18	1196.9762
34.3717901	-1.351442996	1406.6463	-17	1423.6463
34.1257665	-1.455277962	1226.1503	-18	1244.1503
34.5442329	-1.438293303	1311.8380	-17	1328.8380
34.2341474	-1.735293609	1274.4781	-18	1292.4781
35.5024469	-2.584383978	1570.7394	-18	1588.7394
35.1377267	-2.912641465	1607.3250	-18	1625.3250
36.0048933	-3.002355219	813.7883	-18	831.7883

35.8785069	-2.614311454	632.1627	-19	651.1627
35.6971067	-2.171838842	1311.4271	-18	1329.4271
35.8848476	-2.136975414	1199.3977	-19	1218.3977
35.5080707	-2.380822051	1862.2602	-18	1880.2602
35.2706986	-3.223118386	1803.8928	-18	1821.8928
35.8969002	-3.390226829	961.2315	-19	980.2315
35.3419133	-3.520379454	1031.8403	-19	1050.8403
35.6910863	-3.034182836	2616.8156	-18	2634.8156
35.4579216	-3.211353908	2468.1857	-18	2486.1857
35.6732785	-3.446047522	1383.7837	-19	1402.7837
35.5509533	-3.863623788	1736.2306	-19	1755.2306
35.5333609	-3.710292723	1921.2396	-19	1940.2396
35.7460984	-3.670148224	946.6297	-19	965.6297
35.9291624	-3.706405027	1001.1866	-19	1020.1866
37.1253618	-2.867333909	1676.2293	-16	1692.2293
37.4669859	-2.934159368	1973.0354	-17	1990.0354
36.7794031	-2.561278308	1301.9415	-17	1318.9415
36.4823025	-2.529237105	1677.5965	-18	1695.5965
36.6956568	-3.040998695	1386.4216	-18	1404.4216
36.3003031	-2.824402232	1248.5150	-19	1267.5150
36.1142451	-2.730315490	1169.8803	-19	1188.8803
32.2358556	-4.205381818	1175.1000	-17	1192.1000
32.5210493	-4.002499196	1266.5446	-18	1284.5446
32.5144664	-4.400173512	1173.7203	-18	1191.7203
32.6874425	-4.537083164	1202.7188	-19	1221.7188
32.0905187	-4.635129379	1110.4524	-17	1127.4524
39.1133748	-4.835969732	35.5232	-27	62.5232
38.9096449	-4.539005694	121.1716	-25	146.1716
38.7231485	-4.772861515	339.4025	-24	363.4025
38.5738376	-4.904497623	317.1709	-24	341.1709

38.3087089	-4.979307071	381.5722	-23	404.5722
38.2979626	-4.917746177	431.4114	-23	454.4114
36.1652558	-5.154563683	1452.9750	-18	1470.9750
36.4217235	-5.624741959	1419.9112	-18	1437.9112
36.6523495	-5.319714562	1303.7022	-18	1321.7022
36.1606612	-5.574007147	1269.4175	-19	1288.4175
36.4512629	-5.895304745	1177.2721	-19	1196.2721
36.7236035	-5.934101209	1435.2722	-18	1453.2722
37.1850088	-5.400812254	1349.4635	-19	1368.4635
37.5137612	-5.394163529	995.4426	-20	1015.4426
37.9361798	-5.394392476	700.5722	-23	723.5722
37.7802766	-5.902039092	422.2817	-22	444.2817
37.3233417	-5.789524637	818.3309	-19	837.3309
37.0183745	-5.926849505	1093.6811	-19	1112.6811
38.4467307	-5.164366419	293.7137	-24	317.7137
38.8057994	-5.173700071	193.0695	-26	219.0695
38.9882609	-5.409980219	43.8101	-28	71.8101
38.8540834	-5.784032021	-22.1391	-28	5.8609
38.0301091	-5.433394605	681.8244	-23	704.8244
38.2970753	-5.776447428	375.3426	-24	399.3426
38.5812114	-5.864850731	186.9870	-26	212.9870
38.6597540	-5.583002951	91.85060	-26	117.8506
36.4116723	-6.201665183	994.8690	-19	1013.8690
36.8727054	-6.139286113	1231.9704	-19	1250.9704
36.9806779	-6.853117595	466.2077	-21	487.2077
36.4840921	-11.14261361	585.1099	-21	606.1099
37.5792401	-11.02936701	424.4642	-24	448.4642
37.8008214	-10.10494933	381.2633	-24	405.2633
37.0853760	-11.05691065	439.0205	-23	462.0205
38.4794674	-10.12511232	246.9692	-23	269.9692

38.1296820	-10.06851812	468.9911	-23	491.9911
38.9374744	-10.03646013	425.9615	-24	449.9615
38.7579731	-10.04878176	421.0222	-24	445.0222
38.2405480	-10.03546470	352.3691	-23	375.3691
38.2385654	-10.10207233	311.9396	-23	334.9396
38.5179277	-10.10357983	281.8690	-23	304.8690
38.4549619	-11.03868205	277.6672	-25	302.6672
38.9469987	-11.03919128	218.1075	-24	242.1075
38.2147605	-9.137180403	246.2146	-24	270.2146
38.7027713	-9.336534703	254.3455	-24	278.3455
38.6853671	-9.176455405	253.2365	-24	277.2365
38.0153402	-9.701268158	403.9487	-23	426.9487
38.3106566	-9.941379837	327.0155	-23	350.0155
38.5096696	-9.790626591	299.9294	-24	323.9294
39.7164852	-10.00534633	-21.6328	-26	4.3672
39.2662863	-10.0961061	710.3823	-24	734.3823
39.0261388	-10.04919091	276.4936	-24	300.4936
39.3372528	-10.07154242	443.0050	-24	467.0050
39.433589	-10.09322303	472.2890	-24	496.2890
39.8112749	-10.07022614	221.8286	-26	247.8286
39.6681311	-10.02100874	31.4814	-25	56.4814
39.7788100	-10.03989114	68.0020	-26	94.0020
39.2733908	-10.15200487	662.1241	-24	686.1241
39.1080586	-9.667169417	77.8288	-24	101.8288
39.1253277	-9.911703631	305.9694	-24	329.9694
39.4078468	-9.295504426	135.3125	-26	161.3125
39.5630324	-9.120454894	-9.6602	-28	18.3398
39.3156601	-9.063845565	12.6239	-26	38.6239
39.7070301	-9.742948103	-22.7067	-27	4.2933
39.0526929	-9.116938492	138.6139	-25	163.6139

38.9942427	-9.436270129	176.2050	-24	200.2050
36.5238975	-10.02703867	848.7750	-19	867.7750
36.7339225	-10.02219701	690.8274	-20	710.8274
36.9525596	-10.07430847	800.3685	-21	821.3685
36.5218939	-10.08481463	944.7843	-20	964.7843
36.0963785	-10.09538087	788.0554	-19	807.0554
36.6854277	-10.08643828	857.828	-20	877.828
37.7980834	-10.08593511	575.3499	-24	599.3499
37.4511072	-10.08611957	493.8813	-23	516.8813
34.6478205	-11.10489133	493.4573	-18	511.4573
34.9125881	-11.10106515	1595.4015	-17	1612.4015
34.9596971	-11.05903012	475.1730	-17	492.1730
35.2310064	-11.03630978	1046.437	-16	1062.437
35.1739453	-11.12834667	956.1214	-16	972.1214
35.4509896	-11.03190024	739.3677	-16	755.3677
35.6304926	-11.04547872	603.0069	-17	620.0069
35.4023117	-11.03977241	619.5667	-16	635.5667
36.1656925	-11.03542955	696.6423	-19	715.6423
36.0397947	-11.05089353	616.4695	-18	634.4695
36.6591280	-11.05025126	575.0005	-21	596.0005
34.6824175	-10.07100636	465.7803	-17	482.7803
34.9066626	-10.05622138	931.3891	-16	947.3891
34.5961274	-10.04719983	483.6338	-17	500.6338
36.1369604	-10.02751005	759.2924	-19	778.2924
36.3238235	-10.03657324	815.7616	-19	834.7616