Addis Ababa University

Addis Ababa Institute of Technology

School of Civil and Environmental Engineering

VERTICAL ACCURACY ASSESSMENT OF OPEN SOURCE DIGITAL ELEVATION MODEL USING GPS POINT AND REFERENCE DEM OVER ETHIOPIA: A CASE STUDY IN ADDIS ABABA and DIRE DAWA

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By

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This undersigned hear by certify that they have read and recommend to the Addis Ababa University Institute of Technology for acceptance a thesis entitled "*VERTICAL ACCURACY ASSESSMENT OF OPEN SOURCE DIGITAL ELEVATION MODEL USING GPS POINT AND REFERENCE DEM OVER ETHIOPIA A CASE STUDY IN ADDIS ABABA and DIRE DAWA*" by Abdi Ibrahim in the partial fulfillment of the requirement for the degree of Master of Science.

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Abstract

Digital elevation model (DEM) is a digital representation of the surface topography of the earth. Apart from visualization of o 3D surface topography of the earth, DEM is very useful data source to perform various analyses. DEM can be generated from wide range sources including land survey, Photogrammetry and remote sensing satellites. SRTM 30m DEM by The Shuttle Radar Topography mission (SRTM), the global digital elevation model by Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER GDEM) and a global surface model called ALOS Worldview 3D 30 meter (AW3D30) by Advanced Land Observing Satellite (ALOS) are satellite based global DEMs freely available, open source DEM datasets. The specified accuracy of these dataset is often uneven within each dataset due to various reasons including radar characteristics, type of topography in different regions and physical properties of the surface. This study aims to assess the vertical accuracy of ASTER GDEM2, SRTM 30m and ALOS (AW3D30) global DEMs over Ethiopia in two study areas-Addis Ababa and Dire Dawa by using DGPS points and other available accurate topographic reference data. The method used to assess the vertical accuracy of those DEMs range from simple visual comparison to relative and absolute comparisons providing quantitative assessment that used the elevation differences between DEM datasets and reference datasets.

The vertical accuracy of DEMs assessed in three stages based on the reference datasets used. The first vertical accuracy test is done by taking the residual from elevation differencing between GPS points and DEM elevation values at the location of every GPS points. The result of this assessment showed better accuracy of SRTM 30m DEM (having RMSE of 5.14 m and 6.35 m in Addis Ababa and Dire Dawa Study areas), and closely followed by ALOS (AW3D30) DEM which scored RMSE of 5.34 m and 6.33 m in Addis and Dire study areas respectively. ASTER GDEM 2 showed the least accuracy by scoring RMSE of 13.27 m in Addis Ababa and 11.41m in Dire Dawa study areas.

The second test was done by DEM (image) differencing (by subtracting every pixel of DEMs from every pixel of Reference DEM, which gives us the elevation residual). The result from this method assessment gave us RMSE values of 17.2 m, 4.5 m and 4.7 m in Addis Ababa for ASTER, SRTM and ALOS DEMs respectively; RMSE of 9.7 m, 5.43 m and 5.74 m in Dire Dawa Study area for ASTER, SRTM and ALOS DEMs respectively. This also shows the better accuracy of SRTM 30m DEM over the other two at least for this study. The third accuracy assessment was done by analysis of derived products such as slope and drainage network. This also resulted in better quality of derived products for SRTM and ALOS DEM than ASTER GDEM. This concludes SRTM 30m and ALOS (AW3D30) DEM can be used for slope classification and Drainage or watershed delineation in this regions.

Key Words: **DEM, ASTER GDEM2, SRTM 30m, *ALOS (AW3D30), EGM96, Vertical accuracy,***

Table of Content

List of figures

List of tables

List of Acronyms

ALOS – *Advanced Land Observing Satellite*

AW3D30 – *ALOS World 3D 30 meter Topographic Data*

ASPRS – *American Society for Photogrammetry and Remote Sensing*

ASTER – *Advanced Spaceborne Thermal Emission and Reflection Radiometer*

CGIAR-CSI – *Consultative Group for International Agricultural Research - Consortium for Spatial Information*

DEM – *Digital Elevation Model*

DSM – *Digital Surface Model*

DTM – *Digital Terrain Model*

EGM96 –*Earth Geopotential Model of 1996*

EMA – *Ethiopian Mapping Agency*

ERA – *Ethiopian Road Authority*

ESRI – *Environmental Systems Research Institute*

GCP – *Ground Control Point*

GDEM – *Global Digital Elevation Model*

GIS – *Geographic Information System*

GNSS – *Global Navigation Satellite System*

GPS – *Global Positioning System*

LiDAR – *Light Detection and Ranging*

MSL – *mean sea level*

NMAS − *National Map Accuracy Standard*

Chapter 1

1.1 Introduction

Digital elevation model (DEM) is a digital representation of ground surface topography. The term DEM is a generic term that includes two distinct topographic models. The fist is a Digital Surface Model (DSM) - elevation model of surface reflectance features and includes the heights of cultural features such as buildings, road and vegetation as well as bare earth. The second term**,** Digital Terrain Model (DTM), refers to a bare-earth model in which all the cultural features have been removed. Digital Elevation Models (DEMs) are an integral part of any GeoSpatial Analysis. They are important spatial data sources for understanding various energy, environmental, social and geographic issues globally, and they are used in a wide range of scientific investigations such as hydrological, geological, and geomorphological surveys, as well as urban planning, surveying and development (Kyaruzi, 2005).

DEMs can be derived from a wide variety of sources. Historically, surveying techniques involving basic tools such as leveling and triangulation were used to generate DEMs. This was followed by photogrammetric techniques involving multiple stereo paired aerial photos. Recently with the advancement in spaceborne/airborne sensors, very high resolution DEMs can now be generated from the data obtained through radarmetry, interferometry, and Light Detection and Ranging (LiDAR) techniques. Each method has different spatio-temporal resolutions, formats, projection systems, and accuracies (Balzter et al, 2016; Santillan et al., 2016; Mohd et al., 2014 Gamett, 2009) investigated the accuracy of different DEM data sets over various terrain level and environmental settings; and noted that the accuracy of the models depends on multiple factors such as sensor types, methodology involved, terrain type, and grid spacing**.** And others have shown that the quality of a particular DEM depends on the area for which DEM is acquired (Wessel et al., 2014). The accuracies can be estimated by comparing the DEM data with a set of check points measured by high-precision methods, such as GPS or LiDAR.

Medium-resolution DEMs, such as The ALOS World 3D - 30m (AW3D30), ASTER Global DEM Version 2 (GDEM2), and SRTM-30m are Digital Elevation Models (DEMs) that have become available to the general public free of charge; and provide basic topographic information for all or most of the land surface of the Earth. Since their release, these DEMs have become an important data source for a range of applications in Earth and environmental sciences. In developing regions with poor geospatial infrastructure, those free resources can play very important roles to produce reliable information for wide range of applications in hydrology, geomorphology, archaelogy, ecology, and many others. However it is known that the quality of derived information can be influenced by the accuracy of the source dataset. To use these DEMs for the aforementioned or any applications it is important to evaluate their accuracy with the help of higher accuracy standard datasets.

1.2 Statement of the Problem

As a digital representation of a topographic surface, Digital Elevation Models (DEMs) are require by several Earth and environmental applications like hydrological studies, flood simulations, gravity field modeling, identification of the topographic structure, urban design and many others. DEMs can be generated using different techniques such as air-borne and satellite-borne stereoscopic Photogrammetry, RADAR/SAR interferometry, Light Detection and Ranging (LIDAR), and conventional surveying techniques like GPS and leveling. Regardless of which technology is used, DEM generation involves four main steps: 1) data acquisition from source of elevation data, 2) resampling to required grid spacing, 3) interpolation to extract height of required point in between two grid cell centers, and 4) DEM representation, editing and accuracy assessment(Kyaruzi, 2014). All of these steps mentioned above can introduce errors to the final DEM.

A variety of DEMs including ALOS World 3D - 30m (AW3D30), ASTER Global DEM Version 2 (GDEM2), and SRTM-30m are Digital Elevation Models (DEMs) that have become available globally to the general public free of charge. Accuracy assessment and validation of these global DEMs have been conducted globally (Morris et al. 2006; ASTER GDEM Validation Team, 2011) and locally (Santillan et al., 2016) over Philippine, (Sertel, 2010) over turkey, (M. E. Imrani, et al. 2016) over northern Morocco, (Ali, Noamen and Bouaziz 2016) over Tunisia ;and their conclusion shows that these DEMs represented the main topographic features of their respective region well yet there are some erroneous representations over some parts which indicates that the accuracy of these DEM vary regionally and locally. In Ethiopia there are, for example, (Tulu 2005) studies conducted to assess the accuracy of open source Global DEMs, but not enough to establish the accuracy of global DEM over the topography of Ethiopia. Those DEMs such as those from SRTM and ASTER are being used as major sources of topographic information for many applications including hydrological analysis (T. Muluneh and W. Mamo, 2014); Hydrodynamic flood modeling (T.H. Tarekegn, 2009); modeling solar radiation (F.T. Tekle). Accuracy of DEMs used for the aforementioned and other applications were not adequately assessed. Apart from this fact, there is still enough scope to evaluate the open source DEMs over different local regions with accurate reference data such DGPS data, because the accuracy of these DEMs varies regionally and locally.

1.3 Objectives of the Research

1.3.1 General objectives

The main objectives of this research is to evaluate the vertical accuracy of three open source Global Digital Elevation Models (DEMs) – (ALOS, ASTER and SRTM)- over Ethiopia using DGPS points and Reference DEM as a reference(or accuracy test data) in two study Areas, Addis Ababa and Dire Dawa.

1.3.2 Specific objectives include

- To determine orthometric height from measured GPS Ellipsoidal height by using EGM96 geoid model for reference (Vertical accuracy test) dataset.
- To prepare digital elevation model (DEM) from contour/elevation points that used for DEM vertical accuracy assessment reference dataset.
- To determine elevation differences between the three global DEMs against Reference (test) datasets.
- To calculate the vertical accuracy of these DEMs based on elevation differences using statistical measures and compare their vertical accuracy to determine which DEM has better representation of the study areas' topography.
- To evaluate DEM accuracy in terms of their derived surface and applications.

1.4 Research questions

Based on the objective stated this research aims to answer the following questions:

- Which DEM has the lowest elevation differences with elevation of reference datasets and what does this difference mean in terms of overestimation and underestimation of the study area topography?
- What is the level discrepancy between vertical accuracy stated in DEMs' product specification and the measured DEM vertical accuracy determined by this study?
- Which one of the three DEMs has better quality of derivative products and application?

1.5 Scope of the study

The positional accuracy of geospatial data are measured in terms of horizontal and vertical accuracy. This study focused on the vertical accuracy of three Global DEMs, and do not consider the horizontal accuracy. The vertical accuracy of DEM is the measure of positional accuracy of DEM datasets with respect to a specified vertical datum, at specified confidence level. The vertical datum of global DEM is EGM96 (Earth Gravitational Model 1996) geoid. This datum has difference with local M.S.L (mean sea level) datum. This difference and the limitations of EGM96 geoid model are not considered in thus study.

1.6 Thesis structure

This thesis consists of six chapters and it is summarized as follows:

Chapter one presents introduction, problem statement of the study, objectives of the study, scope this study and research questions of this study. Chapter two aims to present literature review which include theory related Digital elevation model, sources of DEM and descriptions of major open source global DEM; height system and datum including Ethiopian height system and EGM96 Geoid model; and concept related to GNSS and vertical accuracy. Chapter three presents the research design and methodology. It is focus on data acquisition, preprocessing, processing and analysis methods. Chapter four focuses on data analysis and result presentation from DEM accuracy assessment results. Chapter five interpreter and discusses result from DEM accuracy analysis by different test datasets. Chapter six aims to present the key research conclusions and recommendation based on the finding of the research.

Chapter 2

2. Literature Review

2.1. Introduction

This chapter reviews the concept of DEM, sources of DEM and reference model to which measured values represented in DEM are referenced; the concepts of GNSS measurement system, accuracy assessment method and accuracy standards are also discussed.

2.2. Digital Elevation Model

The Digital Elevation Model (DEM) which represents the 3-D information on the ground is one of essential layers in the field of geographic information systems. Its applications extend over wide ranges in the scientific fields, e.g., hydrology, geomorphology, ecology, etc., as well as in the practical use, e.g., infrastructure design, disaster monitoring, environmental monitoring, natural resources survey, etc (Takaku et. al, 2016). DEM is a general term that represents a continuous surface representation, mainly referred to a raster. However, in practice, this general term is divided in to two main categories. Digital Terrain Model: which represents the bare ground surface without any natural or man-made structure on top of it such as trees or buildings; and Digital Surface Model, and this represents a draping surface that combines the ground surface and the top of all natural and man-made features(Wassim 2016).

DEM can be represented digitally in many ways, including: a grid model in which elevation is estimated from each cell in regular grid, a triangular irregular network (TIN) which represents a surface of a set of contiguous, non overlapping triangles, and as contour line connecting points of equal terrain height.

For measuring the 3D information on the ground various methods are used depending on target scales or accuracies. Ketarji (2016); Kyaruzi, (2005); B. T. San & M. L. Suzen (2005) have discussed different ways of measuring and collecting elevation (height) data, which forms the basic elements of DEM. The first conventional method for collecting topographic information about terrain was through grand topographic surveying.

Topographic surveying is the science of measuring distances and angles on the terrain and above features, relative to a reference point and height(Wassim 2016).The surveyor collects several points in the study area using special instrument like total station starting from certain well defined points such as national geodetic network, and recomputed their xyz values accordingly. The main output from this method is a set of XYZ points that needs to be interpolated in order to generate continuous surface of the terrain or DEM using various methods of interpolation techniques. Although this method can provide height accuracy result (Leica Geosystem, 2015), it consume more time and depends on the presence of the surveyor in the field along with the equipment. For this reason, it is suitable only for relatively small and accessible areas. Instead, satellite GPS surveying and 3D laser scanning are taking over conventional ground surveying (Haddad, 2011).

Photogrammetry is another method for generating DEM. Photogrammetry is the science and technology of obtaining spatial measurements and other geometrically reliable derived products from photographs. Photogrammetric analysis procedures can range from obtaining approximate distances, areas, and elevations using hardcopy photographic products, unsophisticated equipment, and simple geometric concepts to generating precise digital elevation models (DEMs), orthophotos, thematic GIS data, and other derived products through the use of digital raster images and relatively sophisticated analytical techniques (Thomas, Ralph and Jonathan 2004). Historically, the most common use of Photogrammetry has been to produce hardcopy topographic maps. Today, photogrammetric procedures are used extensively to produce a range of GIS data products such as precise raster image backdrops for vector data and digital elevation models. Thematic data (in three dimensions) can also be extracted directly from photographs for inclusion in a GIS.

Traditionally, topographic maps have been produced from hardcopy stereo pairs in a device called a stereo plotter. With this type of instrument, the photographs are mounted in special projectors that can be mutually oriented to precisely correspond to the angular tilts present when the photographs were taken. Once oriented properly, the projectors recreate an accurate model of the terrain that, when viewed stereoscopically, can be used to plot a planimetric map having no relief distortions. In addition, topographic contours can be plotted on the map and the height of vertical features appearing in the model can be determined (Ibid).

Stereoscopic Photogrammetry is based on the concept of stereoscopic-viewing mentioned above. The advancement of computer technology enabled us to measure 3D features directly from digital images by the means of visualizing stereoscopic- images via specialized computer transmitters and glasses and using ground control points (Linder 2009). Stereoscopic Photogrammetry provides the means to generate DEM by collecting a set of mass points in the form of XYZ. These mass points will be interpolated later on to generate the continuous surface. In addition to stereoscopic aerial photos, there exist several satellite sonsors that provide stereoscopic satellite images. The study in (Krishnan, Sajikumar and Sumam 2016) showed a method of high quality DEM generation from Cartosat-I stereo data. Results from the study shows that the DEM generated from Cartosat-I stereo data using Leica Photogrammetry Suite (LPS) is more accurate than the publically available Carto DEMs.

Other satellite sensors that provide stereoscopic satellite images include: Advanced spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Global Digital Elevation Model (GDEM) and Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) an optical sensor onboard the Advanced Land Observing Satellite (ALOS).

The global elevation data derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER/GDEM) derived from the optical stereo sensors was released in 2009 first. It has the height accuracy of 13 m in 1 arcsec (30 m) pixel spacing (Tachikawa et al., 2011). Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) was an optical sensor onboard the Advanced Land Observing Satellite (ALOS) operated from 2006 to 2011, and was designed to generate worldwide elevation data. The sensor consists of three independent panchromatic radiometers for viewing forward, nadir, and backward producing in-track triplet stereoscopic images in 2.5 m ground resolution (Tadono et al. 2009).

In recent years global DEM datasets derived from spaceborne remote-sensing techniques are being widely used with its wide coverage and homogeneous data quality. Radargrametry is the concept of collecting data through an active sensor that works on the basics of echo, where the sensor periodically transmits a high powered and short-period signal toward the target surface. The system records the backscattered signal and deducts from it the distance based on the time taken for the signal to hit the target and back (Gomarasca, 2009).

The Shuttle Radar Topography Mission (SRTM) was the first global datasets made by spaceborne radar instruments and was released in 2003 first. The data has 3 arcsec (90 m) pixel spacing at the first release in which the absolute and relative height accuracies are ~9 m and ~10 m respectively (90 % errors) (Rodriguez et al., 2006).

Another advance in Radargrametry is the Airborne Interferometric SAR (InSAR) that provides an intermediate level of detail between the Airborne LiDAR and the Spsaceborne SAR sensors. The study in (Byran, 2008) showed that such technology provides either DTM or DSM with 5 meter spatial resolution. On the other hand Light Detection and Ranging

(LiDAR) is one of the best and latest technologies that measure distance by transmitting a laser beam on the target feature and analyzing the reflection. LiDAR sensors can be mounted on airplane, called Airborne LiDAR, or on cars called Terrestrial LiDAR and can reach vertical accuracy higher than 5 centimeters (LiDAR, 2013).

2.1.1. Global (Wide area) DEM

Satellite remote sensing are the only viable technologies to acquire large-area DEMs over large areas. This section describes some of popular wide-area DEMs.

SRTM (Shuttle Radar Topography Mission) acquired DEMs in February 2000 by single-pass SAR interferometry in the C- and X-bands (Farr et al. 2007). There are several versions, with or without holes; patched with data from other sources, etc. the SRTM DEM version discussed here is The SRTM-30m ("SRTM V3.0, 1 arcsec"). The SRTM-30m is a an enhancement to the low resolution SRTM topographic data having 90-m (3arcseconds, which is 1/1200th of a degree of latitude and longitude) resolution covering regions outside the United States (US) which was released publicly in 2003. The new data, released in September 2014, increase the detail to 30-m (or 1 arc-second), revealing the full resolution of the world's landforms as originally released by SRTM in the year 2000 (NASA JPL, 2014). Before this release, the best available 90-m SRTM DEMs for regions outside the US were: (i.) SRTM Version3 (also called "SRTM Plus") released by the National Aeronautics Space Administration (NASA) in November 2013 (NASA LP DAAC, 2013); and (ii.) CGIARCSI SRTM Version 4.1 released by the Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI) in 2008 (Jarvis et al., 2008). According to its mission objectives, SRTM DEMs are expected to have linear vertical absolute height error of less than16m, linear vertical relative height error of less than 10 m, circular absolute geolocation error of less than 20 m, and circular relative geolocation error of less than 15 m (Farr et al., 2007). SRTM-30m accuracy assessments conducted by NIMA, the USGS, and the SRTM project team have shown the absolute vertical error to be much smaller, with the most reliable estimates being approximately 5 m (Kellndorfer et al., 2004).

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM was created from data acquired between 1999 and 2009 with stereo matching of image data in the visible and near-infrared range. It covers the landmasses between 83°N and 83°S at ~30 m grid spacing, with some small holes. The accuracy (95% confidence) is 20 m. Empirical valuations have shown that ASTER has somewhat inhomogeneous quality (Schindler, et al.

2011). The ASTER GDEM Version 2 was considered to be the highest resolution DEM among the free accessible global DEMs during its release in 2011 (Arefi and Reinartz, 2011). The ASTER GDEM v2 contains significant improvements of Version 1 (released in 2009) in terms of spatial coverage, refined horizontal resolution, increased horizontal and vertical accuracy, water masking, and inclusion of new ASTER data to supplement the voids and artifacts (NASA JPL, 2011). In Japan, the ASTER GDEM2 was reported by the ASTER GDEM Validation Team to have an RMSE of 6.1 m in flat and open areas, and 15.1 m in mountainous area largely covered by forest (Tachikawa et al., 2011). In the conterminous US, the RMSE computed for GDEM2 was 8.68m based on the comparison with more than18, 000 independent reference ground control points (Gesch et al., 2012).

The **ALOS** (AW3D30) was released in 2015 by the Japan Aerospace Exploration Agency (JAXA). The AW3D-30 is actually a resampling of the 5-meter mesh version of the World 3D Topographic Data, which is considered to be the most precise global-scale elevation data at this time (JAXA, 2015). AW3D30 was generated using the traditional optical stereo matching technique as applied to images acquired by the Panchromatic Remote sensing Instrument for Stereo Mapping (PRISM) sensor onboard the Advanced Land Observing Satellite (ALOS) (Takaku et al., 2014). Details on how the DEM was generated are discussed in the papers of Tadono et al (2014) and Takaku et al (2014). Tadono et al. (2014) found the AW3D-5m to have height accuracies better than 5m in four test sites with varying terrain features while Takaku et al. (2014) found the same DEM version to have a Root Mean Square Error (RMSE) of almost 4 m based on comparisons with various datasets including airborne LiDAR Digital Surface Model (DSM) and ground control points (GCPs). Recent assessment conducted by Tadono et al (2015) confirmed an RMSE of 4.10 m.

2.3. Height Systems & Datum

Heights are generally related to a particular datum or reference plane, which is primarily dependant on what type of height system, has been employed. Featherstone & Kuhn (2006), in their review of height systems, identify two main types, those that are related to gravity, and those that are not. Height systems that are not related to gravity are generally described as being geometrically derived. The most common geometric height system is the ellipsoidal height system, which is described as being the distance measured along a straight line, normal to a reference ellipsoid and a point of interest on the earth’s surface(Ashagrie 2017).

The ellipsoidal height system is predominately used when deriving a height by utilizing GNSS equipment. Due to the position derived by GNSS equipment being made with reference to an ellipsoid, any height derived from this equipment is subsequently made as an ellipsoidal height. In light of this, the datum that is employed for ellipsoidal heights is generally the reference ellipsoid itself(Ashagrie 2017).

Height systems that are related to gravity generally utilize the geoid as their datum plane. The geoid can be defined as an equipotential surface, perpendicular to the direction of gravity (Johnstone & Featherstone, 1998), where gravity potential is equal to zero. For all intents and purposes, the value of mean sea level is approximately coincident, and generally adopted as this surface(Ashagrie 2017)

The measured value in a DEM represents the elevation or height of the surface with respect to some reference. Taking the center of the Earth as a reference is neither practical nor meaningful, as the majority of the measurements will show relatively close values. While it is commonly assumed that such measurements are taken with respect to the sea level they are, in fact as (Ibid) stated, measured with respect to the two types of references: the Ellipsoid or the Geoid. is defined as the distance from the ellipsoid measured along a normal to the reference ellipsoid.

Ellipsoidal heights (h) refer to a reference ellipsoid such as the WGS84. The height h of a point is defined as the distance from the ellipsoid measured along a normal to the reference ellipsoid. Ellipsoidal heights can be derived from geocentric Cartesian coordinates provided by GPS observations(Heister et al., 1999). Orthometric heights (H) refer to an equipotential reference surface such as the geoid. The difference between orthometric heights and ellipsoidal heights is defined as the geoid height (N). The basic relationship between geoid, ellipsoidal and orthometric heights is given by the following equation:

$\boldsymbol{h = H \pm N}$ *where, h represents the ellipsoidal height; H represents the Orthometric height and N represents the undulation of geoid, the difference between ellipsoid and geoid surface.*

In geodesy, the Earth is modeled into mathematical ellipsoid in order to simplify its complex shape and provide a systematic reference for positioning. Adopting ellipsoid as a reference for height values will result in ellipsoidal height. However, the heights obtained from this reference ellipsoid, representing the mathematical shape of the Earth; do not have any physical meaning, but only a geometrical. Commonly heights are referenced to the mean sea level (MSL), which technically referred as Orthometric height. This reference surface is close to the geoid, which is an equipotential surface computed from gravity. The research by (Badada, 2010) has shown a new geodetic approach to computing absolute vertical reference system for a particular field point in a global sense without connecting to any local height network. A global vertical reference system should be defined by the Earth's gravity field and it must trace level surfaces in space. His work is focused on determining "an absolute Geopotential height system for Ethiopia, making two fundamental contributions. First, it develops a new definition of what a vertical reference system is; secondly it shows that this novel approach is able to predict the results of classical geodetic leveling: the mismatch has a standard deviation of only a few centimeters." In this satellite era one is capable of obtaining a sufficiently accurate model of the gravity field, therefore, most of the Global DEMs are referenced to Earth Gravitational Model EGM96 and 1984 World Geodetic System (WGS84) reference ellipsoid. The development of EGM08 incorporated Ethiopian airborne gravity data (Badada, 2010). Therefore, EGM08 can be used to convert ellipsoidal height measured by GPS to orthometric heights.

2.3.1. Earth Gravitational Model 1996 (EGM96)

The Earth Gravitational Model 1996 (EGM96) is one global geoid models that can be used to calculate the orthometric elevation when the values of ellipsoid heights are given by GPS positioning instruments. It is expressed by a spherical harmonic expansion of the gravitational potential and complete through degree and order 360 with an error range of 0.5 to 1.0m worldwide (Xiong and Hans-Jurgen 2001). This model is the result of collaboration between the National Imagery and Mapping Agency (NIMA), the NASA Goddard Space Flight Center, and the Ohio State University. The joint project took advantage of new surface gravity data from many different regions of the globe, including Africa, Canada, parts of South America, Greenland and parts of the Arctic and the Antarctic, Southeast Asia, Eastern Europe, and the former Soviet Union. In addition, there have been major efforts to improve NIMA's existing 30' mean anomaly database through contributions over various countries in Asia EGM96 model is used to compute geoid undulations accurate to better than one meter (with the exception of areas void of dense and accurate surface gravity data) with reference to WGS84 ellipsoid(Kumar and Chauhan 2006).

2.3.2. Ethiopian Height System

The authority for the Ethiopian geodetic control project was contained in two separate agreements. The first was the Point-4 agreement between the Imperial Ethiopian Government and the Government of the United States 'to study the water resources of Ethiopia for the multi-purpose Blue Nile River Basin investigation' of June 26, 1956. The second was the Special Services agreement of March 5, 1957, between the International Cooperation Administration of the U.S. State Department and the Coast and Geodetic Survey of the U.S. Department of Commerce The Special Services agreement called for the Coast and Geodetic Survey to undertake the establishment of geodetic control in the Blue Nile River basin and to utilize, to the maximum extent, Ethiopian nationals who were to be given on-the-job training in geodetic procedures and methods. Preparations for the Coast and Geodetic Survey's participation in the project started in the fall of 1956 [Karo, 1960], and field operations commenced in April 1957 [Jones, 1960]. The project continued without interruption until the completion of the field work in November of 1960. The region of the Blue Nile River basin geodetic-control project includes the entire Ethiopian watershed of the river, an area of approximately 120,000 mi^2(Ashagrie 2017)

The adjustments of the field observations of the Ethiopian survey data were performed by means of computational techniques that have been developed and are in current use by the U.S. Coast and Geodetic Survey. These computations included a least-squares adjustment of the 905 permanent bench marks of the level net and a solution of the reciprocal vertical-angle observations taken at all 370 triangulation stations. Twenty-three triangulation stations were established as bench marks, and these stations furnished the control for the vertical-angle adjustment. The elevations so obtained for the triangulation stations were then used to compute sea-level corrections for the horizontal directions. The triangulation network includes first-, second-, and third-order stations, 11 Laplace azimuths, 9 invar-taped bases, and 78 Tellurometer measurements.

The vertical control network is referred to mean sea level at Alexandria, Egypt, and is made up of over 1976 miles of spirit leveling. The completed level lines consist of a line from the Sudanese connection eastward to the eastern edge of the triangulation and a large loop south ward through Addis Ababa which connects back into the first line. A number of small loops were completed in the vicinity of Addis Ababa. The closure of the large loop was 0.40 meter. A level line was also run to the Red Sea with a closure of 0.18

meter. The maximum rate of correction for the long links of the adjustment is 0.26 ram/kin. The computations were made by applying 'level,' 'length of rod,' and 'temperature of the rod' corrections. Orthometric corrections based on theoretical values of gravity were computed. Two determinations of the water surface elevation of Lake Tana were obtained. The elevation at the north shore is 2 cm higher than that at the south shore. Since the determinations were made near the end of the dry season, they approximate the low-water elevation of the lake (Ibid).

The adjustment of the vertical-angle observations began with the computation of a difference of elevation over each triangulation line in the network. The reciprocal zenith distance observations were used in these computations. These differences were checked to ensure that the ratio of the sum of the zenith distances of the two stations minus 180 ø, divided by the distance between them, gave reasonable Coefficients of refraction. The differences were then plotted on a sketch of the work, and those observations were accepted which, in general, yielded a minimum algebraic sum of the differences of elevation around each triangle.

A least-squares solution of these differences was then completed by means of observation equations. Elevations approximating the final values were first assumed for each station. To these assumed values were added X's (unknowns) to be determined by the adjustment. The equations were formed by comparing the differences of the assumed elevations with the differences determined by computation. The weight assigned to a difference of elevation in the solution was the reciprocal of the square of its length. The Cholesky method for the solution of the normal equations was used. The X's so obtained were the corrections applied to the various assumed elevations to give final elevations.

Excellent closures were obtained between points of fixed elevation when the accepted unadjusted differences were used, except for the arc between the Sudan connection and the Gullui base. In this section closures were poor, and these Observations were used in the adjustment with one-tenth the normal weight. In this area of the country the terrain is quite level, and the high temperatures at the time of the observations caused extreme refraction effects over these long lines.

The highest elevation in Ethiopia, Mount Ras Dashan, third highest mountain in Africa, was determined to be 14,902 feet (4542 meters) as t he result of nonreciprocal vertical-angle observations. The final elevations obtained as the result of the least-squares adjustment are probably good within ±3 meters, except those for stations above 13’ ø latitude. The elevations of these stations may be good only to ±10 meters. The triangulation was computed on the Clarke spheroid of 1880 and is based on the Adindan, or 30th meridian, datum. The two stations held fixed in geographic position for this adjustment were obtained from the Survey Department, Sudan, E. Africa, in October of 1958. This choice of weighting gave a satisfactory solution with minimum distortion to both the angular and the Tellurometer distance measurements. The Tellurometer measurements were primarily grouped into quadrangle measurements, serving as length control at arc intersections. The average length change to the 78 Tellurometer-measured lengths used as observation equations in the solution was 1:267,000. The maximum length change on a Tellurometer measured line was 1:68,400. The ends of two invar-taped bases established by the Italians in the 1930's were re-covered by Coast and Geodetic Survey personnel. The lengths of these bases were available and, after preliminary testing, were also held fixed in the scheme (Blackwell 1962).

2.4. GNSS (Global Navigation Satellite System) Measurement System

A global navigation satellite system is made up a network of satellites that transmit ranging signals used for positioning and navigation anywhere around the globe as well as air or sea. Examples of such systems include the famous and oldest US Global Positioning System (GPS), the Russian GLObal NAvigation Satellite System (GLONASS), Galileo Navigation Satellite System of the European Union, Beidous/Compass of China, Quasi Zenith Satellite System (QZSS) of Japan and IRNSS (Indian Regional Navigation Satellite System) of India. GNSS includes four segments: the space segment, the Control segment, user segment and the ground Segment. The space segment includes the constellation of GNSS satellites, which transmit radio signals to the user’s receiver. The control segment (example for GPS) consists of a worldwide network of tracking stations, with a master control station (MCS) located in the United States at Colorado Springs, Colorado. The primary task of the operational control segment is tracking the GPS satellites in order to determine and predict satellite locations, system integrity, and behavior of the satellite atomic clocks, atmospheric data, the satellite almanac, and other considerations. The user segment consists of user hardware and processing software for positioning, navigation, and timing applications. Ground segment includes civilian tracking networks that provide the user segment with reference control, precise ephemerides, and real time Differential GPS service (Alfred, Lev and Tatarnikov 2015).

Determining receiver position (i.e. latitude, longitude, and height) relies on calculated distance to several satellites. Each satellite continuously broadcasts navigation message. The receiver uses the received message, from satellites in the view, to determine the transit time of each message and compute the distance to each satellite. Constellation with a sufficient number of satellites must be launched for each GNSS to ensure that at least four satellites are simultaneously visible from any point on Earth. GNSS positioning is based on trilateration, which is the method of determining position by measuring distances to points at known coordinates. Trilateration requires a minimum of three ranges to three known points. Each satellite covers a range; each range defines a surface of sphere, where the satellite is in the center of this sphere.

In principle, three satellites are enough to determine longitude, latitude and height from the three sphere equations. The satellites have atomic clocks which can be synchronized to the level of nanosecond, but this is not the case with current receivers, as the atomic clocks are expensive. Therefore, receivers' manufactures use inexpensive crystal clocks. However, one micro second synchronization error leads to a position error of 300 meters. To overcome the synchronization problem, a fourth satellite signal will be needed to calculate Δt. To solve four unknowns (x, y, z and Δt), there must be four equations. Using more satellites not only allows Δt calculation, but also increases the accuracy of the receivers' position calculation. This study previews GNSS measurement principle based on the Global Positioning System (GPS) of US.

2.4.1.Global Positioning System

The United States Department of Defense (DoD) has developed the Navstar GPS, which is an all-weather, space based navigation system to meet the needs of the USA military forces and accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis. GPS satellite constellation buildup started with a series of 11 satellites known as Block I satellites. The first satellite in this series (and in the GPS system) was launched on February 22, 1978; the last was launched on October 9, 1985. Block I satellites were built mainly for experimental purposes. The inclination angle of the orbital planes of these satellites, with respect to the equator, was 63°, which was modified in the following satellite generations. Although the design lifetime of

Block I satellite was 4.5 years, some remained in service for more than10 years. The last Block I satellite was taken out of service on November 18, 1995(Ahmed 2002).

The launch of the second generation of GPS satellites, called Block II, began in February 1989. In addition to radiation-hardened electronics, these operational satellites had full SA/AS capability and carried a navigation data message that was valid for 14 days. Additional modifications resulted in the satellite called Block IIA. These satellites can provide about 6 weeks of positioning service without contact from the control segment. Twenty-eight Block II/IIA satellites were launched between 1989 and 1997 into six planes, 55° inclined. The first third-generation GPS satellite, called Block IIR (R for replenishment), was successfully launched in 1997. These satellites have the capability to determine their orbits autonomously through UHF cross-link ranging and to generate their own navigation message by onboard processing. They are able to measure ranges between themselves and transmit observations to other satellites as well as to ground control. In recent years, GPS has undergone a major modernization. Most importantly, the GPS satellites are transmitting more signals that allow a better delineation of military and civilian uses, and thus increase the performance of GPS even more (Alfred, Lev and Tatarnikov 2015).

The idea behind GPS is rather simple. If the distances from a point on the Earth (a GPS receiver) to three GPS satellites are known along with the satellite locations, then the location of the point (or receiver) can be determined by simply applying the well-known concept of resection. Each GPS satellite continuously transmits a microwave radio signal composed of two carriers, two codes, and a navigation message. When a GPS receiver is switched on, it will pick up the GPS signal through the receiver antenna. Once the receiver acquires the GPS signal, it will process it using its built-in software. The partial outcome of the signal processing consists of the distances to the GPS satellites through the digital codes (known as the pseudoranges) and the satellite coordinates through the navigation Message(James Bao 2005).

As mentioned before, theoretically, only three distances to three simultaneously tracked satellites are needed. In this case, the receiver would be located at the intersection of three spheres; each has a radius of one receiver-satellite distance and is centered on that particular satellite. From the practical point of view, however, a fourth satellite is needed to account for the receiver clock offset.

The accuracy obtained with the method described earlier was until recently limited to 100m for the horizontal component, 156m for the vertical component, and 340 ns for the time component, all at the 95% probability level. This low accuracy level was due to the effect of the so-called selective availability; technique used to intentionally degrade the autonomous real-time positioning accuracy to unauthorized users (Hoffmann-Wellenhof 1994). GPS positioning accuracy can be improved by the so-called differential method, which employs two receivers simultaneously tracking the same GPS satellites. In this case, positioning accuracy level of the order of a sub-centimeter to a few meters can be obtained.

2.4.2. GPS Signal

Each GPS satellite broadcasts radio signals containing synchronized orbital information and timing signals at two frequencies, designated by L1and L2 (Hofmann-Wellenhof & Moritz, 2006). L1 is the principal GPS carrier signals, at a frequency of 1575.42 MHz, equivalent to a wavelength of about 19 cm. The GPS L2 signal, transmitted by the satellite at 1227.60 MHz (~ 24 cm wavelength), was established to provide GPS user receivers with a second frequency for ionospheric delay corrections. The combination of L1 and L2 frequencies provides a real time technique for determining the ionospheric delay effects on the GPS signal paths caused by the free electron content in the ionosphere (Gao & Liu, 2002; Liao, 2000). The signals of each satellite allow the user to measure an approximate distance from the receiver to the satellite, which is called the Pseudorange. The Pseudorange is calculated from the signals time of travel from a satellite to the receiver. Radio signals travel at the speed of light c and geodetic latitude, longitude and ellipsoidal height and calculated from Pseudorange measurements with respect the 1984 World Geodetic System (WGS84) reference ellipsoid.

c = 299,792,458 m/s.

Pseudorange = (time difference) ×c

2.4.3. GPS Errors

GPS measurements are potentially subject to numerous sources of error in addition to clock bias. Among these are uncertainties in the satellite orbits (known as satellite ephemeris errors), errors due to atmospheric conditions (signal velocity depends on time of day, season, and angular direction through the atmosphere), receiver errors (due to such influences as electrical noise and signal matching errors), and multipath errors (reflection of a portion of the transmitted signal from objects not in the straight-line path between the satellite and receiver). Such errors can be compensated for (in great part) using differential GPS measurement methods. In this approach, simultaneous measurements are made by a stationary base station receiver (located over a point of precisely known position) and one (or more) roving receivers moving from point to point. The positional errors measured at the base station are used to refine the position measured by the rover(s) at the same instant in time. This can be done either by bringing the data from the base and rover together in a postprocessing mode after the field observations are completed or by instantaneously broadcasting the base station corrections to the rovers (Thomas, Ralph and Jonathan 2004)

2.5. Accuracy Assessment

Accuracy refers to the bias of an estimator; it measures how close an estimated or calculated value is to its true value. In positional accuracy assessment, we are interested in characterizing the accuracy of a geospatial data set. We take samples to determine if a bias (systematic inaccuracy) exists in the data set, and we estimate the magnitude and precision of the bias. The Glossary of the Mapping Sciences (ASPRS and ASCE, 1994) defines positional accuracy as “the degree of compliance with which the coordinates of points determined from a map agree with the coordinates determined by survey or other independent means accepted as accurate.” positional accuracy has been assessed by comparing the coordinates of sample points on a map against the coordinates of the same points derived from a ground survey or some other independent source deemed to be more accurate than the map. Positional accuracy can refer to either horizontal (planimetric) or vertical (elevation) accuracy. Since the aim of this research is to assess the vertical accuracy of open source Digital Elevation Models this section will focus on the vertical (height) aspect of positional accuracy assessment.

According to the United States National Map Accuracy Standards (NMAS) published by U.S. Bureau of the Budget (U.S. Bureau of the Budget, 1947) Vertical accuracy defined as:

> Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10% of the elevations tested shall be in error by more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale. The accuracy of any map may be tested by comparing the positions of points whose locations or elevations are shown upon it with corresponding positions as determined by surveys of a higher accuracy. Tests shall be

made by the producing agency, which shall also determine which of its maps are to be tested, and the extent of such testing.

American Society for Photogrammetry and Remote Sensing (ASPRS) (ASPRS, 2014) also stated that "vertical accuracy is the measure of the positional accuracy of a data set with respect to a specified vertical datum, at a specified confidence level or percentile."

2.5.1. Accuracy assessment methods

Estimating positional error parameters requires the comparison of coordinates and/or elevations of identical sample locations from (FGDC, 1998):

- The spatial dataset to be assessed (map or imagery) and
- The reference data, which must be an "independent source of higher accuracy"

Accuracy assessment can be qualitative or quantitative. The goal of quantitative accuracy assessment is the identification and measurement of DEM errors. This quantitative assessment is done through sampling, because measuring every point in the geospatial data set being assessed would be prohibitively expensive, and sampling can provide highly reliable estimates of the error population's parameters (Congalton & Green, 2008). NSSDA (FGDC, 1998) outlines several requirements fort sampling design and collection which includes:

- The reference data may be independent from the data being tested.
- For statistical rigor, more than 20 sample locations should be chosen.
- The sample points must also be well distributed across the project area, and represent the full variety of topography.

Using metric units, ASPRS recommends 100 static vertical checkpoints for the first 2,500 square kilometer area within the project, which provides a statistically defensible number of samples on which to base a valid vertical accuracy assessment. Checkpoints should be distributed generally proportionally among the various vegetated land cover types in the project (ASPRS, 2014).

To assess the vertical accuracy of a DEM, there exist three main techniques that rely on statistics: Root Mean Square Error (RMSE), variance, and 95th percentile. The NSSDA uses root-mean-square error (RMSE) to estimate positional accuracy. RMSE is the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points (FGDC, 1998).RMSE is given as

$$RMSE = \sqrt{\frac{\sum(Zi - Zt)^2}{n}}$$

*Where **Zi** is the interpolated DEM elevation of a test point, Zt is the true elevation of a test point and **n** is the number of test points.*

When using RMSE it is assumed that systematic errors have been eliminated as best as possible and if vertical error is normally distributed, the factor 1.9600 is applied to compute linear error at the 95% confidence level (Greenwalt and Schultz, 1968). Therefore, vertical accuracy, Accuracy reported according to the NSSDA shall be computed by the following formula:

Accuracy = 1.9600 *RMSE.

Two problems with this as a measure of DEM quality are that normally it is based on a very small sample of check points and perhaps more importantly it does not assist in identifying the source of the error - it is not possible to determine whether the level of error found is due to random errors, systematic errors or blunders (wise, 2000). Despite this, it has been used as a means of comparing the quality of DEMs produced by different methods (Gorokhovich et al., 2006; Chaieb et al., 2016).

DEM accuracy assessment can be done through comparison of DEM derivatives like slope, aspect and drainage extracted from DEM in question and reference DEM. quality assessment can also be carried out visually by preparing shaded relief map and profile studies (Indian space research Organization, 2014).

Slope identifies the steepest downhill slope for a location on a surface. Slope is calculated for each triangle in TINs and for each cell in rasters. For a triangulated irregular network (TIN), this is the maximum rate of change in elevation across each triangle. For rasters, it is the maximum rate of change in elevation over each cell and its neighbors. Aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors. It can be thought of as the slope direction. The area upon which water falls and the network through which it travels to an outlet are referred to as a drainage system (ESRI, 2016).

Reddy, G.P.O., et al(2017) studied automatic extraction of stream network based on digital elevation models from ASTER GDEM and Cartosat-1 of 30 m resolution and compared the result. In this study they found that threshold of 0.05 km^2 is optimum to obtain the finer drainage networks particularly from Cartosat-1 DEM, when compare to the ASTER GDEM of same resolution.

2.5.2. Accuracy Standards

There exist several national and international standards that define the norms and accuracy limits of DEM products and link it to its usability. One of the national standards that have international impact is the National Geospatial Program Standards and Specifications, which was developed by the United States Geological Survey (U.S. Geological Survey, 2015). As previously defined, the accuracy of a DEM is defined by its RMSE, which must be calculated using a minimum of 28 control points, 20 interiors and 8 on the edges. The standard divides DEM products into three levels and sets a specific standard for each:

- Level 1: Includes standard 7.5-minute DEM product in the US, which have a spatial resolution on 1 arc-second or approximately 30 meters or any equivalent DEM from stereo profiling or image correlation. An RMSE less than or equal to 7 meters is desired, with a maximum of 15 meters allowed
- Level 2: Includes DEMs that were generated from hypsographic and hydrographic data collected using Photogrammetry or existing maps. An RMSE of one-half contour interval is the maximum allowed, with no errors greater than one contour interval.
- Level 3: Similar to Level 2, but includes additional data to represent the terrain more accurately, such as ridge lines and transportation features. An RMSE of one-third contour interval is the maximum allowed, with no errors greater than two thirds contour interval.

Another ‘continental’ standard is the European Commission’ Infrastructure for Spatial Information in the European Community (INSPIRE), Data Specifications on Elevation (INSPIRE Thematic Working Group Elevation, 2013). This standard is spread among all the European countries that are part of the European Union. The specification document divides the elevation value depending on the geometry of the data:

- Vector or TIN: The maximum allowed vertical RMSE is equal to the contour line interval divided by six. In low reliability areas such as dense forests, the maximum RMSE can be increased by 50%.
- Raster: The maximum allowed vertical RMSE is equal to the spatial resolution (referred to as Ground Sample Distance in the documentation) of the raster divided by three.

National agencies like Ethiopian road Authority provide their own standards specification, for example the survey requirements associated with the geometric design process in the Geometric Design Manual state that elevation of photogrammetric DTM points on hard surfaces are accurate to within ±60 millimeters (ERA, 2002).

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Chapter 3

3 Methodology

3.1 Description of the study area

3.1.1 Addis Ababa

Addis Ababa is located in the central highlands of Ethiopia, which covers an area of about 540 km2. Its geographic location is between 38.638^o and 38.906^o east and 8.832^o and 9.09^o north. Addis Ababa is located on the shoulder of the Western Main Ethiopian Rift escarpment. Its elevation ranges generally between 1780 m and 3380 meter a.m.s.l. However, the portion of the area with elevation greater than 3200 meter a.m.s.l is negligibly small. The Northern part is within the elevation range of 2670 meter and 3000 meter a.m.s.l. This area is very sloppy, however, both elevation and slope decreases progressively towards the South. A large portion of the central part Addis Ababa falls in a narrow elevation range of 2313 and 2491 meter a.m.s.l. As shown digital elevation model map below. Proceeding further south wards, the topography becomes very gentle and a very wide area falls under a smaller elevation range of 2053 meter and 2192 meter a.m.s.l. (Tsegaye, 2014). The boundary of the study area was delineated according to the current administrative boundary of Addis Ababa city administration which has the total area of 519.46 km^2. Figure 3.1 shows Addis Ababa city boundary and topography.

3.1.2 Dire Dawa

Dire Dawa Administrative Council is located between 9 ^{o} 27`N and 9 $^o$ 49`N latitude and 41 ^{o} 38`Eand 42 $^o$ 19`E longitude, and in the eastern marginal catchment of Awash basin. It is about 515kms road distance to the east of Addis Ababa and 311kms to the west of Djibouti port. The total area of the region is about 128,802ha. The total Dire Dawa area can be divided in to three major areas; the south and south-eastern part of the city is characterized by a chain of mountains and upland at the foot of the mountain chain covering 45%; and low lying flat land accounting for 40% of the land area. Its elevation range is between more than 2200m at near Dhangago to below 1000m at the north part of Shinile town (Ephrem, 2006). From the total area of Dire Dawa Administrative Council the total area cover by the town is 8738.47ha. The boundary of the study area selected in this research is based on the boundary of the structural plan of the city and aerial photographic project undertaken in 2012, which has an area of 104.5km^2 as in figure 3.2.

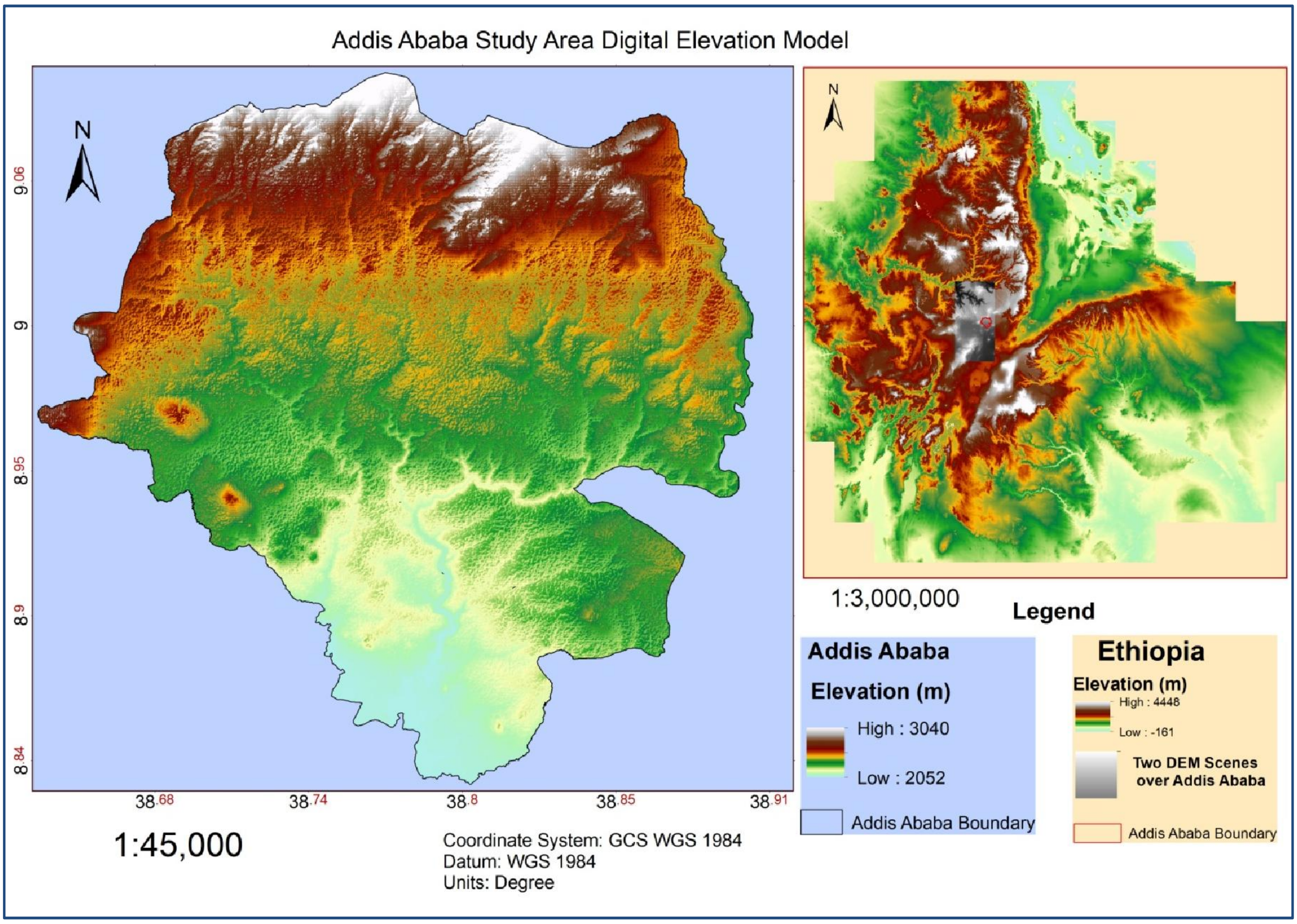


Figure 3.1 Addis Ababa City Boundary and Topography from SRTM 30m Digital Elevation Model.

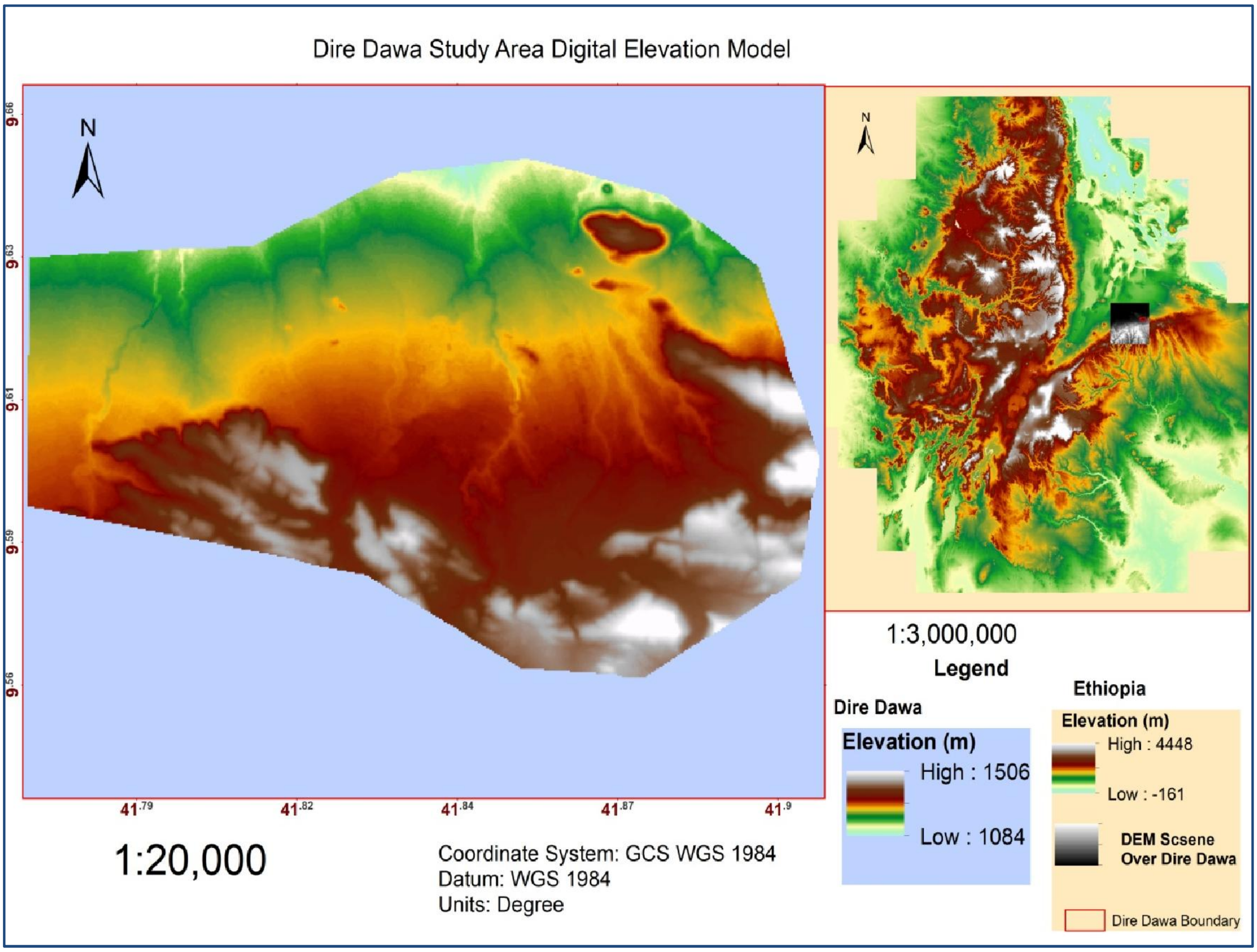


Figure 3.2 Dire Dawa City Boundaries and Topography from SRTM 30m Digital Elevation Model.

3.2 Data source

The three open source DEMs and the reference data (test data) available for this research are described under this topic.

3.2.1 ALOS World 3D - 30m (AW3D30)

The AW3D30 was released in 2016 by the Japan Aerospace Exploration Agency (JAXA), and can be downloaded free of charge from ttp://www.eorc.jaxa.jp/ALOS/en/aw3d30/. The AW3D-30 is actually a resampling of the 5-meter mesh version of the World 3D Topographic Data, which is considered to be the most precise global-scale elevation data at this time (JAXA, 2015). The data is Digital Surface Model (DSM) processed in unprecedented 5 m grid spacing utilizing the original triplet stereo images in 2.5 m resolution. The target accuracy of the product was set to 5 m (RMSE) in vertical accuracy. The DSM datasets are generated on 1°x1° tiles of geographic latitude/longitude grids as the final products. Total number of output tiles to be processed is approx. twenty-three thousand for global land areas(J. Takaku, et al. 2016). One tile covers the Dire Dawa and Addis Ababa is covered by two DSM tiles. Table 3.1 gives details of this dataset.

3.2.2 SRTM-30m

The SRTM-30m ("SRTM V3.0, 1 arcsec") is a an enhancement to the low resolution SRTM topographic data having 90-m (3arcseconds, which is 1/1200th of a degree of latitude and longitude) resolution covering regions outside the United States (US) which was released publicly in 2003. The new data, released in September 2014, increase the detail to 30-m (or 1 arc-second), revealing the full resolution of the world's landforms as originally released by SRTM in the year 2000 (NASA JPL, 2014). SRTM 30m DEM Data was downloaded from USGS official website. Detail about this DEM dataset are given in table 3.1

3.2.3 ASTER GDEM2

The ASTER GDEM Version 2 was considered to be the highest resolution DEM among the free accessible global DEMs during its release in 2011 (Arefi and Reinartz, 2011). The ASTER GDEM v2 contains significant improvements of Version 1 (released in 2009) in terms of spatial coverage, refined horizontal resolution, increased horizontal and vertical accuracy, water masking, and inclusion of new ASTER data to supplement the voids and artifacts (NASA JPL, 2011). In Japan, the ASTER GDEM2 was reported by the ASTER GDEM Validation Team to have an RMSE of 6.1 m in flat and open areas, and 15.1 m in mountainous area largely covered by forest (Tachikawa et al., 2011). The data was downloaded from USGS official website. Table gives details of DEM datasets.

The geodetic reference for SRTM 30m ALOS World 3D 30m and ASTER GDEM2 data is the WGS84/ EGM96 geoid as documented in respective data source official websites.

Table 3.1 Global DEM product details.

DATA	Data specification				
	Source	grid spacing	Datum Hor.	Datum Ver.	product specified ver. Accuracy(m)
ALOS (AW3D30)	http://www.eorc.jaxa.jp/ALOS/en/aw3d30/	30 meter	WGS84	EGM96	5
SRTM-30m	https://lpdaac.usgs.gov/	30 meter	WGS84	EGM96	16
ASTER GDEM2	*https://lpdaac.usgs.gov/*	*30 meter*	*WGS84*	*EGM96*	17

3.2.4 Reference/Test Datasets

The reference data (accuracy test data) used for this study are ground control points measured by GPS instruments and DEM created from digital contour data. These test datasets are described as follows.

3.2.4.1 GPS data

Two groups of GPS data were used in this study as reference data. The fist data was collected by Ethiopian Mapping Agency (EMA) during the establishment of Ground Control Points (GCP) for cadastral mapping purpose in Addis Ababa and Dire Dawa. There were no much documentation about this data, but the discussion made with employee of the Agency shows that this data was collected with dual frequency Laica GNSS receivers. The measured ellipsoidal height (h) was converted to orthometric height (H) using EGM96 global geoid model. This data include all GCP points used in Addis Ababa study area and 128 GCP points for Dire Dawa

The second group of GPS data was collected by Dire Dawa Land Administration Office, during which the researcher involved as team leader in data collection campaign lasting between the periods from 10/18/2016 to 10/24/2016. The instruments used were dual frequency SOKKIA GRX2 GNSS receivers and the post processing was done during this present study using MAGNET Tools ver. 4.0 which is commercial software providing a full featured environment for the processing and adjustment of GPS data collected by family of Topcon and SOKKIA instruments.

3.2.4.2 Reference DEM

The reference DEMs are used evaluate accuracy of ALOS, SRTM and ASTER DEMs in absolute and relative methods. In absolute accuracy assessment method elevation variation is compared pixel-wise and any deviations can be analyzed statistically and qualitatively(Kyaruzi 2005).The reference DEM also used to assess accuracy of DEMs in terms of surface derivatives such as Slope, drainage extraction and other DEM uses. This DEM data was created from digital contour data of 2 meter contour interval in Arc GIS 10.4 software environment and LAS (point cloud) file for Dire Dawa and Addis Ababa respectively. The contour data was produced by EMA from 15 centimeter resolution aerial Photograph of the study areas in 2011 for Dire Dawa and point cloud DSM was collected for Addis Ababa in 5/6/2018 as specified by data owner INSA in Addis Ababa photogrametrically. Table 3.2 shows Test datasets used in this study.

Table 3.2 Description of Reference/Test datasets

Data	***Source***	***number of GCP***	***Datum Hor.***	***Datum Ver.***
ADDIS ABABA GCP	*EMA*	*635*	*UTM Adindan 37N*	*EGM96*
Dire Dawa EMA GCP	*EMA*	*128*	*UTM Adindan 37N*	*EGM96*
Dire Dawa GCP measured	***Dire dawa Adm. Land mng. Office***	***167***	***Datum Hor.***	***Datum Ver.***
ADDIS ABABA DEM	*INSA*	*10 meter point spcing*	*UTM Adindan 37N*	*Msl*
DIRE DAWA contour DEM	*EMA*	*2 meter contour interval*	*UTM Adindan 37N*	*Msl*

3.3 Data Processing and Analysis Method

3.3.1 DEM accuracy assessment methods

To assess the accuracy of publicly available DEMs (ALOS, SRTM and ASTER) two techniques have been used. The fist technique is absolute accuracy assessment method, which measures how accurate elevation is at each pixel. DEM vertical accuracy assessment using absolute technique is by comparing elevation difference between reference DEM and DEMs to be validated. In this method, for proper comparison, both DEMs must be subseted to cover a common area and resampled to the same cell size (which is 30 meter) using bilinear resampling method that ensures the original cell structure is maintained (ESRI, 2016). The elevation differences are computed using ***ArcGis 10.4 Raster Math Toolset*** by the formula:

dH= Z(Ref.DEM)- Z(DEM)____(1)

Where:

dH = Elevation Difference(delta H)

Z(Ref.DEM)= Elevation values of Reference(test) Surface(DEM)

Z(DEM)= Elevation values of ASTER, SRTM and ALOS DEM

In relative (point wise) DEM vertical accuracy assessment the elevation values extracted from DEM to be assessed are subtracted from the measured GPS elevation values. ArcGis's '**extract values to point'** tool is used to extract values from each DEM for GPS point locations.

dH = ZGPS – ZDEM*____*(2)

Where:

dH & ZDEM are as in equation(1)

ZGPS = Elevation values of Reference control points as measured by GPS

This method relies on statistical measures such as RMSE, Maximum and Minimum, and mean Errors, and Standard deviation. RMSE is considered as a standard way of assessing the accuracy of DEM (Federal Geographic Data Committee, 1998). RMSE for DEM vertical accuracy is defined by the USGS as:

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum(\boldsymbol{Zt}-\boldsymbol{Zi})^2}{\boldsymbol{n}}} \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(3)}$$

Where ***Zi*** is the interpolated DEM elevation of a test point, Zt is the true elevation of a test point and ***n*** is the number of test points.

When using RMSE it is assumed that systematic errors have been eliminated as best as possible and if vertical error is normally distributed, the factor 1.9600 is applied to compute linear error at the 95% confidence level (Greenwalt and Schultz, 1968). Therefore, vertical accuracy, Accuracy reported according to the NSSDA shall be computed by the following formula:

Accuracy = 1.9600 *RMSE.

In this research, in addition to RMSE, accuracy measures like Minimum Error, Maximum Error, Mean Error, and Standard Deviation ware used.

- Minimum Error = min (|Zt –Zi|)___________________________________(4)
- Maximum Error = max (|Zt –Zt|) ___________________________________(5)
- Mean Error = $\frac{(|Zt - Zi|)}{n}$ ___________________________________(6)
- SD= $\sqrt{\frac{1}{n-1}\sum(Zt - Zi)^2}$___________________________________(7)
- SD= standard deviation

The second relative technique is based on comparison of DEM derived surface that are generated from DEM and different application that uses DEM with same products generated from higher standard DEM. This method as stated in Wassim K. (2016) and G. mile (2013) is a relative accuracy assessment method that shows how accurate the derived surface and application are presented. To perform DEM accuracy test in this method:

- Profile graph along the same line in both reference and public DEMs were compared.
- The slope derived from ALOS, SRTM and ASTER DEMs and Reference DEMs and compared though visual inspection. Accuracy of these DEMs with reference to terrain slope was analyzed.
- Drainage network extracted from ALOS, SRTM and ASTER DEMs were compared with same product of Reference DEM for same.

3.3.2 Data preprocessing

3.3.2.1 GPS *Data Processing*

GPS data obtained from EMA was processed and adjusted by EMA. The coordinate system of this data is Adindan datum, UTM Zone 37 North and Ellipsoidal height converted to Orthometric height by EGM96 geoid model. In order to calculate DEM accuracy on the same datum with that of the three Global DEMs these EMA GPS points were projected to geographic coordinates and WGS84 geodetic datum. The transformation parameters between Adindan WGS84 datum is given in table 3.4 below.

GPS data acquired from Dire Dawa Land Administration and Management Office was processed during this present study. The data collection campaign undertaken starting from 10/18/2016 to 10/24/2016 and static GPS observation was made on each station for minimum of one hour. Dual frequency SOKKIA GRX2 GNSS receivers ware used to collect a total of 167 GCP points. In order to perform the GPS observations of the GCP points in a "static mode" it is necessary to observe simultaneously with 2 GPS equipment stationed on 2 different station Points tracking the same satellites which are visible at the time of observation. When observing points that are located at a distance of 5 Km with GPS, the minimum duration of the observation recommended by the supplier of the equipment is 15 min. The row data downloaded from GNSS receiver (in TPS format) ware processed using MAGNET Tools ver. 4 software (a commercial GPS processing software supplied Dire Dawa land administration Office with SOKKIA GRX2 instrument) to compute the geodetic latitude, longitude and ellipsoidal height. The IGS Orbit product precise Ephemeris was used for GPS post processing and adjustment. Using this software the coordinates for each GCP points ware computed to millimeter accuracy with reference to WGS84 datum Reference Ellipsoid.

For every processed GPS point, geoid height (undulation) was calculated in MATLAB software using a built in MATLAB functions: geoidegm96. This function interpolates geoid heights from a 15-minute grid of point values in the tide-free system, using the EGM96 Geopotential Model to the degree and order 360. The geoid undulations are relative to the WGS84 ellipsoid (MathWorks, 2017). The calculated geoid height (N) values helped to calculate orthometric height (H) from the GPS measured Ellipsoidal height (h). The full report of determined coordinates is given in appendix A.

3.3.2.2 DEM Processing

The elevation values in ALOS (AW3D30), SRTM-30m and ASTER GDEM2 are given with reference to 1996 Earth Geopotential Model (EGM96), thus they can be used with the calculated GPS Orthometric data. These DEM data have geographic coordinate reference system of WGS84. In order to use those DEMs for application based analysis they have to be projected to local projected coordinate system which is Adindan UTM Zone 37 North. The transformation parameters between these two datum are given in table 3.4 below. When accuracy is assessed by GPS points and Reference DEM (test data), global DEM datum transformation is not needed because GPS data is the measured GPS data is given in WGS84 and EMA GCP data is projected to geographic coordinates and WGS 84 datum.

Table 3.3 transformation parameters between WGS84 and Adindan Datum.

Parameters: WGS84 to Adindan UTM_37N	
Dx	-162
Dy	-12
Dz	206
Rx	0
Ry	0
Rz	0
Scale(ppm)	0

The first three are the translation parameters between the two systems, the following Rx, Ry and Rz are the rotation parameters of the X, Y and Z axes from the reference WGS84 to the local system, and the scale factor is expressed in parts per million.

3.3.2.3 Reference DEM Preparation

The reference DEMs used in this study was produced from contour line data using 'ArcGis 10.4's Topo to raster tool'. Topo to raster tool is an interpolation method specifically designed for creation of hydrologically correct DEMs. It is based on the ANUDEM program developed by Hutchinson et al., (2011). This method was applied to create DEM with spatial resolution of 30 meters, same pixel resolution with DEMs under investigation, as shown in figur2.3. This tool uses drainage (stream) data to enforce conditions which, according to ANUDEM user guide (2011), increases the accuracy of DEMs in terms of drainage properties and surface shape. The ***Topo to raster*** interpolation method (ANUDEM) has been designed to take the advantage of the type of input data commonly available and the known characteristics of elevation surface. This method uses an iterative finite difference interpolation technique. It is optimized to have the computational efficiency of local interpolation method such as Inverse Distance Weighted (IDW) without losing the surface continuity of global interpolation method such as kriging and spline(ESRI 2016). Srajis Saleke et al. (2018) compared three interpolation method and found that ANUDEM produced a more realistic and consistent DEM, relative to IDW and Natural Neighborhood Interpolation method.

The quality of produced DEM was assessed by comparing contour derive from the interpolated DEM having 1 meter interval with the original contour line having 2 meter interval. As shown in figure 2.3 the derived contour line (1 meter contour interval) lies on and between the original contour line (2 meter). The accuracy of contour derived DEM also validated by 20 elevation reference data points from direct leveling collected by I.G.T.C. consultancy in 2005 for Dire Dawa Land Administration Agency. According to validation result this DEM has accuracy of 1.5 meter. This DEM here after called as DDEM (standing for Dire Dawa reference DEM) to distinguish it from Addis Ababa reference DEM (ADEM) which was created from point cloud DSM data obtained from INSA(information network security agency). DEM was created from LAS file which store point cloud data. This process was done in ***Global Mapper v. 18 software*** environment using average binning method that creates elevation grid (DEM) from average of all values. This DEM assumed to be accurate considering its source. Figure 2.4 shows DEM created from LiDAR data for North-West part of Addis Ababa covering two sub-cities (kolfe and Nifas-silk), about 122 sq. km in total area. The coordinate systems of these DEMs were converted to WGS84 datum with geographic coordinate system.

Chapter 4

4 Analysis and Result Presentation

4.1 Preprocessing Results

4.1.1 GPS Processing Result

GPS data for Dire Dawa study area processed and adjusted by Magnet Tools Software. The horizontal and vertical RMS for processed coordinate is 7.1 cm and 4.8 cm and the maximum standard deviation for Northing, Easting and up (NEU) coordinates are 8.1 cm, 3.7 cm and 10.01 cm. The final processing report is given in Appendix A. The geoid height (N) was calculated using EGM96 geoid model in Matlab software. The Matlab function ***N=geoidheight [lat, long]*** takes the latitude and longitude coordinates as input and gives geoid undulation or geoid height (N). Appendix B shows the calculated geoid height and orthometric height from GPS measured Ellipsoidal height of coordinates. Table 4.1 gives the first 15 records from table in appendix B.

Table 4.1 samples of processed GPS coordinates with calculated geoid and orthometric heights.

Name	Latitude	Longitude	Ell. Height (h)	Geoid Height(N)	Ortho.Height (H)
223	9.58833454	41.85666564	1214.248	-13.03	1227.278
224	9.58317292	41.8614294	1221.512	-13.03	1234.542
226	9.60026342	41.87344578	1184.832	-13.07	1197.902
232	9.60399285	41.84690304	1181.054	-13.04	1194.094
242	9.60830438	41.82856194	1166.875	-13.03	1179.905
247	9.61060683	41.83328861	1159.443	-13.04	1172.483
249	9.60326103	41.82140891	1182.624	-13.02	1195.644
250	9.59488831	41.84094548	1190.986	-13.02	1204.006
253	9.6029934	41.84213292	1183.124	-13.04	1196.164
254	9.6023251	41.84346854	1184.448	-13.04	1197.488
256	9.60030601	41.85783549	1186.861	-13.05	1199.911
257	9.60041231	41.8362182	1190.088	-13.03	1203.118
260	9.59460355	41.8559103	1196.741	-13.04	1209.781
264	9.6025232	41.87433495	1179.71	-13.07	1192.78

4.1.2 Reference DEM Preparation Result

The two Reference DEM (for Test datasets) ware interpolated from digital contour and point cloud data for Dire Dawa and Addis Ababa study areas. Both DEMs were assessed for vertical accuracy using available elevation test points. The Addis Ababa DEM accuracy test was evaluated by 152 EMA GCP points and the Dire Dawa DEM was assessed by 20 elevation points collected by leveling instruments in 2005(I.G.T.C. consultancy, 2005). The vertical accuracy of these two DEM is given in table 4.2. The created DEMs are shown in figure 4.1 and 4.2 below. Table 4.3 shows the details of Reference DEMs

Table 4.2 accuracy statistics of reference DEM

Statistics of height difference (GCP/Level Minus DEM)		
Accuracy Measure	**Addis Ababa DEM**	**Dire Dawa DEM**
MAX	3.89	2.15
MIN	0.01	0.01
Mean	1.81	0.57
standard Dev.	2.02	0.84
RMSE	2.02	0.82
Accuracy(95%)	3.95	1.60

Table 4.3 details of Reference DEMs

Properties	***Dire Dawa DEM***	***Addis Ababa DEM***
Minimum elevation	***1083.176m***	***2075.408m***
Maximum elevation	***1502.018m***	***2855.168m***
Mean elevation	***1190.582***	***2341.405***
Total Area	***100 sq km***	***122 sq km***

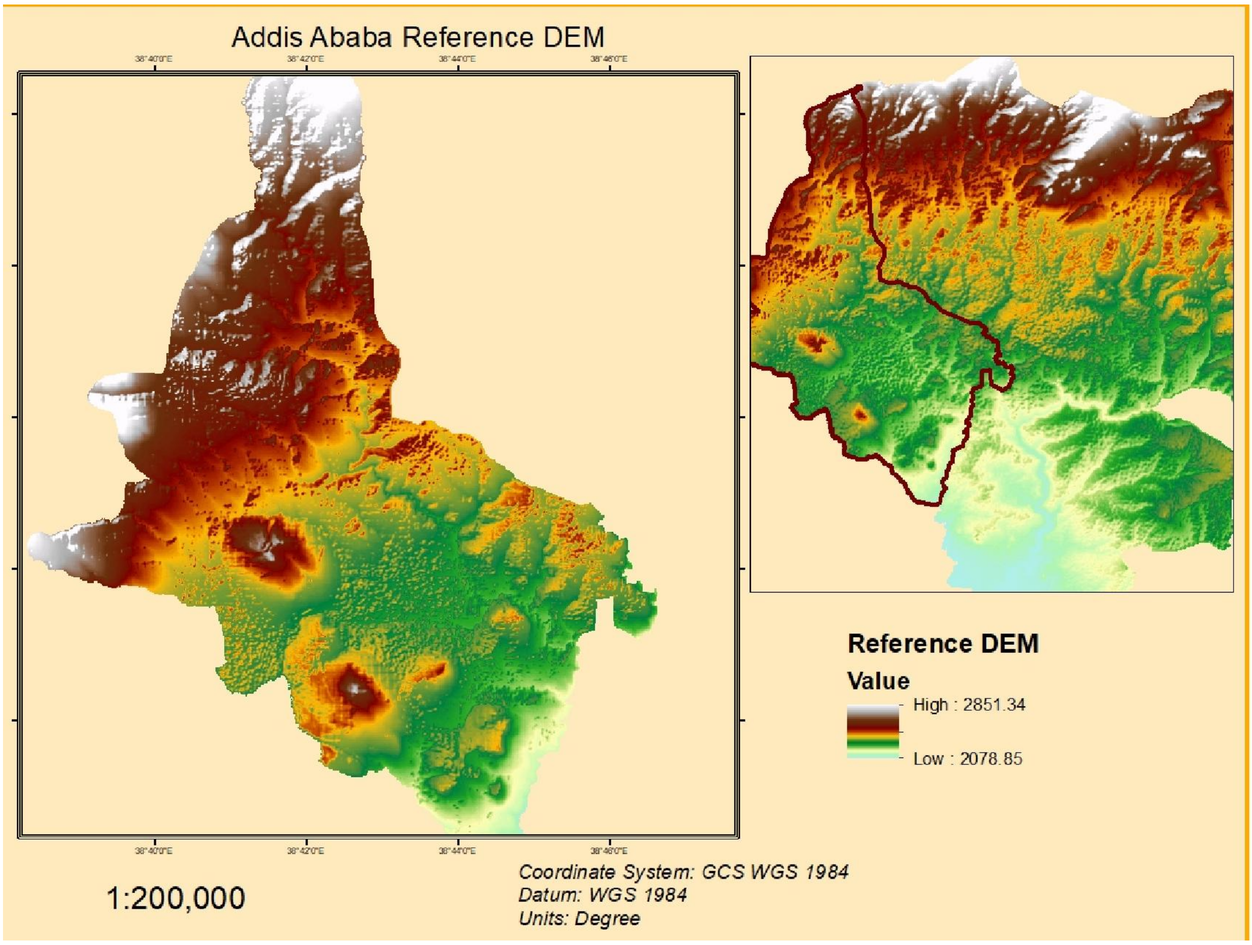


Figure 4.1 Addis Ababa Study Area Reference DEM boundary extent and topography.

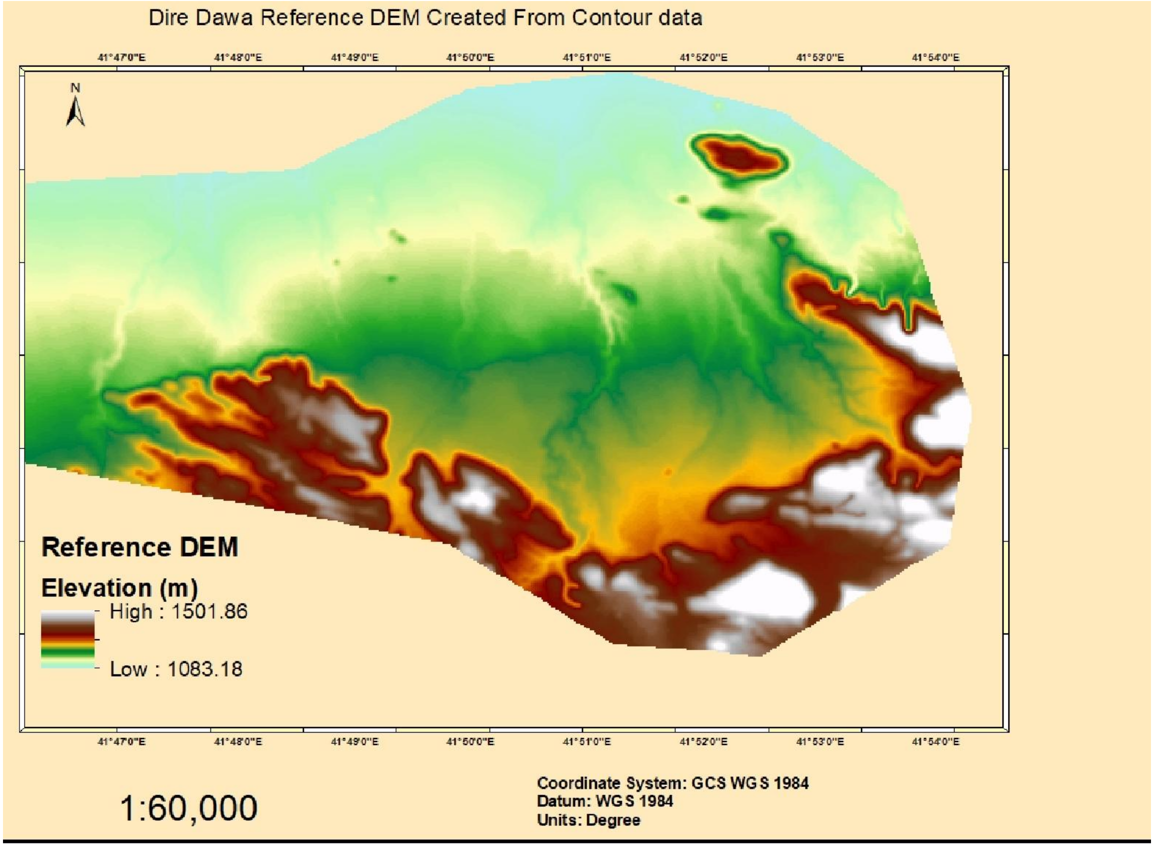
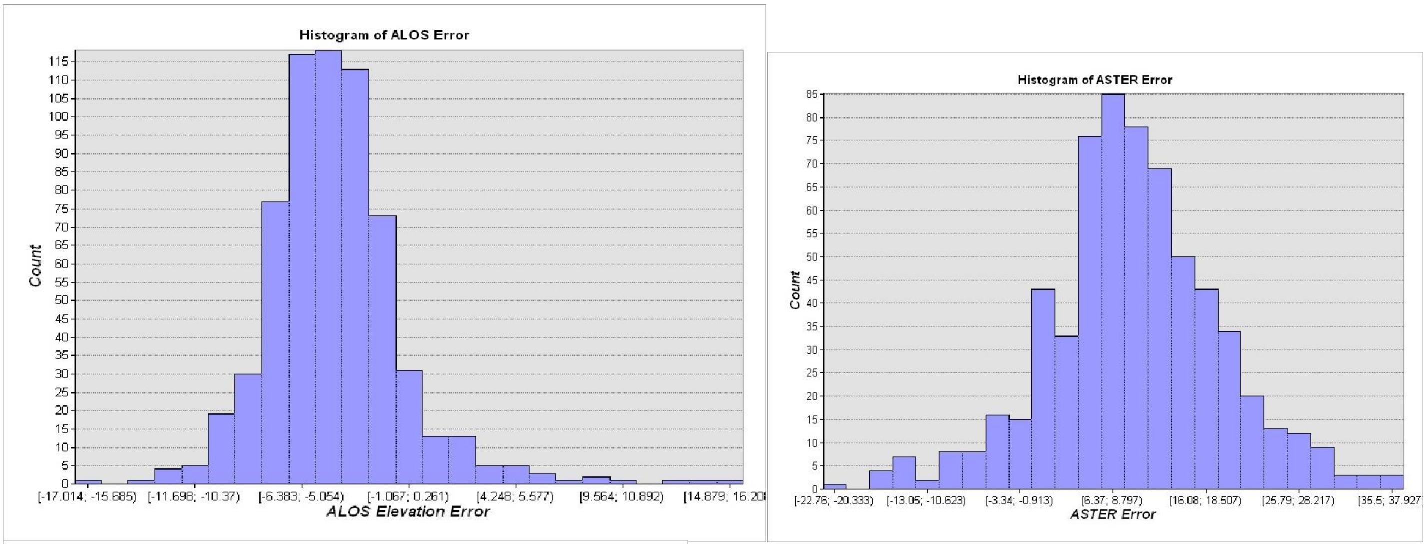


Figure 4.2 Dire Dawa Study Area Reference DEM boundary extent and topography.

4.2 Accuracy Assessment Using DGPS Points

To determine the vertical accuracy of the ASTER, SRTM and ASTER DEMs ground control points surveyed by GNSS instrument used as reference data. 635(for Addis Ababa) and 295 (for Dire Dawa) DGPS surveyed control points are available being well distributed in both study areas. Z (Elevation) values of ASTER, SRTM and ALOS (here after called ZASTER, ZSRTM and ZALOS) are extracted from corresponding DEM pixel for each point using Spatial Analyst Tools of Arc GIS software (i.e. Extract Value to point). The elevation values of DEMs (i.e. ZASTER, ZSRTM and ZALOS) were subtracted from the corresponding GPS surveyed point's elevation values (ZGPS) to calculate the error (using equation 2 through 7). Elevation error histograms were drown for investigating the error distribution behavior of these three DEMs (figure 4.3 and 4.4). Mean error, maximum error, minimum error and standard deviation of the elevation difference between GPS elevation points and DEMs were calculated. Finally DEM accuracy is assessed through calculating vertical RMSE (table 4.4).

The relative frequency distribution of the height differences between reference (GPS) data and examined DEMs is provided in figure.4.3 and 4.4. The RMSE statistics are essentially a standard deviation and are thus based on the assumption that errors in the DEM are random and normally distributed. However, the histograms of elevation differences shows positive or negative skew for these DEMs which indicate that the examined DEMs are underestimates or overestimate the terrain elevation of study areas. To calculate the accuracy of these DEMs, a constant factor of NSSDA standard (at 95% confidence) can be used: *1.96*RMSE*. Accordingly, the RMSE values are 13.66 m, 5.13 m, and 5.28 m for ASTER, SRTM and ALOS DEMs respectively in Addis Ababa study area. For Dire Dawa the RMSE values are 11.70, 5.80 and 5.13 for ASTER, SRTM and ALOS DEMs respectively.



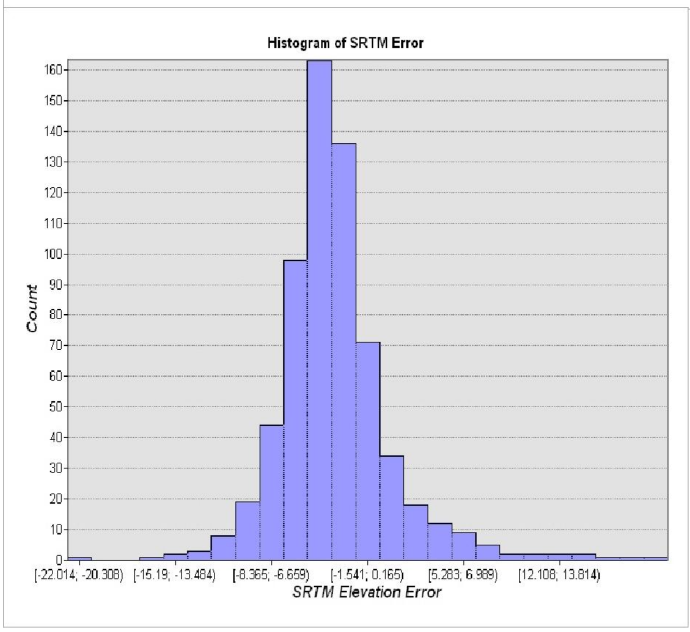


Figure 4.3 histogram of ASTER, SRTM and ALOS DEM Elevation differences with GPS data for Addis Ababa Study area.

Table 4.4 Statistics of Elevation difference between GCP points and ASTER, SRTM and ALOS DEM

Statistics of height difference (GCP Minus DEM),all units are in meters						
Accuracy Measure	*Addis Ababa*			*Dire Dawa*		
	ASTER	*SRTM*	*ALOS*	*ASTER*	*SRTM*	*ALOS*
MAX	*38.93*	*24.01*	*17.01*	*51.74*	*23.27*	*24.98*
MIN	*0.01*	*0.00*	*0.02*	*0.01*	*0.00*	*0.04*
Mean	*11.43*	*4.22*	*4.58*	*9.39*	*4.24*	*3.94*
standard Dev.	*13.67*	*5.13*	*5.28*	*12.39*	*6.15*	*5.43*
RMSE	*13.66*	*5.13*	*5.28*	*11.70*	*5.80*	*5.13*
Accuracy(95%)	*26.77*	*10.05*	*10.34*	*22.93*	*11.38*	*10.05*

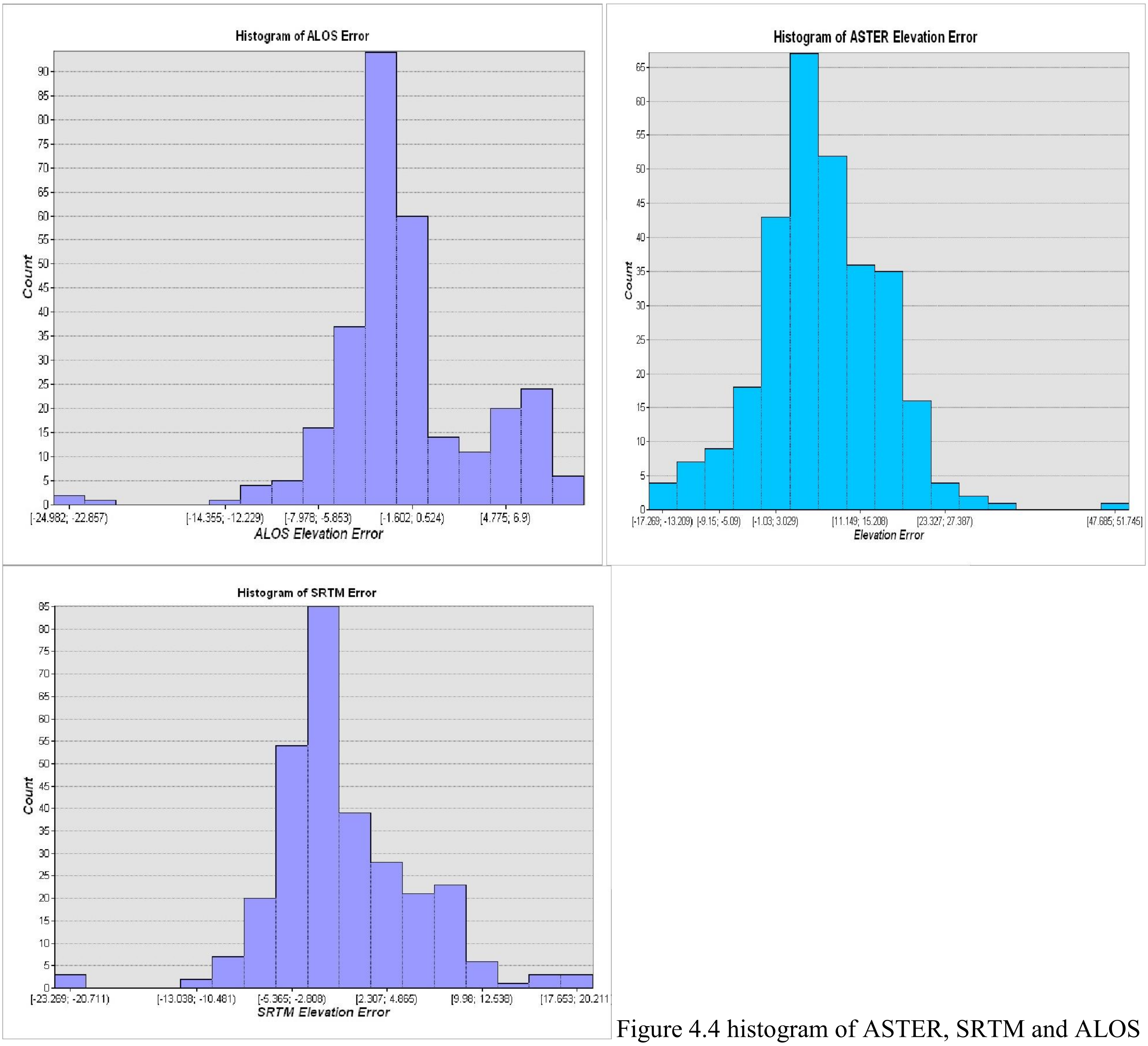


Figure 4.4 histogram of ASTER, SRTM and ALOS DEM Elevation differences with GPS data for Dire Dawa Study Areas.

The scatter plot graph in figure 4.5 and 4.6 compares the error of ASTER, SRTM and ALOS DEM. In the graphs ASTER elevation differences with GPS elevations have mainly positive values. This shows ASTER GDEM has under estimated the topography of these two areas. SRTM and ALOS elevation differences with GPS elevation are mainly negative and scattered around the line of zero value. These shows SRTM and ALOS DEMs have moderate overestimation of the study area topography.

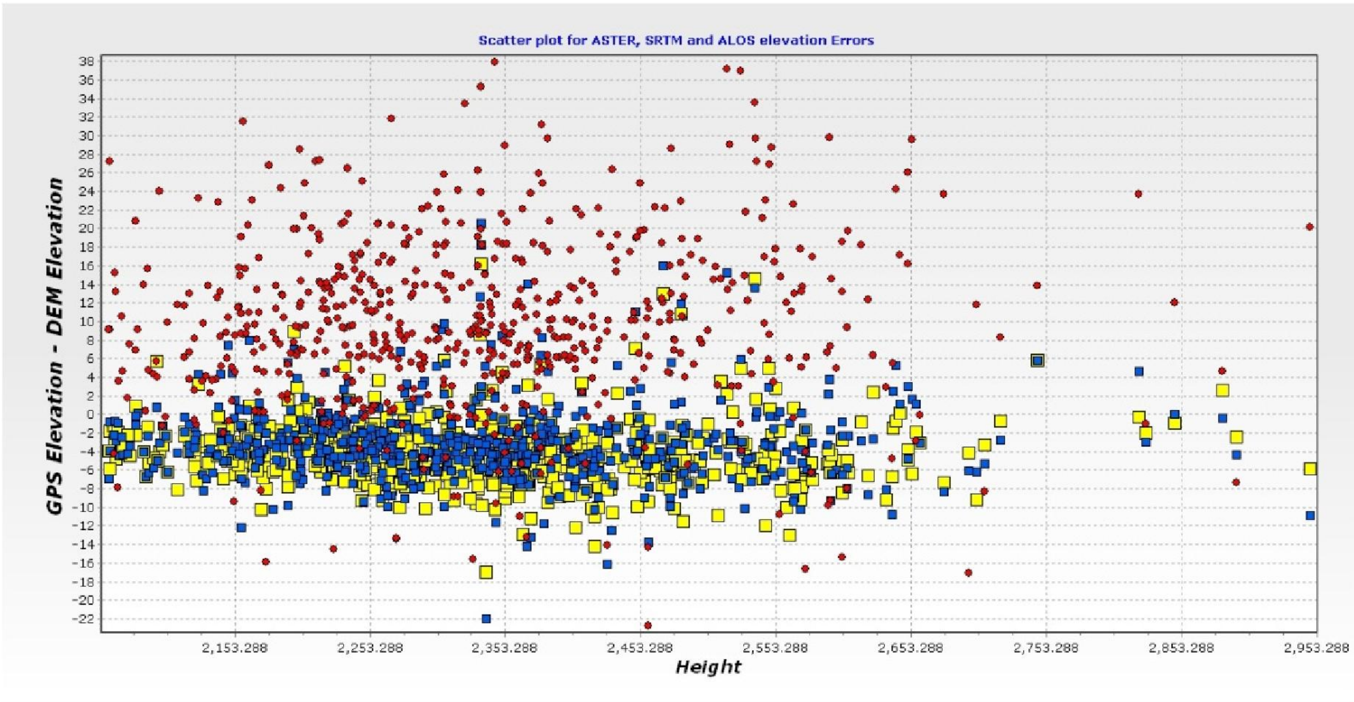


Figure 4.5 scatter plot of elevation differences for ASTEWR (red), SRTM (Blue) and ALOS (yellow) DEMs in Addis Ababa.

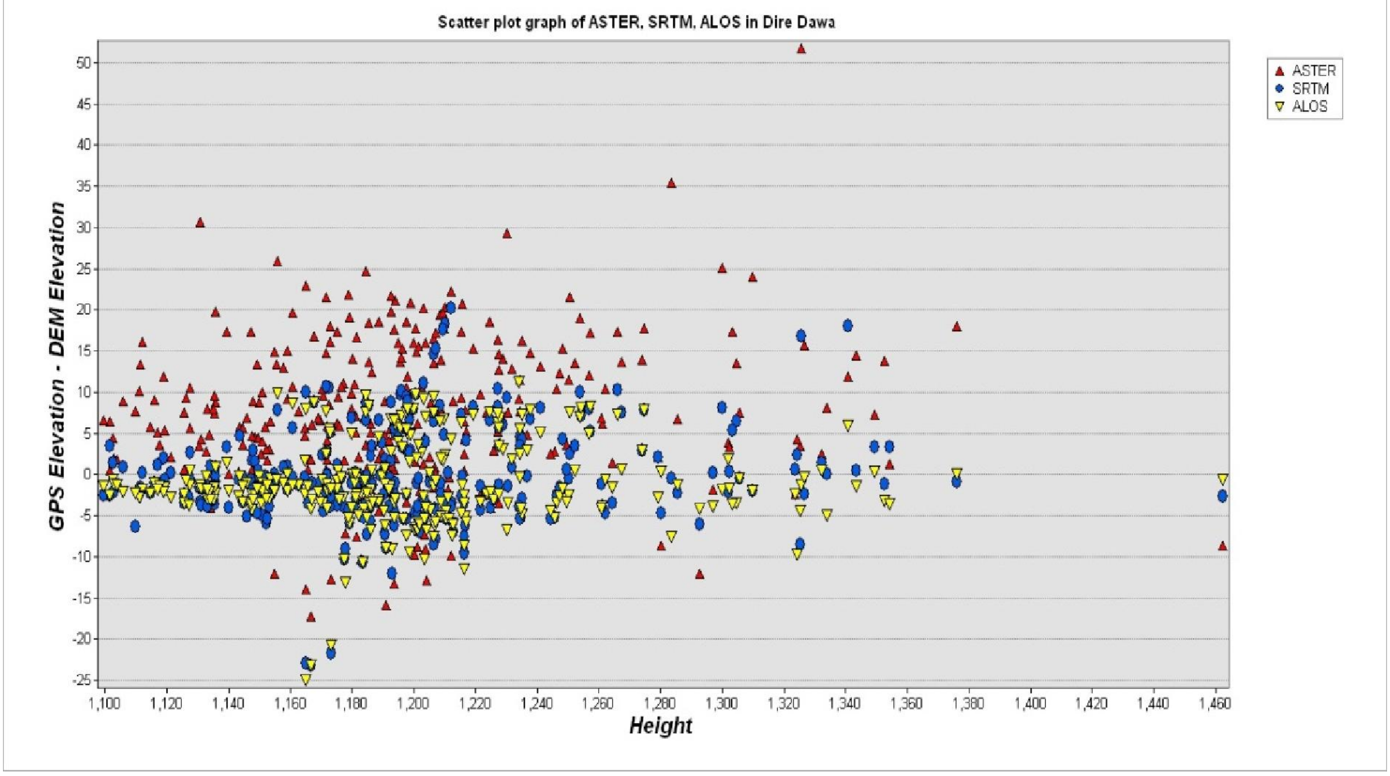


Figure 4.6 scatter plot of elevation differences for ASTEWR (red), SRTM (Blue) and ALOS (yellow) in Dire Dawa.

ASTER GDEM elevation differences are higher than that SRTM and ALOS DEMs. It can be seen from figure 4.5 and 4.6 that ASTER elevation differences goes up to 50 m in Dire Dawa and 28 m in Addis Ababa study area. Figure 4.6 (for Dire Dawa) also shows that all three DEM have relatively higher negative (-10 to -25) elevation error between topographic height of 1160 and 1200 meters. The cause of this higher elevation difference can be investigated in the next section using error image map resulting from image differences between reference DEM and those investigated DEMs.

4.3 Accuracy Assessment Using Reference DEM

One DEM for each study area (ADEM and DDEM) was created as mentioned before to assess the absolute accuracy of three DEM (ASTER, SRTM and ALOS).The accuracy assessment process is performed by subtracting pixels of DEM to be assessed from the reference DEM pixels. This operation is undertaken in Arc GIS software which provides tools to make DEM differences and perform statistical analysis of the resulting Difference image. This operation gives two results: Difference Image (or error image) that shows the distribution of error magnitude (figure 4.7 and 4.8) within the DEMs, and statistical output that extracted from this error map. Since the resultant error image stores (as its pixel value) the elevation difference between the reference DEM and the three DEM to be assessed, it is possible to obtain these values by converting each pixel to point which stores the value of the pixel itself. Accordingly, the maximum, minimum and mean errors are calculated. Finally the standard deviation and RMSE can be calculated to give the accuracy of these three DEM.

In order to quantify DEM error through this method it is important to access the pixel values of the raster image obtained by the subtractions of ASTER, SRTM and ALOS DEMs from Reference DEMs. Error or difference in elevation acquired through raster to point operation in Arc Map. Accordingly the error image was converted to points which contain the values of the raster (error values). For each error image resulting from: Error_ ASTER = reference DEM - ASTER, Error_ SRTM= reference DEM – SRTM and Error_ ALOS = reference DEM – ALOS about 129868 points were extracted in Addis Ababa study area and 104702 points for Dire Dawa. Microsoft excel used to calculate the statistical measures. Besides, the error images and the converted points representing the DEM elevation difference values are overlaid with slope to analyze the relationships between slope of terrain and DEM elevation error (covered by next topic).

The error image can give some insight in to the characteristics of error distributions and also to some extent the cause of errors. As it can be seen from error images the green and indicolite green colors are dominating where elevation is higher and around river valleys in error images of ALOS and SRTM DEMs for Addis Ababa (which indicates negative error or overrepresentations). These colors also cover built up areas in ASTER DEM error image for this study area. For Addis Ababa error image in figure 4.7 for ASTER shows high deviation in positive error direction which is 119.9 m and its negative difference is -73.82 m. SRTM elevation difference is the lowest of the three DEM, 41.52 m and -36.1 m positive and negative elevation differences. ALOS elevation difference with reference DEM elevation ranges between -74.6 m and 42.5 m in this study area. The golden and brown colors representing lower positive and negative elevation differences are the major error characteristics of ALOS and SRTM DEMs for Addis study area and around 97% of their elevation differences range from 0m to -10 and 10 meters (table 4.5). The light-gray and indicolite-green colors representing extreme values of positive and negative elevation differences are found only in few areas of SRTM and ALOS error images in Addis and accounts for less than 3% of their elevation differences (table 4.5).

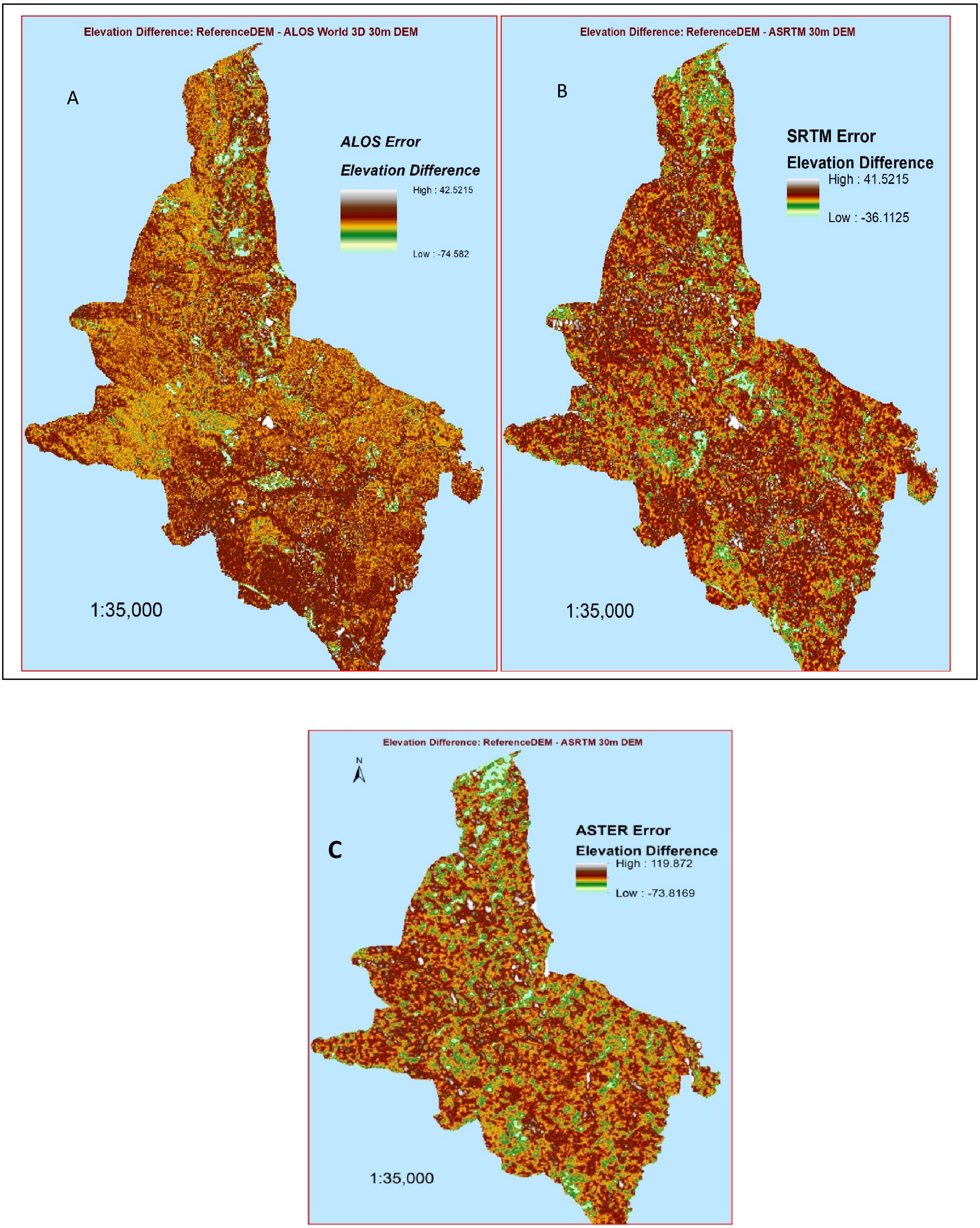
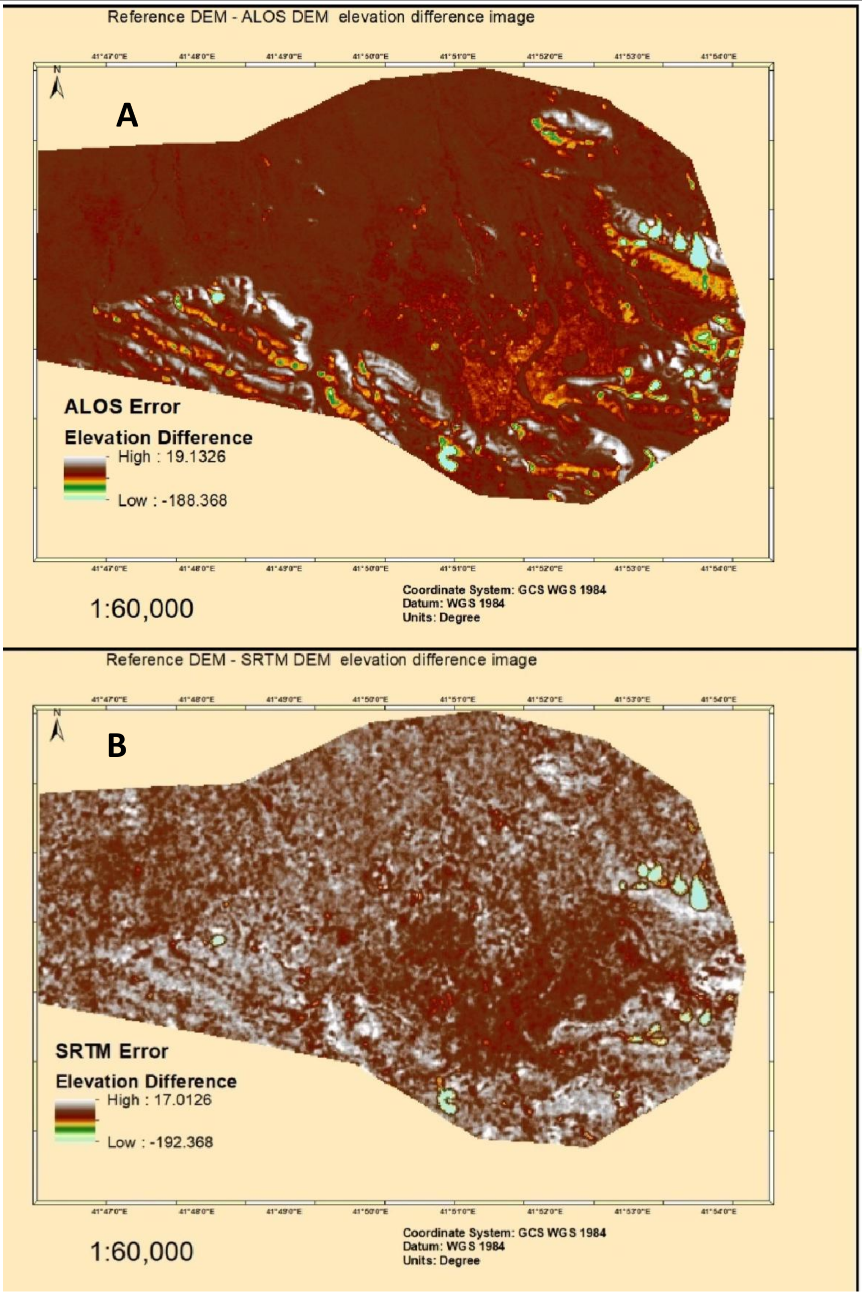


Figure 4.7 Error Image for ALOS (A), SRTM (B) and ASTER (C) DEM in Addis Ababa Study area.

In Dire Dawa study area, ALOS elevation differences range with Reference DEM is between 19.13 m and -188. 4 m. These elevation differences range between 17.01 m and -192.4 m for SRT; and between 60.4 m and -174.4 m for ASTER in Dire. Figure 4.8 shows color coded elevation error image of Dire Dawa study area. The color coding increases from dark-brown to light-gray the elevation difference increases from 0 m to nearly 19 m for ALOS and SRTM DEMs and from 0m up to 60 m for ASTER DEM in this study area. As figure 4.8 A and B shows ALOS and SRTM elevation difference with reference DEM is less than 20 meters and as table 4.5 shows about 98% of their errors are between -10 and 10 meters. In this study area 73% of ASTER's errors are also between -10 and 10 meters.



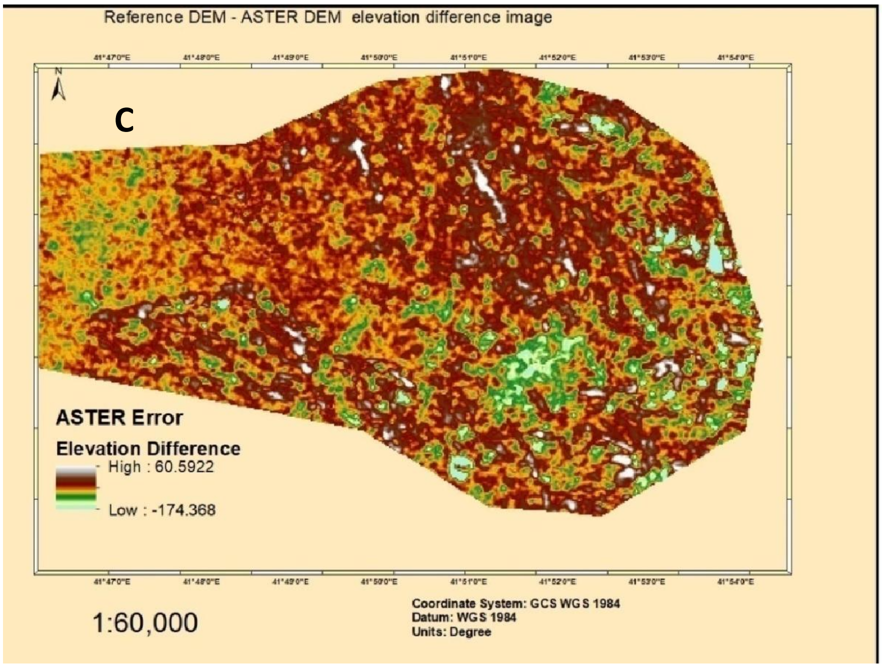


Figure 4.8 Error Image for ALOS (A), SRTM (B) and ASTER (C) DEM in Dire Dawa Study area.

Elevation differences are categorized in to three categories (as shown in table 4.5): error below -10 m, error between-10 m &+10 m and error above +10 m in both study areas. The result shows majority of error values are between-10 m &+10 m. Table 4.4 gives the percentage of error in each category for each DEM. Only less than 3% of the total observed errors are below 10 m for SRTM and ALOS DEMs. For ASTER DEM 75% and 33% of errors are below 10 m in Dire and Addis study areas respectively.

Table 4.5 Error distribution characteristics of DEM as percentage of the total numbers of elevation differences between Reference DEM and the three global DEMs.

Error Categories	Addis Ababa			Dire Dawa		
	number of errors in %			number of errors in %		
	ASTER	SRTM	ALOS	ASTER	SRTM	ALOS
Above +10	64.67	0.51	0.20	23.23	0.01	0.29
Below -10	2.21	2.66	1.91	1.47	1.10	2.25
Between-10&+10	33.12	96.84	97.89	75.30	98.88	97.46
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00

The indicolite-green color that appeared in all error images of both study area shows extreme values of elevation differences. It was tried to further investigate the extreme values by identifying the locations of these error values on Google Earth image. From this investigation it seems that these few extreme values of elevation differences between those DEM and the reference DEM have happened due to steep slope, cliff like terrain structure and new developments on the ground like housing construction and query sites. Figure 4.9 and 4.10 show the absolute value DEM elevation difference image with reference to same location Google Earth image. The flag points used mark general error value locations between the two images.

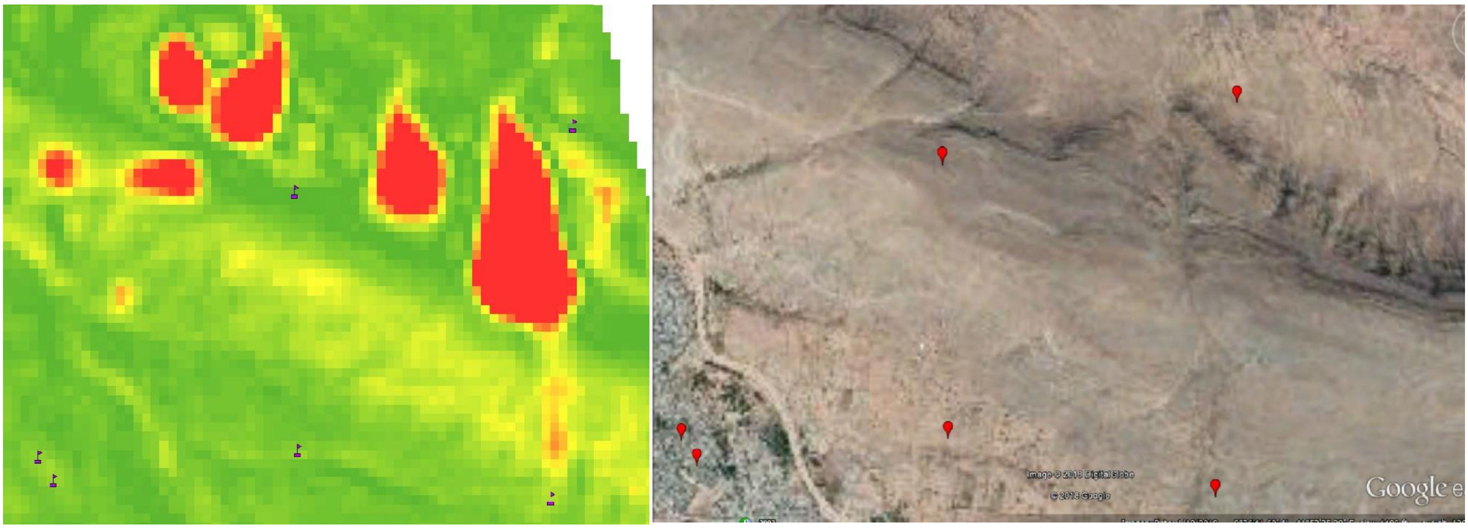


Figure 4.9 locations of extreme value elevation differences in Error image and Google Earth image in Dire Dawa.

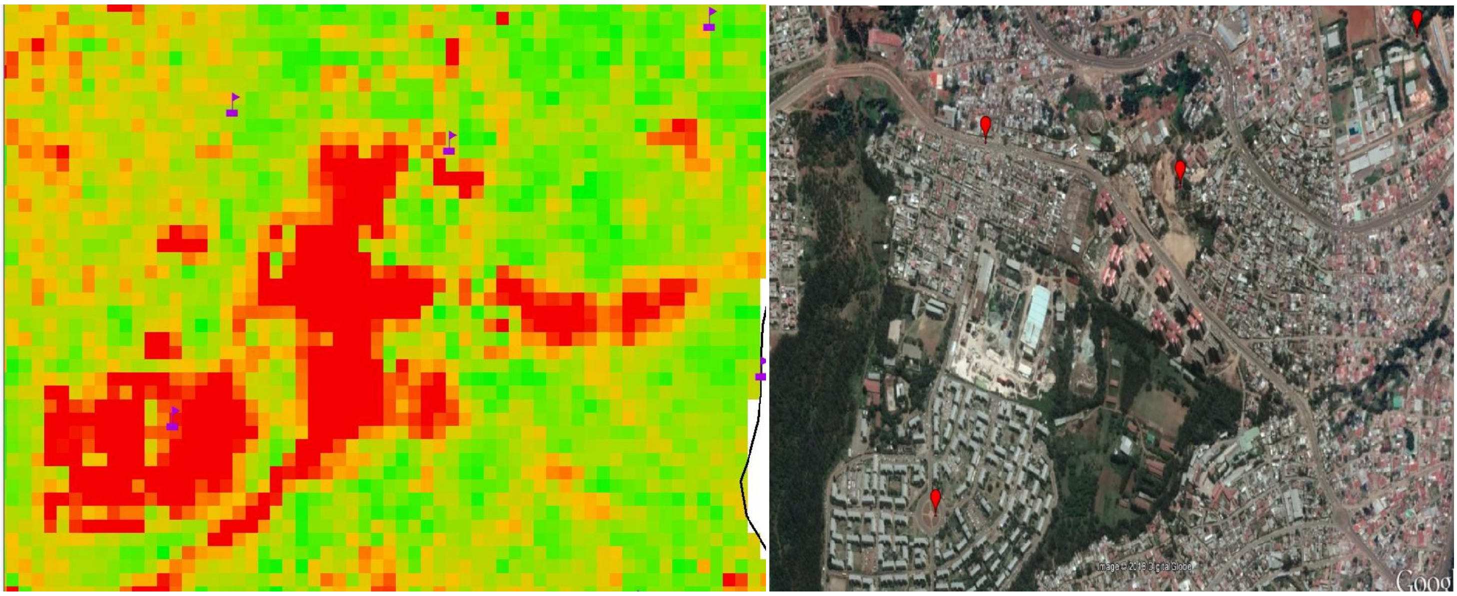


Figure 4.10 locations of extreme value elevation differences in Error image and Google Earth image in Addis Ababa.

In the above two figure the red color in left image shows extreme values of error image and right image taken from Google Earth for same area as the error image. In figure 4.9 the possible cause of extreme difference value is terrain morphology and in figure 4.10 the possible cause of extreme difference value is high rising building. But this is only visual analogy between DEM error and its causes. This should be verified through further studied. More image for absolute value DEM elevation differences are given in appendix C.

The results of statistical analysis shows ASTER GDEM has the lowest accuracy as the maximum, minimum and mean error difference with Reference DEM were **119.87, 0 m and 14.52 meters** respectively in Addis Ababa, and **174.37 m, 0 m, and 7.4 m** in Dire Dawa. In both study areas SRTM and ALOS DEMs have better accuracy with maximum minimum and mean error of **41.52 m, 0 m and 3.37 m** for SRTM and **74.58 m, 0 m, 3.87 m for ALOS DEM.** RMSE for these two DEMs are 4.45 m and 4.56 m meter in Addis Ababa, and 5.33 m and 5.64 m in Dire Dawa. The accuracy of ASTER (at 95% confidence level) is 33.7 meter in Addis Ababa and 18.65 meter in Dire Dawa. SRTM and ALOS DEMs here also showed similar accuracy (at 95% confidence interval) of 8.72 m and 8.94 m in Addis Ababa, 10.45 and 11.05 meters respectively in Dire Dawa. Table 4.6 shows the vertical accuracy statistics of ASTER, SRTM and ALS DEMs as assessed by reference (test) dataset (reference DEM).

Table 4.6 DEM accuracy assessed by image difference method

Statistics of height difference (Ref. DEM Minus ATER, SRTM and ALOS), all unit in meters						
Accuracy Measure	**Addis Ababa**			**Dire Dawa**		
	ASTER	**SRTM**	**ALOS**	**ASTER**	**SRTM**	**ALOS**
MAX	**119.87**	**41.52**	**74.58**	**174.37**	**192.37**	**188.37**
MIN	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Mean	**14.52**	**3.37**	**3.87**	**7.40**	**2.87**	**3.37**
standard Dev.	**17.19**	**4.45**	**4.56**	**9.51**	**5.33**	**5.64**
RMSE	**17.19**	**4.45**	**4.56**	**9.51**	**5.33**	**5.64**
Accuracy 95%	**33.69**	**8.72**	**8.94**	**18.65**	**10.45**	**11.05**

4.4 DEM Derivative Analysis

In this section DEM accuracy has been assessed by comparison of derived DEM products namely- slope and drainage network, as specified in(S.Wise 2000),(National Remote sensing Center Indian SpaceResearch orginazation Dept. of Space, Govt. of India 2014) and (Gorokhovich and Voustianiouk 2006), with same products derived from Reference DEMs prepared for the purpose of this present study. Visual interpretation of derived surface like shaded relief map and profile studies can give some information about DEMs quality DEM such as whether these DEMs could capture the general topographic features of the study areas (Sertel 2010). Comparing the produced shaded relief map with that of reference DEM clearly shows the problem of investigated DEMs particularly in valley and low elevation areas. All derivative analysis carried out by ArcGis 10.4 software 3D analysis toolset.

4.4.1 Profile and Shaded Relief map Studies

In Addis Ababa study area visual interpretation of shaded relief and profile graph reveal that SRTM and ALOS DEMs are more close to reference DEM. ASTER GDEM 30m is poorly represented the topography of the area (figure 4.11). This DEM's shaded relief map also shows more sinks/spikes than the other two DEMs as compared to reference DEM (figure 4.12). The profile graph was drawn along 16 km road line that crosses different topography in the study area confirms the statistical result obtained in the previous section since the line in the profile graph for ALOS and SRTM DEMs is more similar to that of reference DEM.

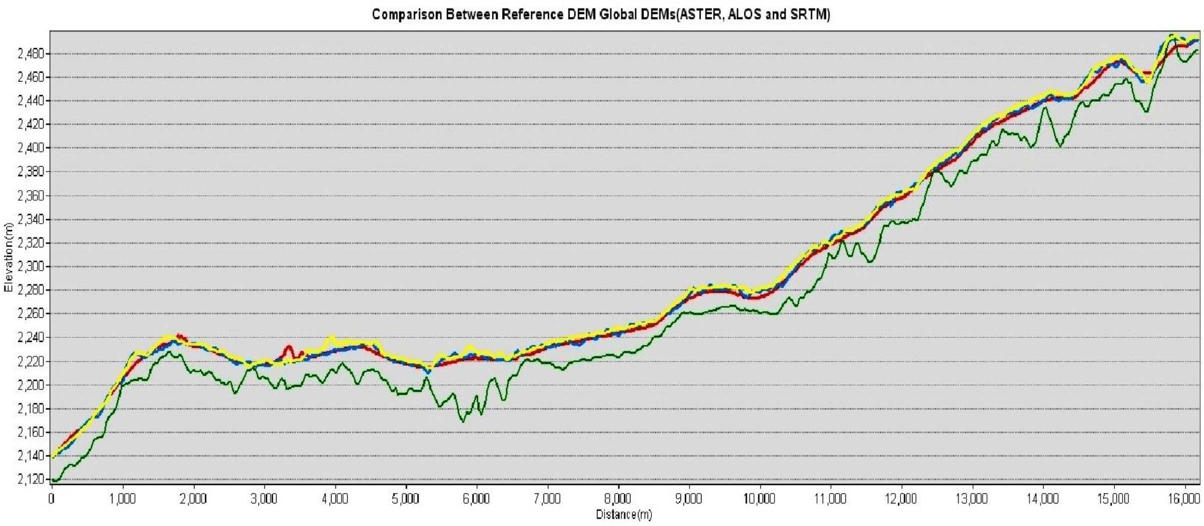


Figure 4.11: profile graph for ASTER (green), SRTM (blue), ALOS (Yellow) and Ref. DEMs for a Line along 16km long road in Addis Ababa.

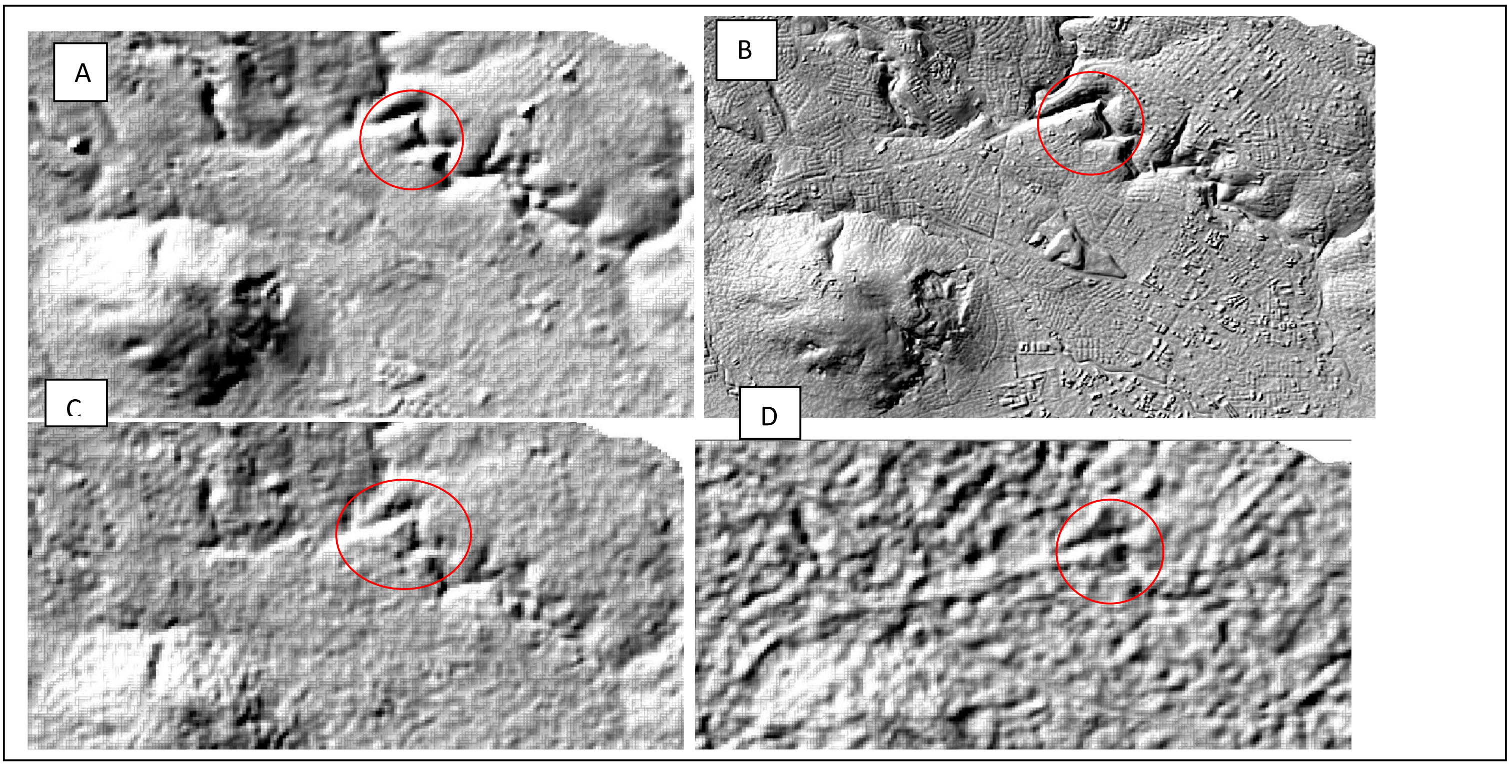


Figure 4.12 shaded relief maps for: ALOS (A), Ref.DEM (B), SRTM (C) and ASTER (D) DEMs in part of Addis Ababa study area.

From the above figure we can understand that ALOS DEM has good appearance as compared to the ASTER and SRTM with respect to reference DEM. The area in the red circle shows ASTER DEM could not capture the river/stream valley and this would affect the extraction of drainage network from this data.

The profile graph extracted from the three DEM and Ref. DEM along a road that include bridge shows that ALOS and SRTM DEMs have the same characteristics in Dire Dawa study area. These two DEMs have over represented the topography of the selected road, because in the profile graph the line representing these two DEMs lies over the line for reference DEM (figure 4.13). This result was further investigated by colleting RTK GPS survey points along the some road centerline and profile graph for this data confirms the previous result (figure 4.14).

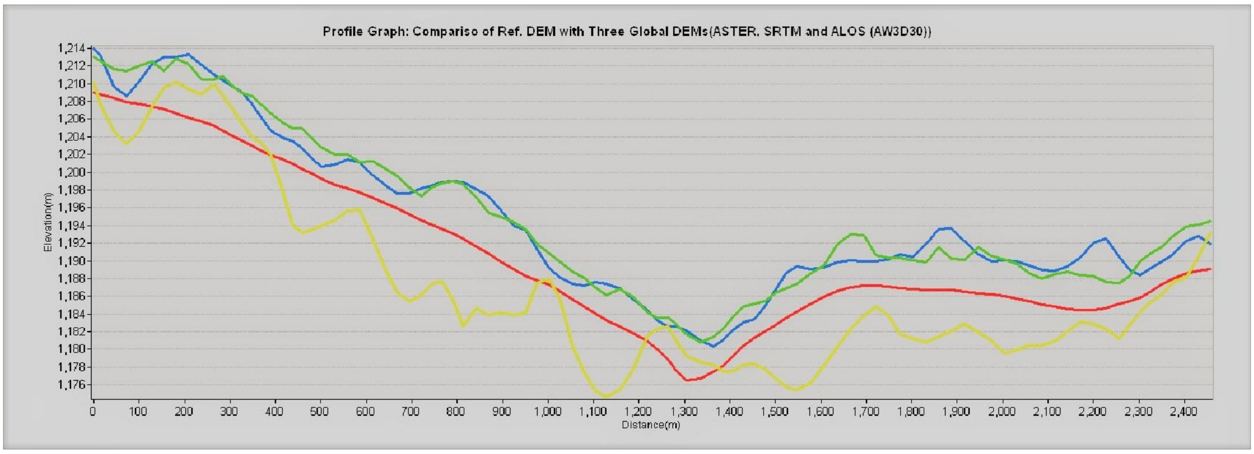


Figure 4.13: profile graph for: ASTER (yellow), SRTM (blue), ALOS (green) and Ref. DEM (red) for a line along road centerline in Dire Dawa.

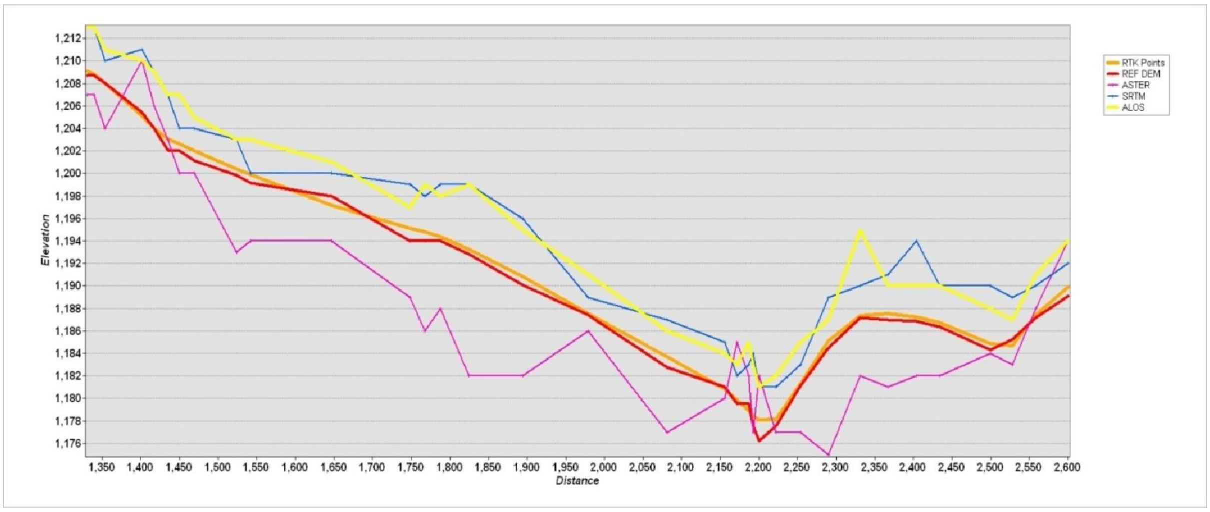


Figure 4.14: profile graph for RTK GPS points along the same road centerline in figure 4.9, the green points represents RTK GPS points.

Shaded relief map for this study area also reveals that ALOS DEM mostly has good representation of the topography of the study area. ASTER shows more artifacts like it did in previous study area (figure 4.15).

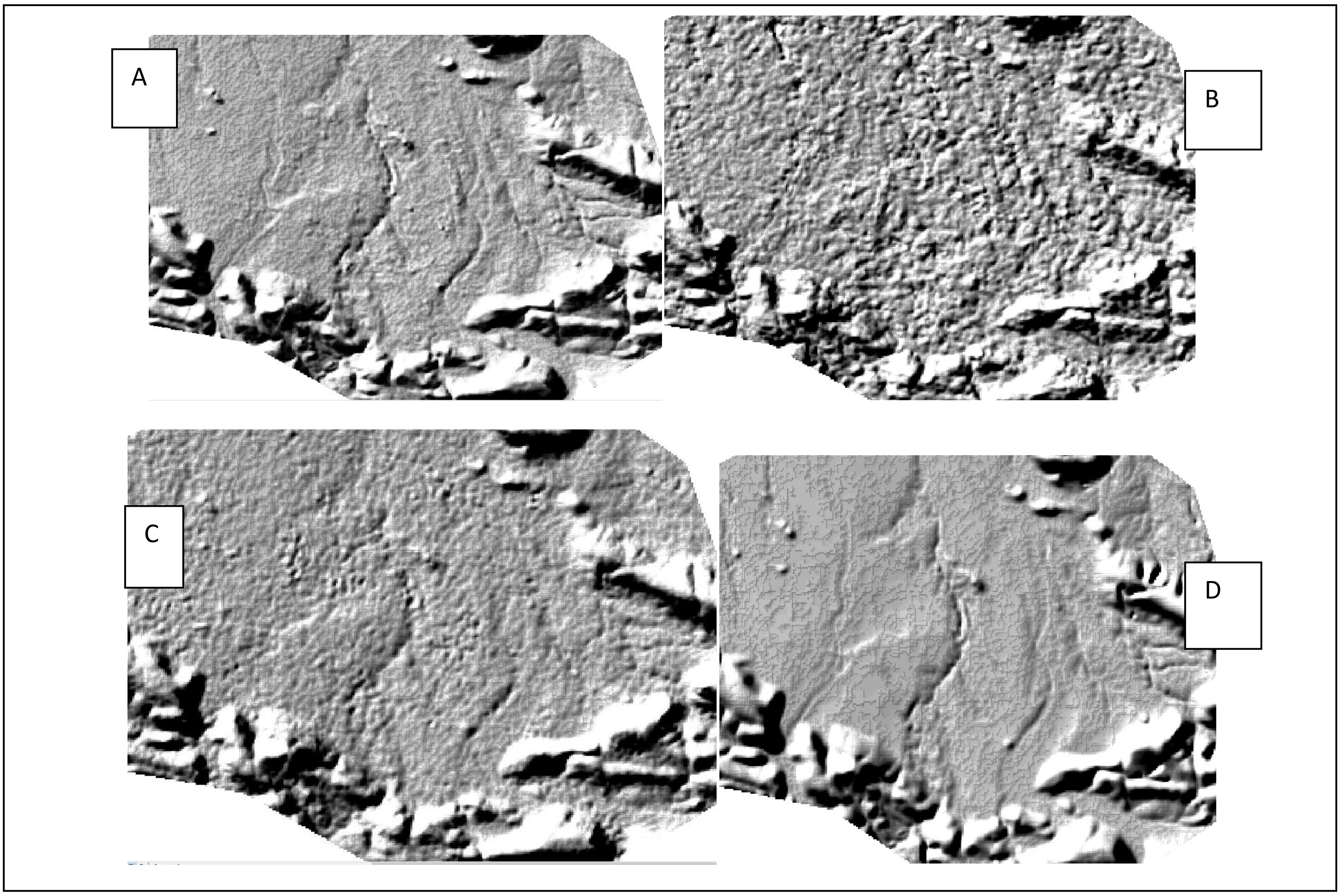


Figure 4.15: shaded relief map for: ALOS (A), ASTER (B), STRM(C) and Ref. DEM (D) in Dire Dawa study area.

4.4.2 Terrain Slope and DEM Accuracy

Slope of terrain topography is major influencing factors for vertical accuracy of DEM (M. E. Imrani, et al. 2016). Slope identifies the steepest downhill slope for a location on a surface. Mathematically, slope of a line in a two-dimensional Euclidean system describes the steepness of this line. For rasters, it is the maximum rate of change in elevation over each cell and its eight neighbors (ESRI, 2016). As terrain slope affects the accuracy of DEMs, its quality also affected by the quality of its source, one of which is DEMs. In this study slope analysis used in two ways: one is assessing the quality of DEMs by visual inspection of slope derived from DEMs. The other is by investigation of the influence of terrain slope on the accuracy of DEMs. To do all DEMs are classified into nine (9) altitude zones and slope surface was derived from each DEM. All these process was performed in ArcGis software environment using 3D and spatial analyst toolsets.

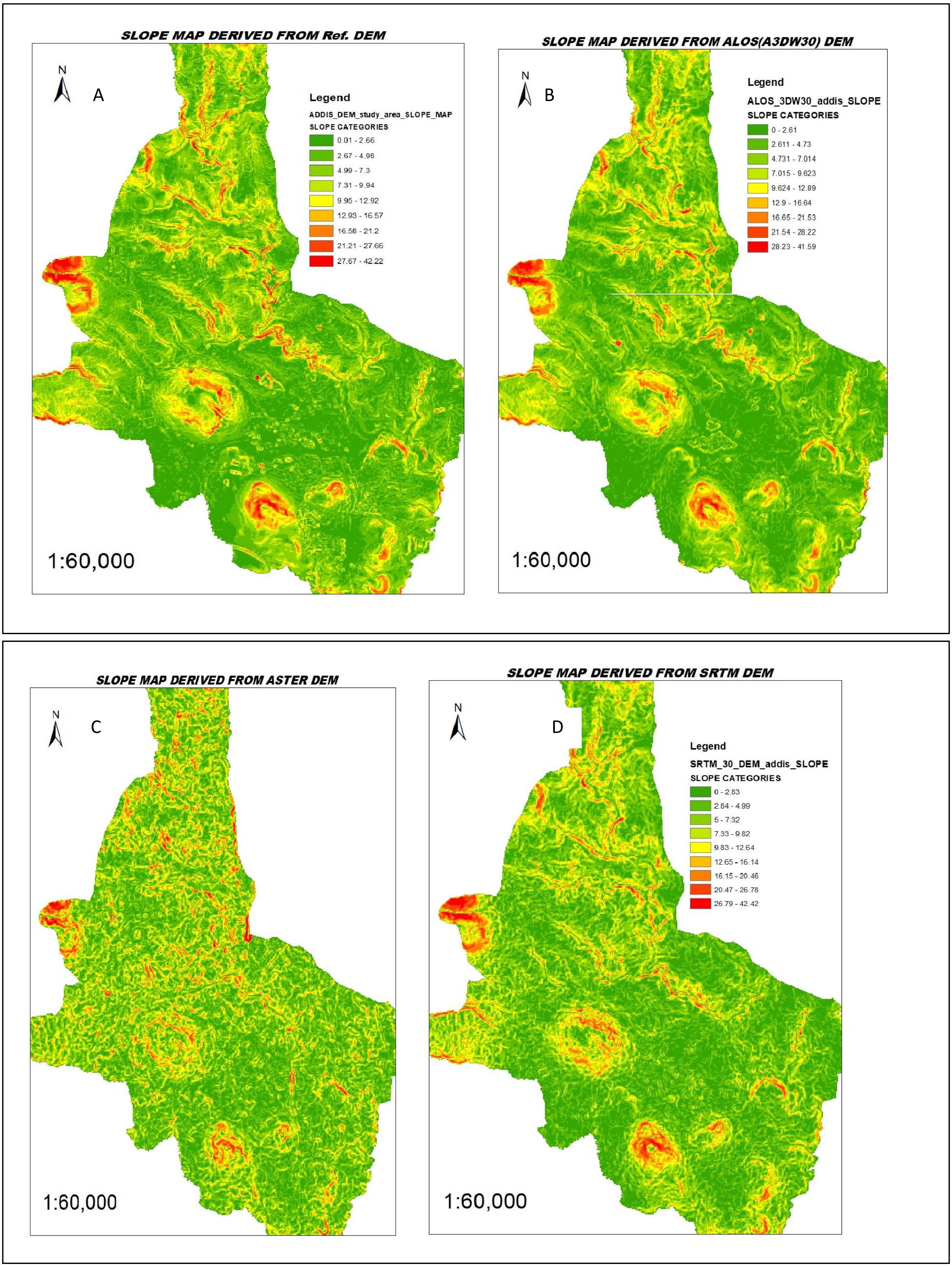


Figure 4.16 slope maps derived from Ref. DEM (A), ALOS DEM (B), ASTER DEM (C) and SRTM DEM (D).

As figure 4.16 shows slope derived from ALOS DEM is better than those derived from SRTM and ASTER DEMs as compared to reference DEM for this study area. Slope extracted from ASTER DEM reveals the rough accuracy of the dataset.

As the above figure shows the red color that represents rugged slope is distributed over the low land areas in slope map extracted from ASTER DEM. On the other hands SRTM and ALOS slope maps are more similar to that of Ref. DEM.

The slope maps for Dire Dawa study Area also shows the same results to that of Addis Ababa as figure 4.17 shows. However, ASTER derived slope relatively better looking in this study area.

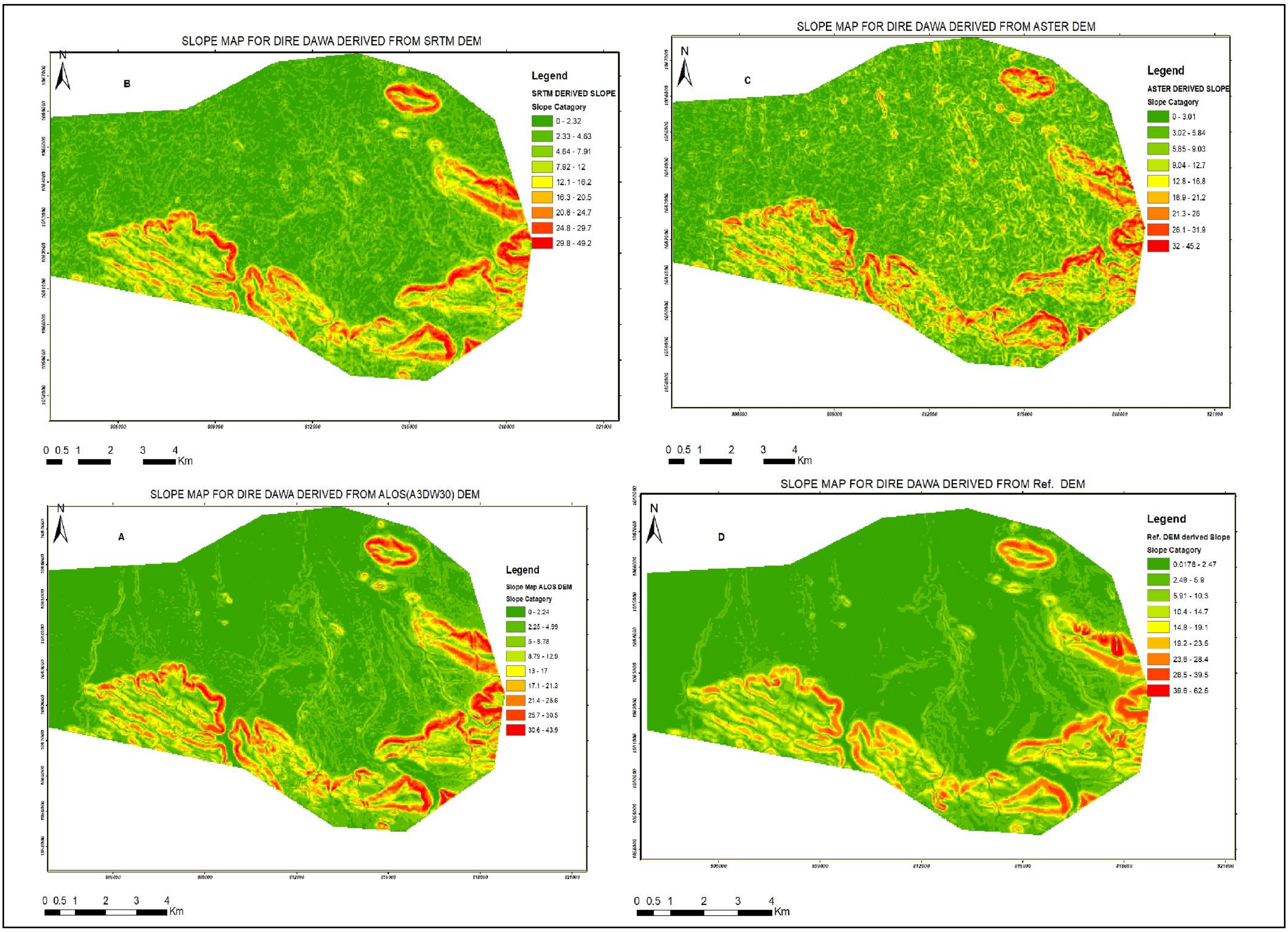


Figure 4.17 slope Maps for Dire Dawa area Derived from: A) ALOS, B) SRTM, C)ASTER and D) Ref. DEM.

In general visual analysis of slope map shows that ALOS DEM has better representation of the topography of these two study area followed by SRTM DEM. This can be further investigated by calculating area covered by each slope category and compare with reference DEM derived slope as in table 4.7 and 4.8. In this table slope was classified in to 9 slope zones and area under each zone calculated in square kilometers. It can be seen that ALOS has the lowest difference with reference derived slope categories and ASTER has the highest difference in both study areas.

Table 4.7 area covered by each slope zone and its comparison with reference DEM derived slope for Dire Dawa study area.

Slope category	Reference Area sq.km	ASTER Area sq.km	difference	SRTM Area sq.km	difference	ALOS Area sq.km	Difference
0-2	54.18	23.81	30.37	35.37	18.81	47.65	6.54
2.1 – 6	16.64	30.96	14.33	29.88	13.25	20.80	4.16
6.1 – 10	8.24	17.30	9.06	11.52	3.28	8.98	0.74
10.1 – 14	6.00	9.50	3.50	6.62	0.62	5.98	0.02
14.1 – 20	4.87	5.90	1.03	5.19	0.32	4.94	0.06
20.1 – 26	3.95	4.73	0.78	3.98	0.03	3.84	0.11
26.1 – 30	3.02	3.36	0.34	2.92	0.10	3.08	0.06
30.1 – 40	1.47	2.13	0.65	2.19	0.72	2.37	0.90
>40	0.15	0.89	0.75	0.91	0.77	1.04	0.89
Sum	98.52	98.59	60.82	98.59	37.90	98.66	13.48

Table 4.8 area covered by each slope zone and its comparison with reference DEM derived slope for Addis Ababa study area.

Slope Zone	Reference	ASTER		SRTM		ALOS	
	Area sq.km	Area sq.km	Difference	Area sq.km	Difference	Area sq.km	Difference
0 - 2.5	28.04	9.48	18.56	28.66	0.62	28.89	0.85
2.501 - 5.5	35.44	29.23	6.22	33.30	2.14	34.47	0.97
5.501 - 7.5	25.22	20.36	4.86	25.78	0.56	25.31	0.09
7.501 - 10.5	14.39	26.26	11.86	15.50	1.11	14.91	0.52
10.501 - 13.5	8.51	15.69	7.18	9.12	0.60	9.04	0.53
13.501 - 17.5	5.24	12.81	7.57	5.57	0.33	5.20	0.05
17.501 - 21.5	3.19	4.91	1.72	2.68	0.51	2.78	0.41
21.501 - 28.5	1.59	1.67	0.08	1.29	0.30	1.21	0.37
>28.5	0.52	1.84	1.32	0.33	0.18	0.30	0.21
Sum of diff. abs	122.14	122.23	59.38	122.23	6.34	122.12	4.01

4.4.2.1 Effect of Terrain Altitude and Slope on DEM Accuracy

In order to evaluate the effect of terrain slope on DEM accuracy slope and terrain altitude was classified in to nine zones. First slope values are extracted from each slope map and compared to the values of slope extracted from Ref. DEM and then DEM error that obtained by differencing each DEM from Ref. DEM was analyzed here for each altitudinal and slope zones. The statistical characteristics of slope values derived from each DEM are given in table 4.9 for Addis Ababa and table 4.10 for Dire Dawa.

Table 4.9 Statistical characteristics slope derived from Ref.DEM, ALOS, SRTM and ASTER DEM datasets for Addis Ababa.

	SLOPE STATISTICS															
	REF. DEM				ALOS				SRTM				ASTER			
ELEVATION	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
2,060 - 2,150	0.01	2.66	1.63	0.66	0.00	36.52	5.01	4.28	0.00	41.17	5.71	4.41	0.00	49.61	8.38	5.32
2,150.01 - 2,240	2.66	4.98	3.79	0.66	0.00	34.75	5.36	4.14	0.00	42.42	5.94	4.54	0.00	51.83	8.78	5.62
2,240.01 - 2,330	4.98	7.30	6.04	0.66	0.00	38.12	5.88	4.23	0.00	39.48	6.03	4.33	0.00	50.12	8.72	5.33
2,330.01 - 2,420	7.30	9.94	8.46	0.76	0.00	37.96	6.32	4.50	0.00	33.81	6.14	4.24	0.00	46.16	8.73	5.25
2,420.01 - 2,510	9.94	12.92	11.27	0.85	0.00	33.55	6.41	4.45	0.00	33.76	6.36	4.24	0.00	53.30	9.13	5.56
2,510.01 - 2,600	12.92	16.57	14.53	1.05	0.00	34.12	6.59	4.85	0.00	30.89	6.59	4.52	0.00	47.03	9.24	5.69
2,600.01 - 2,690	16.57	21.20	18.48	1.28	0.00	41.14	7.40	5.76	0.00	28.73	6.60	4.54	0.34	35.69	9.21	5.54
2,690.01 - 2,780	21.20	27.64	23.75	1.78	0.00	39.40	9.55	7.54	0.00	29.31	6.82	4.58	0.00	43.42	9.21	5.83
2,780.01 - 2,870	27.66	42.22	31.42	3.30	0.00	41.59	16.46	11.65	0.34	27.57	6.51	4.48	0.00	26.79	8.56	5.02

The minimum, maximum, mean and standard deviation of slope value higher for ASTER as compared to SRTM and ALOS as it can be seen from table 4.9. The reference DEM also shows Higher mean slope in Addis Ababa, which increases as elevation increases when compared to Dire Dawa’s Ref. DEM (table 4.10) mean slope.

Table 4.10 Statistical characteristics slope derived from Ref.DEM, ALOS, SRTM and ASTER DEM datasets for Dire Dawa.

	SLOPE STATISTICS															
	REF. DEM				ALOS				SRTM				ASTER			
ELEVATION	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
1,084 - 1,130	0.0592	61.074	4.4611	6.7351	0	39.7243	4.667	6.37776	0	24.12	2.571808	1.7134	0	2.902	1.868779	0.7109
1,131 - 1,176	0.0287	62.5	4.7994	6.7542	0	39.9633	5.1823	6.91739	0	29.31	2.914713	2.1565	3.01696	5.808	4.290965	0.8166
1,177 - 1,222	0.0176	54.595	5.6293	7.0443	0	41.1595	6.2575	7.68911	0	31.64	4.067523	3.3576	5.87557	9.016	7.235581	0.8971
1,223 - 1,268	0.0935	42.174	6.7903	7.6155	0	39.8688	6.9751	8.05205	0	36.09	6.744566	5.0863	9.03994	12.06	10.40875	0.8825
1,269 - 1,315	0.0536	36.753	8.0934	8.3163	0	43.6681	7.4746	8.2103	0	38.09	11.39877	6.2823	12.0883	16.87	14.30148	1.3937
1,316 - 1,361	0.0203	36.257	8.4506	8.4705	0	41.113	7.4469	7.98631	0	40.5	16.42154	6.3002	16.8955	21.29	18.9461	1.2568
1,362 - 1,407	0.2099	37.923	8.7318	8.5113	0	43.8932	7.2717	7.80329	0	46.83	20.65177	6.1667	21.3069	26.09	23.54002	1.3617
1,408 - 1,453	0.2762	34.7	8.6885	8.7192	0	43.6671	7.3015	7.79121	0	49.21	23.7652	5.7339	26.1034	31.99	28.5128	1.6707
1,454 - 1,500	0.1994	33.132	8.1861	8.9472	0	33.8801	7.3024	7.17528	1.0675	40.33	26.70639	5.4813	31.9951	45.15	35.3077	2.7416

The relationship between slope and DEM Error (accuracy) is given in table 4.11 and 4.12 for Addis Ababa and Dire Dawa respectively. More importantly, when DEM mean errors plotted against different slope categories as presented in figure 4.18 to 4.22 the influence of terrain slope is more evident. In figure 4.18 (in Addis) DEM error decreases as terrain slope increases for ASTER DEM. This shows ASTER DEM elevation difference with reference DEM is higher in flat areas. SRTM elevation differences (error) showed slight and gradual increases toward negative axis as slope increases which means that SRTM's slight overestimation of terrain heights of the study area is slightly increasing as slope increases. ALOS DEM showed relatively constant elevation differences (error) throughout all slope zones. These figures also showed that ASTER elevation difference or Error is always higher than that of SRTM and ALOS DEMs. This is also true for Dire Dawa area as shown in figure 4.19 where SRTM and ALOS DEM though the graph seems more smooth when stacked with ASTER graph, both DEMs are erroneous as shown in figure 4.20 (zoomed in version of figure 4.19).

The other thing that can be concluded from DEM error graphs (figure 4.18 and 4.19) and tables (table 4.10 and 4.11), with respect to terrain slope, is that ASTER mean error is always higher than mean error for SRTM and ALOS DEMs which confirms the result obtained in DEM accuracy assessment by GPS and Image differencing methods discussed above. It is also clear that ASTER DEM mean error has, in all cases, positive values which mean ASTER has underestimated the topography of the study area. On the other hands SRTM and ALOS have always negative mean error values (except when taking absolute values of DEM errors), which asserts that these two DEM have slightly overestimated the study area topography from 2 to 6 meters.

Table 4.11: ASTER, SRTM and ALOS DEM mean errors for different terrain slope zones in Addis Ababa.

	DEM ERROR STATISTICS FOR ADDIS ABABA											
	ALOS				SRTM				ASTER			
SLOPE	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
0.01 - 2.66	0.000	42.980	3.733	2.447	0.000	44.039	3.392	2.994	0.002	105.001	15.117	8.662
2.67 - 4.98	0.000	41.948	3.807	2.573	0.000	46.300	3.379	3.007	0.000	119.126	15.030	9.268
4.99 - 7.3	0.000	45.183	3.807	2.736	0.000	44.183	3.394	3.028	0.001	107.087	14.284	8.977
7.31 - 9.94	0.000	56.117	3.895	2.868	0.000	34.945	3.351	2.942	0.003	109.109	14.306	9.244
9.95 - 12.9	0.005	50.073	3.909	2.882	0.000	33.094	3.381	2.903	0.003	110.331	14.631	9.271
12.93 - 16.	0.002	34.225	3.920	2.897	0.000	22.753	3.469	2.862	0.004	103.427	13.890	9.055
16.58 - 21.	0.001	29.861	3.887	2.810	0.000	30.747	3.490	3.054	0.001	52.455	13.256	8.623
21.21 - 27.	0.006	26.210	4.161	3.134	0.001	25.163	3.721	3.104	0.011	77.479	13.469	8.685
27.67 - 42.	0.003	21.709	5.031	4.331	0.014	17.921	3.802	2.929	0.107	38.118	12.272	6.867

Table 4.12: ASTER, SRTM and ALOS DEM mean errors for different terrain slope zones in Dire Dawa.

SLOPE	DEM ERROR STATISTICS											
	ALOS				SRTM				ASTER			
	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
0.01 - 2.47	0.00	199.00	3.13	4.32	0.00	41.50	2.59	1.87	0.00	48.87	6.47	4.19
2.48 - 5.9	0.00	183.77	3.34	5.46	0.00	61.00	2.67	2.07	0.00	70.00	6.88	4.55
5.91 - 10.3	0.00	142.75	3.54	4.80	0.00	65.00	2.88	2.58	0.00	71.00	7.53	5.36
10.4 - 14.7	0.00	76.42	3.64	3.71	0.00	77.97	3.02	3.72	0.00	65.77	8.09	6.12
14.8 - 19.1	0.00	69.42	3.73	3.75	0.00	189.00	3.16	6.76	0.00	170.00	8.83	8.04
19.2 - 23.5	0.00	59.00	3.60	3.21	0.00	207.00	3.84	10.71	0.00	189.00	9.61	10.67
23.6 - 28.4	0.00	43.21	3.45	2.99	0.00	175.00	4.05	10.70	0.00	162.00	9.76	10.76
28.5 - 39.5	0.00	52.50	3.72	3.92	0.00	162.00	4.62	11.84	0.02	146.00	10.41	11.34
39.6 - 62.5	0.00	43.20	3.64	3.55	0.02	138.36	4.52	8.27	0.02	110.36	11.34	10.16

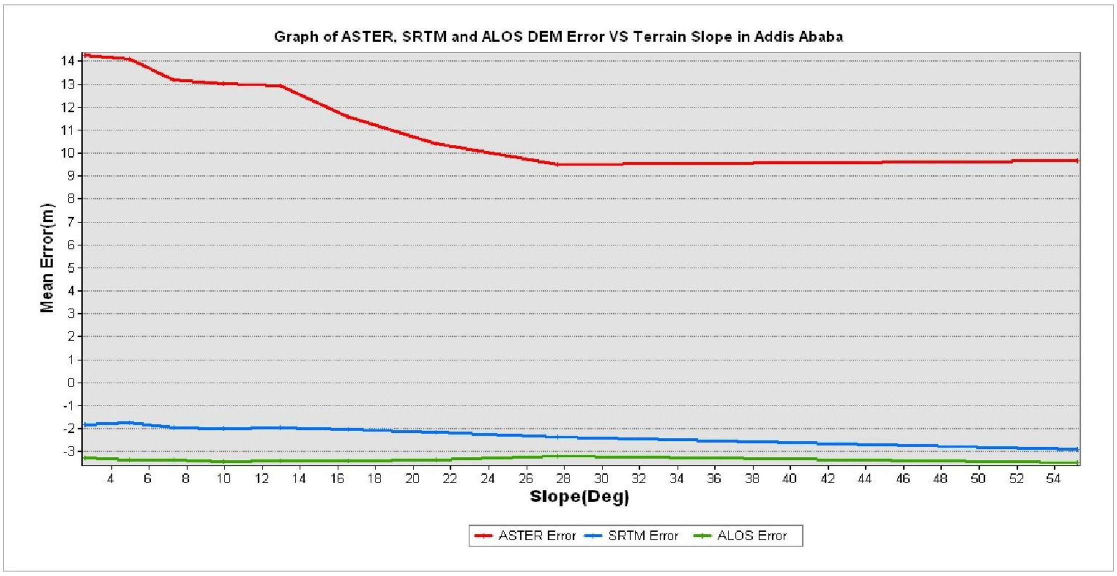


Figure 4.18: ASTER, SRTM and ALOS DEM mean error with reference to terrain slope for Addis Ababa Study Area.

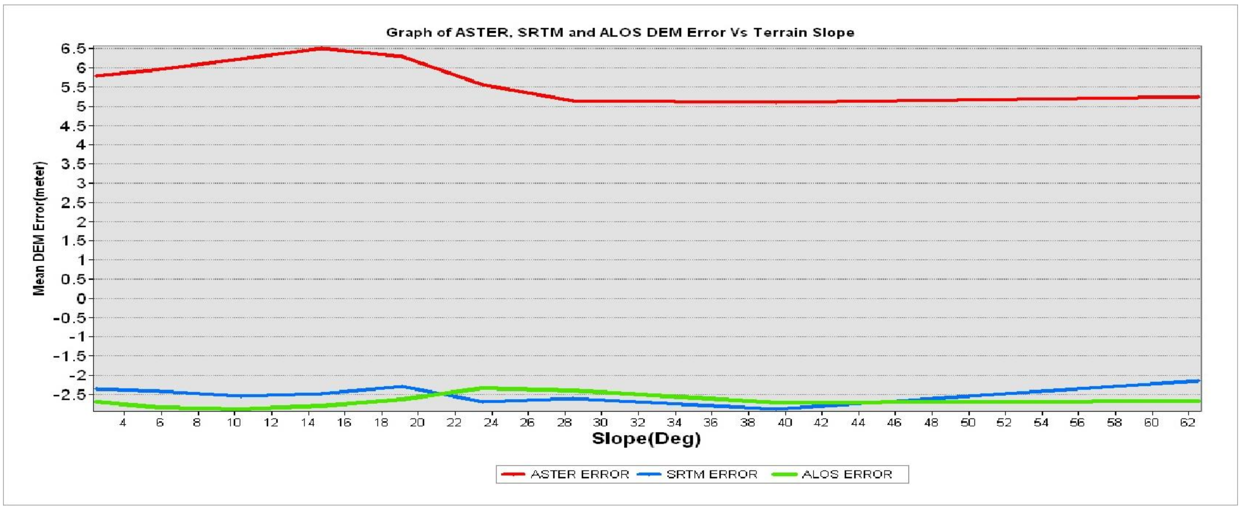


Figure 4.19: ASTER, SRTM and ALOS DEM mean error with reference to terrain slope for Dire Dawa Study Area.

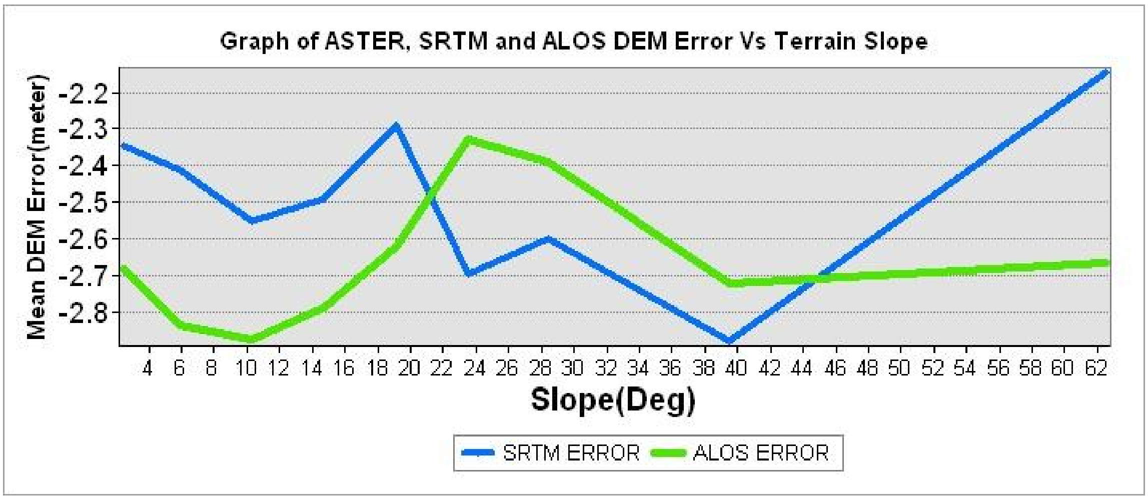


Figure 4.20: SRTM and ALOS DEM mean error with reference to terrain slope for Dire Dawa Study Area (zoomed in version of fig.4.19).

Taking the absolute values of DEM errors, mean error graph (figure 4.21) for SRTM and ALOS DEMs reveal that the mean error for ALOS is always higher than SRTM mean error in Addis Ababa. In Dire Dawa, mean error for ALOS is higher than that of SRTM in the slope zone from 0 to 23 deg slope. Beyond 23 deg terrain slope ALOS mean error is less than that of SRTM. Therefore, the accuracy of SRTM is batter, in all Slope categories, than the accuracy of ALOS and ASTER DEMs in Addis Ababa. For Dire Dawa, SRTM accuracy is better in flat areas (terrain slope less than 23 deg.) and in rugged (or steep slope) terrain areas ALOS has better accuracy than SRTM.

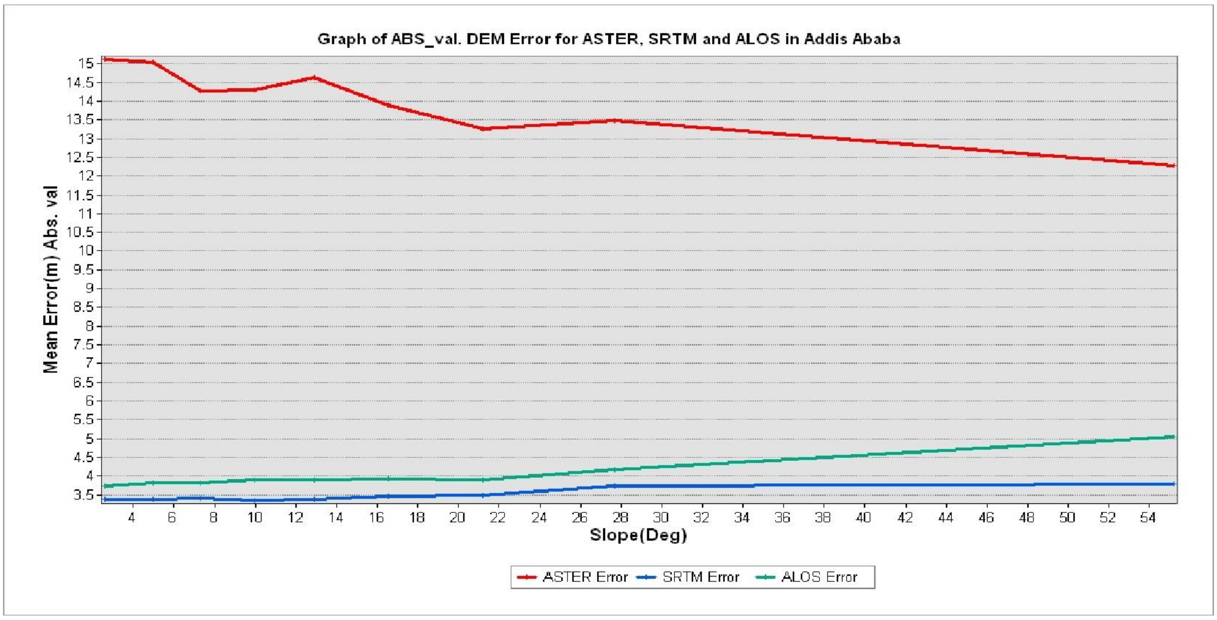


Figure 4.21: ASTER, SRTM and ALOS DEM mean error (taking Absolute values) with reference to terrain slope for Addis Ababa Study Area.

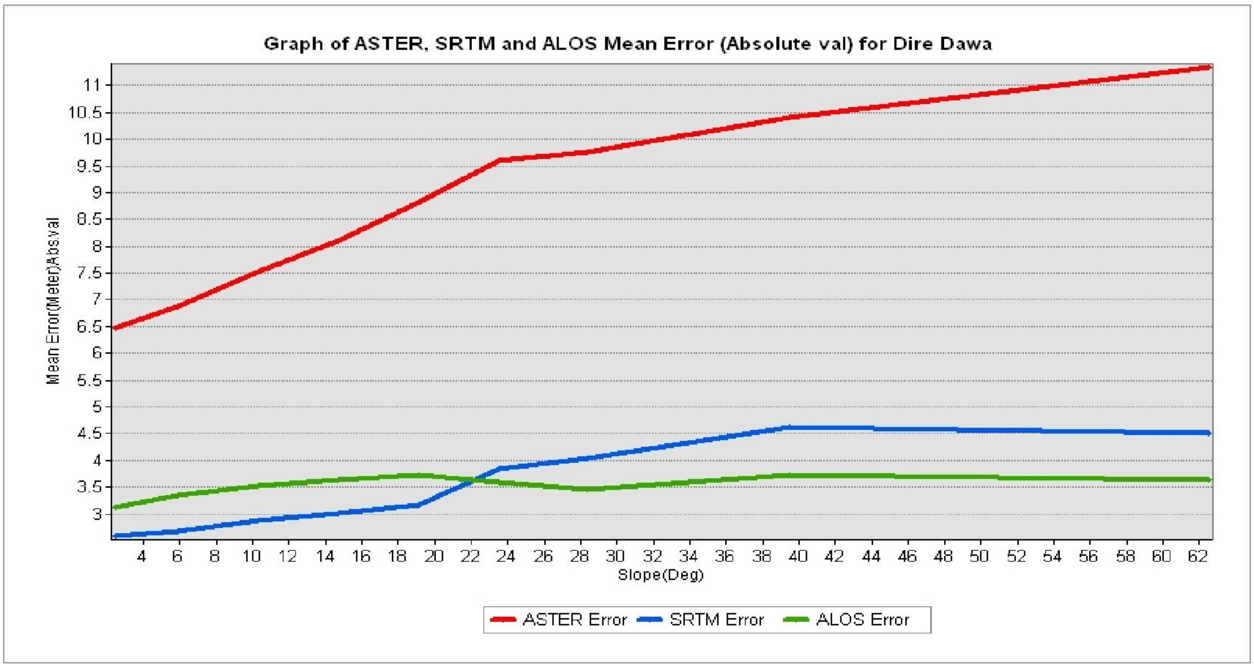


Figure 4.22: ASTER, SRTM and ALOS DEM mean error (taking Absolute values) with reference to terrain slope for Dire Dawa Study Area

4.4.3 DEM Accuracy Assessment by Comparison of Derived Drainage Network

DEM as a source of may surface and topographic based application is one of widely used spatial data source for drainage network extraction application. Comparative assessment of the accuracy of DEMs through comparison of drainage (stream) network derived different DEM dataset could assist others in determining whether or not a specific DEM dataset is appropriate for such application at a particular accuracy level. Drainage network is a network of water passes through which water travels to the outlet. It is one hydrologic unit. According to the Federal Standard for Delineation of Hydrologic Unit Boundaries.(United States Geological Survey, 2004): "A hydrologic unit is a drainage area delineated to nest in a multi-level, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface waters. A hydrologic unit can accept surface water directly from upstream drainage areas, and indirectly from associated surface areas such as remnant, non-contributing, and diversions to form a drainage area with single or multiple outlet points. Hydrologic units are only synonymous with classic watersheds when their boundaries include all the source area contributing surface water to a single defined outlet point."

In this research stream networks ware derived from all DEMs under investigation and compared with stream (drainage) network derived from Reference DEMs in both study areas. Multiple tools are available which are specialized for derivation of watersheds and drainages networks, including Arc hydro and Arc SWAT (ESRI, 2016). These tools use DEM as input and can perform watershed and drainage network extraction in an automated manner. However, in this study drainage network extraction was performed through the hydrologic modeling tools in the ArcGIS Spatial Analyst extension toolbox. The ArcGIS hydrologic tools allow us to identify sinks, determine flow direction, calculate flow accumulation, delineate watersheds, and create stream networks (ESRI, 2016). To automate the process and integrate with other ArcGIS tools such as Raster Calculator, a model tool was created in ArcMap's MadelBuider window, which helped to simplify workflows by string together sequences of tools, feeding the output of one tool into another tool as input (figure 4.23).

The model tool used here takes DEM as input and performs the following processes (ESRI, 2016):

1. Using Flow Direction tool the direction in which water would flow out of each DEM cell is determined.
2. Any sinks in the original DEM are identified using Sink Tool. A sink is usually an incorrect value lower than the values of its surroundings. Sink tool uses the output from floe direction.
3. To ensure proper drainage mapping, sinks must be filled using the Fill tool. The output raster from sink helps to identify sink location and their depth which helps to determine the Z-limit for Fill tool.
4. Ones Sinks are filled using proper Z-limit, Flow Direction is calculated and used in the subsequent processes.
5. In order to create stream network the output from step 4 is used to calculate Flow Accumulation. The Flow accumulation tool used to calculate the number of upslope cells flowing to a location.
6. Using Raster calculator tool of spatial analyst toolbox on the output from step 6 (Flow accumulation raster) stream networks is defined by selecting cells (from Flow accumulation raster) where cells value exceeds specified threshold. Since there is no standard procedure to select this threshold value it was selected though trial-and-error method, the syntax: "flow accumulation" >= 70 applied as stream network selector.

7. To represent the order of each of the segments in a network, the Stream Order tool was applied to the output in step 6. The steam ordering method used was the **Strahler** method recommended by ESRI.
8. Finally the Arc toolbox's *stream to feature* to was used to convert the stream network from raster to vector polyline feature class data.

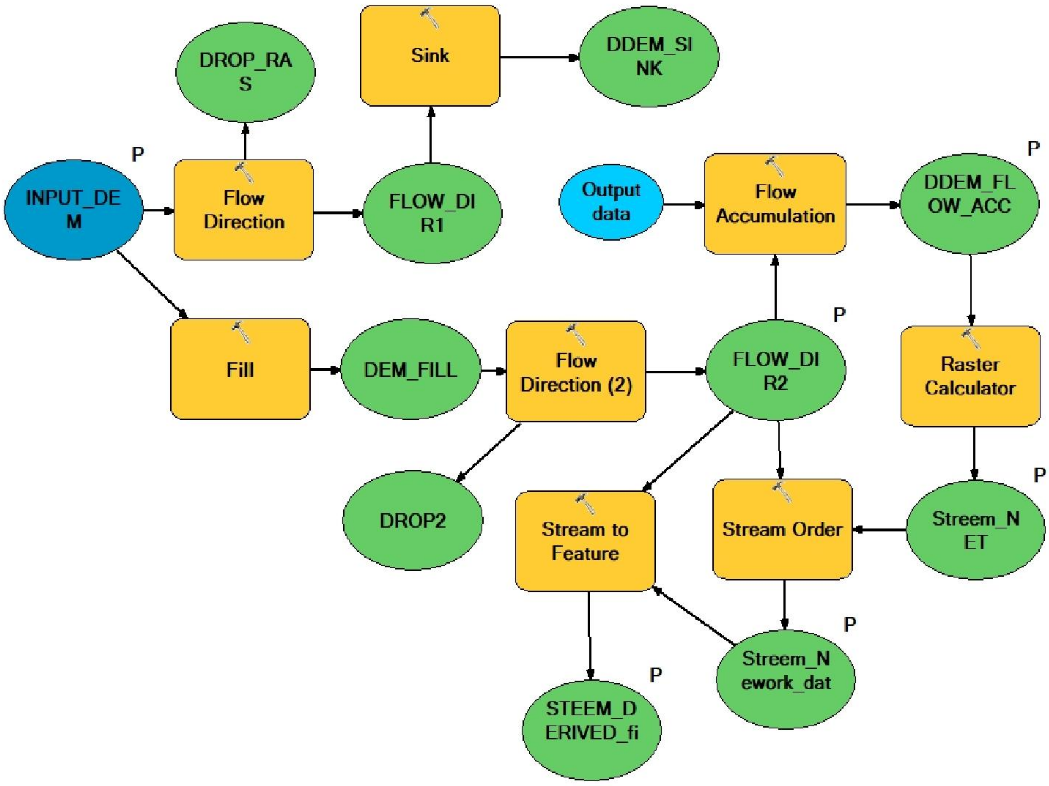
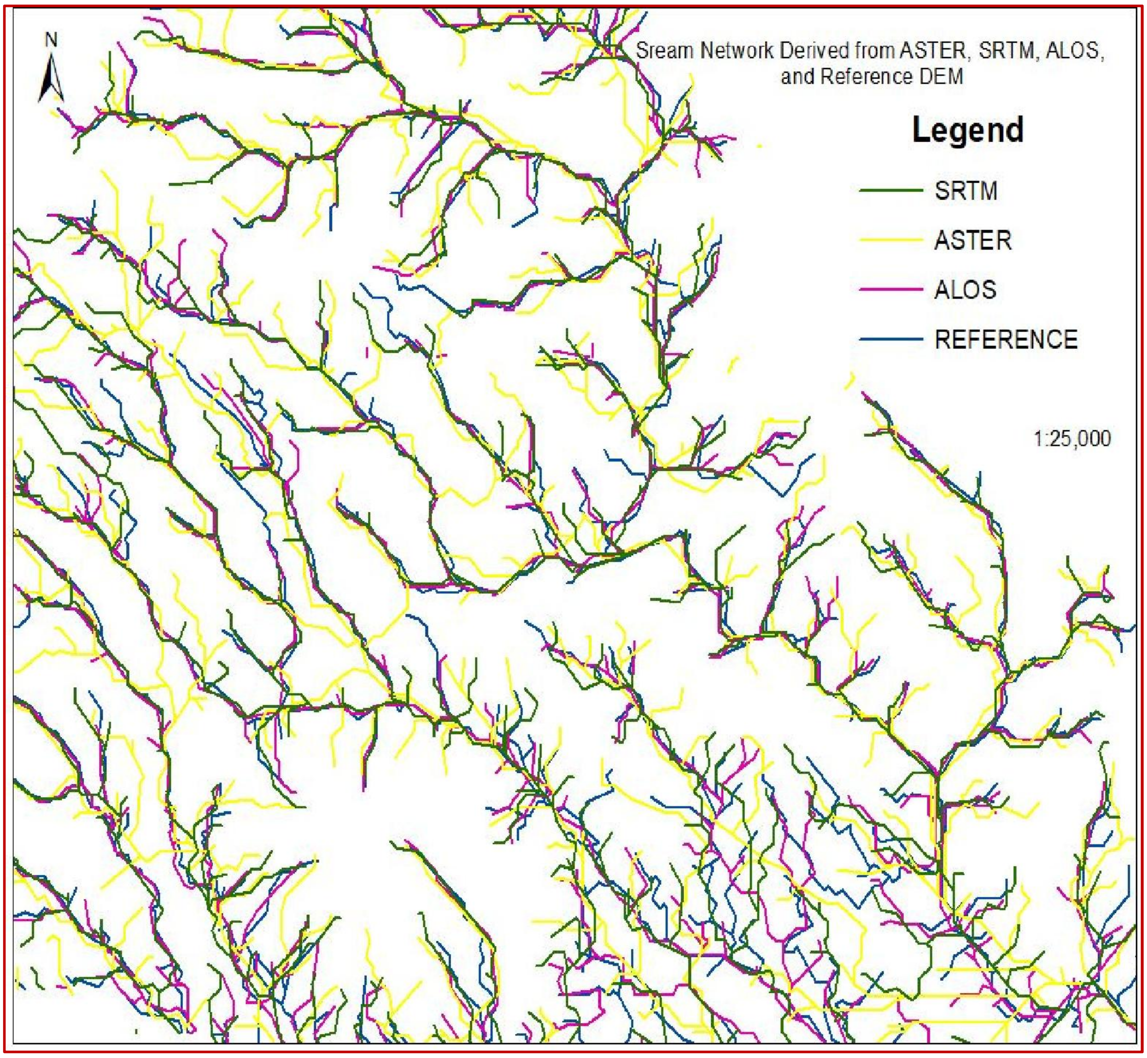
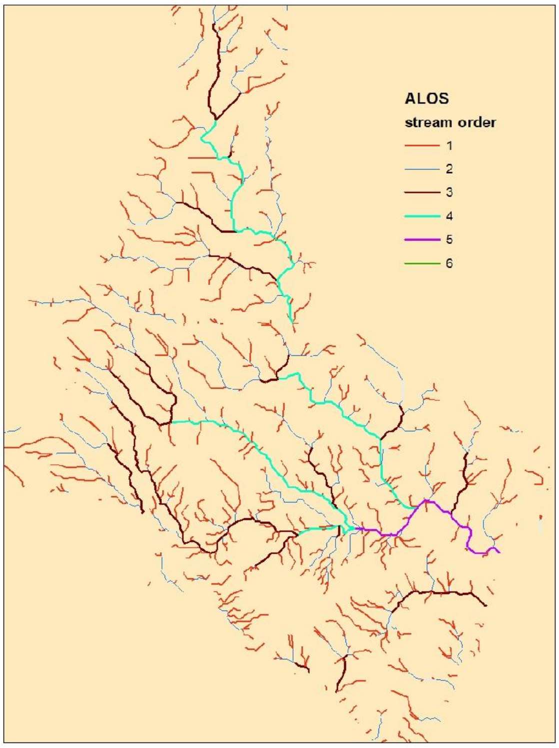
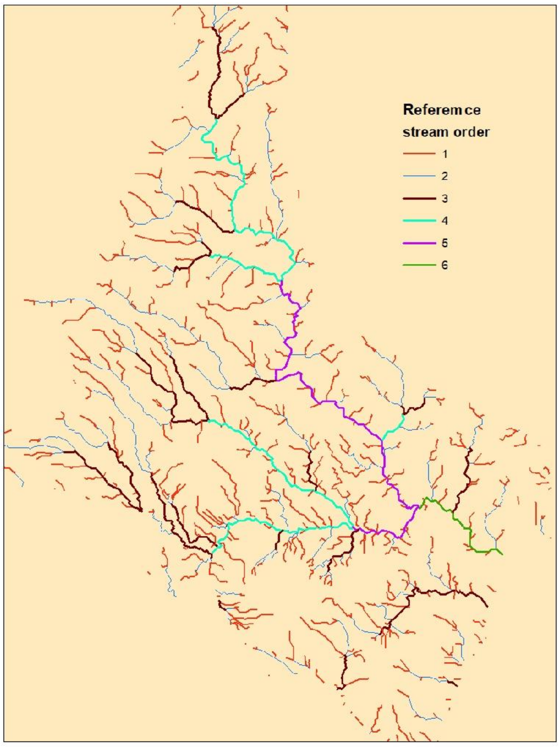


Figure 4.23 a model tool created in ArcMap for Drainage network derivation from DEMs

The output from the above drainage extraction model tool that used to assess the relative accuracy of the three DEMs is the final stream network. The stream network from the three DEMs, namely ASTER, SRTM and ALOS was first visually compared (as in figure 4.23) with stream network derived from reference DEMs for both study areas. Then, steam length and numbers (count) at 6 different stream orders was compared with that of reference stream network data in both study area.


N
Sream Network Derived from ASTER, SRTM, ALOS, and Reference DEM
Legend
SRTM
ASTER
ALOS
REFERENCE
1:25,000


ALOS
stream order
1
2
3
4
5
6


Referemce
stream order
1
2
3
4
5
6

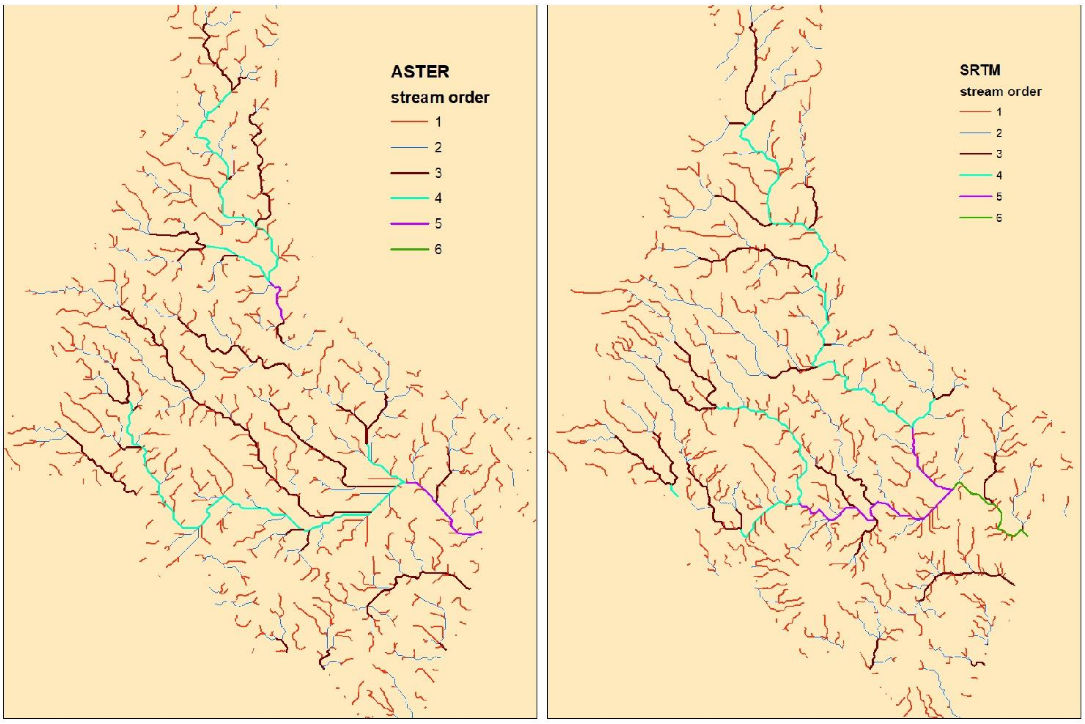


Figure 4.24 Steam Network derived from: top-details from all; upper right-ALOS, upper left-Reference DEM, lower right ASTER and lower left DEM for Addis Ababa.

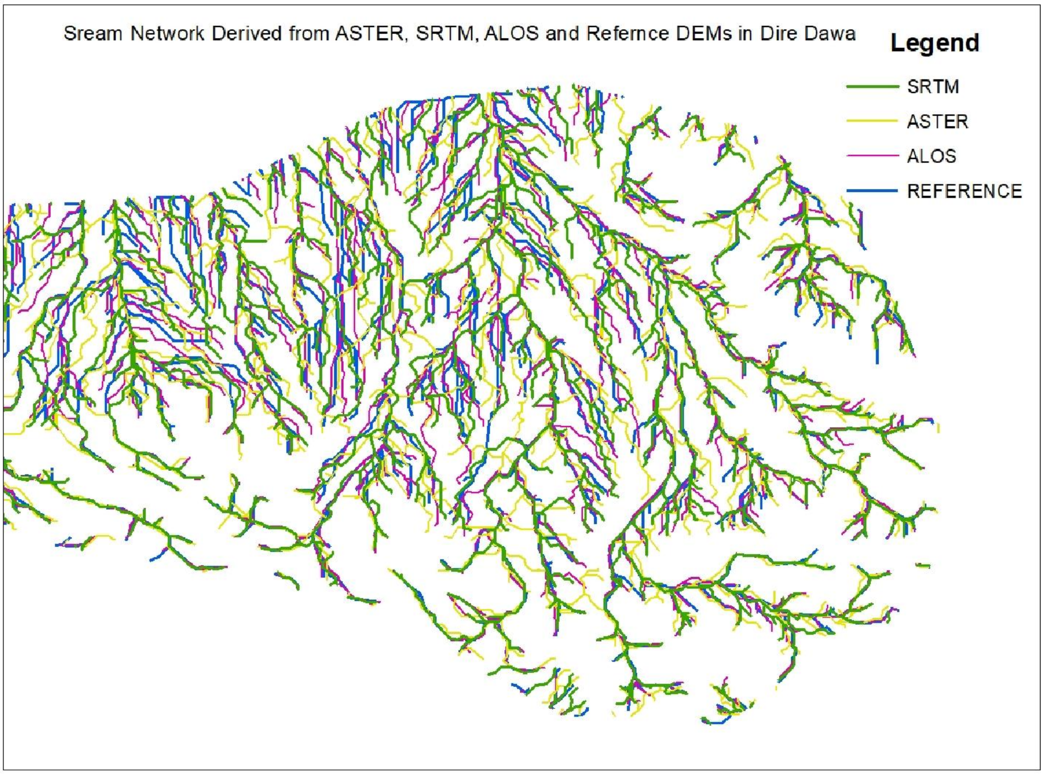


Figure 4.25 Steam Network derived from ASTER, SRTM, ALOS and reference DEM for Dire Dawa study area.

The visual inspection of the derived stream network shows that ASTER DEM (yellow color in the above figure) has the most deviation from the reference stream network and SRTM has the least deviation. SRTM and ALOS stream line features(green and pink color) are more similar and close to the Ref.DEM derived stream line features in both study areas(fig.4.24 and 4.25). SRTM stream network is more accurately produced than ASTER and ALOS DEMs when compared with respect to Ref. DEM derived stream networks.

When compared by stream length and order, ASTER derived stream network the highest first order stream but the lowest higher order stream lines. The total length of first order stream lines is 187 km and 151 km for ASTER, 165km and 179km for ALOS, 185km and 152km for SRTM and 176km and 168km for Ref. DEM respectively in Addis Ababa and Dire Dawa. The rest order combined is 106km and 134km for ASTER , 137km and 133km for ALOS, 158km and 140km for SRTM and 148km and 143km for Ref. DEM respectively in that order for Addis Ababa and Dire Dawa.

Table 4.13 stream length differences for 6 stream orders derived from ASTER, SRTM ALOS and Reference DEM in Addis Ababa study area.

Stream	Reference		SRTM			ALOS			ASTER		
order	Count	Length	Count	Length	**Difference**	Count	Length	**Difference**	Count	Length	difference
1	4876	175.82	5205	184.5	**-8.68**	4597	164.83	**10.99**	5248	187.6	**-11.78**
2	2266	77.76	2402	81.91	**-4.15**	2282	77.42	**0.34**	2356	80.73	**-2.97**
3	1049	36.02	1035	35.3	**0.72**	1000	33.97	**2.05**	1330	45.53	**-9.51**
4	571	19.61	598	20.51	**-0.9**	619	20.86	**-1.25**	617	21.37	**-1.76**
5	355	12.11	211	7.56	**4.55**	147	5.06	**7.05**	113	3.96	**8.15**
6	94	3.22	85	3.01	**0.21**	0	0	**3.22**	0	0	**3.22**
Total	9211	324.54	9536	332.8	**-8.26**	8645	302.14	**22.4**	9664	339.19	**-14.65**

As table 4.13 shows stream network derived from ALOS DEM is better than the reference Stream networks. ASTER has the highest difference (-14. 65 m) in total.

Table 4.14 stream length differences for 6 stream orders derived from ASTER, SRTM ALOS and Reference DEM in Dire Dawa study area.

Stream order	Reference		SRTM			ALOS			ASTER		
	Count	Length	Count	Length	**Difference**	Count	Length	**Difference**	Count	Length	difference
1	4836	168.453	4246	151.625	**16.828**	5125	179.972	**-11.519**	4206	150.832	**17.621**
2	2256	74.716	2314	78.439	**-3.723**	2062	68.894	**5.822**	2080	70.812	**3.904**
3	1418	47.064	1161	39.808	**7.256**	1303	43.787	**3.277**	1227	42.355	**4.709**
4	453	15.18	607	20.772	**-5.592**	501	16.633	**-1.453**	579	20.271	**-5.091**
5	162	5.475	30	0.948	**4.527**	94	3.218	**2.257**	28	0.921	**4.554**
6	19	0.572	0	0	**0.572**	0	0	**0.572**	0	0	**0.572**
Total	9144	311.459	8358	291.594	**19.865**	9085	312.505	**-1.046**	8120	285.19	**26.269**

Chapter 5

5 Result Interpretation and Discussion

This chapter discusses and gives interpretation of the result found by this particular study for the two study areas. The study investigated vertical accuracy of three global and open source DEMs: ASTER GDEM2, ALOS (AW3D30) and SRTM 30m DEMs by using DGPS and supplementary topographic data as a reference data. The GPS ellipsoidal height was converted to orthometric height by EGM96 geoid model. This chapter presents the findings of DEM accuracy assessed 1) by GPS points 2) by Image differencing and 3) by DEM derivative analysis, separately for the two study areas.

5.1 Addis Ababa Study Area

In this study area 635 GPS points were used to assess the accuracy of three DEMs (ASTER, SRTM and ALOS). The elevation values of these DEMs were extracted for the location of GPS points and subtracted from these GPS points' elevation values. The histogram graphs of elevation differences (i.e. ZGPS-ZDEMs) show that negative error for ALOS and SRTM DEMs and positive error for ASTER DEM. The mean error value for negative and positive error values of ASTER is positive 9m. Its maximum positive error is 38.93 m and its maximum negative error is 22.76m, thus ASTER DEM has underestimated the topography of this study area. The absolute value maximum, minimum and mean errors for ASTER DEM are 38.93 m, 0.01 m and 11.43 m respectively.

The slight negatively skewed histogram graphs of SRTM and ALOS DEMs show that this DEMs have slight overrepresentation for this study area topography, which confirmed by the mean of positive and negative error values of these two DEMs being -3.04 and -4.1 meters for SRTM and ALOS DEMs respectively. The absolute value maximum, minimum and mean error these two DEMs are 24.01 m, 0.0 m, and 4.22 m (for SRTM), and 17.01 m, 0.01 m and 4.11 m (for ALOS). This shows that SRTM and ALOS DEMs have smaller deviation than ASTER DEM from the reference elevation values.

The RMSE for ASTER is 13.66 m. The corresponding estimates of accuracy at the 95% confidence level value are computed using National Standard for Spatial Data Accuracy-NSSDA (FGDC, 1998; ASPRS, 2014). Thus vertical accuracy of ASTER as per this study is 26.77 m. This accuracy value is higher by about 1meter than the assumed vertical accuracy of the product which is 25 meters. This accuracy value is very low as compared to accuracy assessed by other researchers over different regions;(Elkhrachy (2017)) studied accuracy of

ASTER and SRTM over Saudi Arabia and found RMSE of 5.9m for SRTM and 5.07m for ASTER by using GPS survey points. The same study used elevation values from topographic data as reference data and found RMSE of 6.87m and 7.9m for SRTM and ASTER GDEM V2 DEMs respectively. These values are comparable for SRTM in this study.

This study shows that SRTM 30m DEM has RMSE value of 5.13 m and thus, vertical accuracy of 10.05 m, which is good when compared to its assumed vertical accuracy of 20m (Ferr et.al, 2007). The RMSE value for ALOS DEM is 5.28 m which is comparable with ALOS vertical accuracy (RMSE) computed by Tadono et, al. (2016) as lower 5 m. Vertical accuracy (at 95% confidence interval) of 10.34 m was recorded for AOS DEM in this study area.

The second accuracy assessment test was carried out by using local DEM as reference datasets. As it was mentioned in data processing and analysis section of this paper, image differencing method was used to assess the vertical accuracy of the three DEMs under investigation. The reference DEM for this study area assumed to be of higher accuracy because it was produced high resolution aerial photo. The residual image (error image) was visually and 129868 points were extracted from both reference DEM and the other three global DEMs, and the elevation values of the global DEMs were subtracted from the reference DEM elevation values for all extracted points.

The result from this method shows that ASTER GDEM has the highest positive error value, which, again reveals that the result found in the previous method is true in that ASTER has underestimated the topography of this area having maximum, minimum and mean error of 119.87 m, 0.0 m and 14.52 m. The vertical accuracy of ASTER is also the worst of the three DEMs as compared to reference DEM, which is 33.7 m (well over the assumed accuracy).

SRTM and ALOS DEM have better accuracy as compared to ASTER, SRTM being slightly better than ALOS in accuracy. The RMSE for SRTM is 4.45m and that of ALOS is 4.56 m and thus, their vertical accuracy are 8.72 m and 8.94 m respectively. Study by (Santillan and Makinano-Santillan 2016) shows that ALOS(AW3D30) DEM has RMSE 5.68m and SRTM-30m has RMSE of 8.28 and that of ASTER GDEM2 11.98 over Philippines, which are comparable to the RMSE values obtained in this study except for ASTER GDEM. Therefore SRTM and ALOS DEMs have better representation of the topography of this study area.

From the above discussions we can consider SRTM 30m as better representative of the topography of Ethiopia particularly, Addis Ababa and Dire Dawa areas. ALOS (W3D30m) DEM can also be considered as best second option, having being couscous of the two DEMs slight overestimation of the terrain heights in these two study area.

The other accuracy test was done through comparisons of derived products with same products derived from reference datasets. In this method, DEM derivatives, namely profile graphs, shaded relief map, slope and drainage networks have been used to assess the quality of the three Global DEMs. Studying the profile graphs along 16 km long road line extracted from these three DEMs and comparing it with that of Ref. DEM confirms the result obtained in the previous two methods. As profile graph in figure 4.18 and 4.19 shows ASTER GDEM has clearly under represented the topography of this area, because the line for ASTER lies well under the reference line. This graph also showed that SRTM-30m and ALOS (AW3D30m) have overestimated the study area topography relatively by smaller amount than ASTER GDEM. The shaded relief map produced from these three DEMs also shows poor quality in ASTER GDEM having contamination of may be artifacts.

In this study the accuracy of DEMs under investigations are also assessed in relation with the terrain slope. The relationship between topographic slope and DEM error shows that mean elevation error for ALOS increased from 3.7 m in flat slope(slope < 2.6 deg) to 5.03m in steeper slope (slope > 30 deg). SRTM also behaved in the same manner. ASTER showed higher error in flat terrain, 15 m mean error, and lower error in higher slope, 12 m mean error. From this we can say that ASTER has lower accuracy in flat terrain.

The slope maps derived from these DEM shows that slope calculated from ALOS DEM is more close to that of reference DEM.

The derived drainage network for these DEMs showed that SRTM have produced stream networks that are in good agreement with reference DEM stream networks. On the other hands ASTER GDEM produced stream networks that have the highest deviation from the reference stream networks.

In general the result from this method has also confirmed the previous result that STRM has better accuracy closely followed by ALOS and ASTER has the least accuracy of the three DEMs assessed in this research at least for this study area.

5.2 Dire Dawa Study Area

In this study area 128 Ground control of EMA and 167 GPS survey points measured by GNSS instrument, a total of 295 GPS measured ground control points were used to assess the vertical accuracy of ASTER GDEM2, SRTM 30m and ALOS(AW3D30) DEMs using the same procedure used for Addis Ababa study area. The maximum, minimum and mean error values for ASTER DEM are 51.74 m, 0.01m and **9.39** m, and its RMSE value is 11.7 m. The corresponding estimates of accuracy at the 95% confidence level (NSSDA: RMSE*1.9600) value is 22.93 m, which is within the range specified as expected accuracy by the producer.

SRTM 30m and ALOS (AW3D30) DEMs error values show similarity as in the previous study area. The maximum error for SRTM is 23.27 m and for ALOS is 24.94 m. Their mean error values are 4.24 m and 3.94 m respectively for SRTM and ALOS. The RMSE value for SRTM is 5.8 m and that of ALOS is 5.13 m, therefore accuracy (95%) of 11.38 m and 10.08 m, which are within the limit of producer's specified accuracy value for both datasets. These two DEM datasets have batter accuracy over ASTER DEM at least for this study.

ASTER GDEM has under-estimated the topography of this study area too as in the previous case, because only 24.34% of the total errors have positive error value. In contrast, SRTM and ALOS DEMs have over-represented this area's topography because 73.4% (for ALOS) and 69.9 %(for SRTM) of their total error values positive.

The DEM used in this study area as reference DEM has accuracy of 1.6 m (at 95% confidence interval). The result of image differencing has been analyzed visually and statistically evaluated. According to this study by this method, ASTER DEM showed the highest error value in this region. Some extreme error or elevation differences have occurred in all DEMs but in very localized few areas. As error image shows and later compared with Google Earth image, the reason for these extreme values occurrences seems to be terrain morphology and changes that occur on the ground such as high rising buildings. But this should be verified by further studies.

According to the result from this method RMSE value of ASTER is 9.51 m, which is better than that of Addis study area, thus accuracy (95%) of 18.99 m was recorded, which is also better than the RMSE value obtained by GPS point's evaluation method.

The RMSE error value of SRTM is 5.33 m and that of ALOS is 5.64 m, therefore SRTM 30m DEM has better accuracy(10.45 m) than ASTER and ALOS which have the second accuracy of 11.05 m). This study also showed that SRTM and ALOS have overestimated slightly the terrain topography of this study area because, the residual values from image differences (Ref. DEM-SRTM and Ref. DEM-ALOS) indicates that only 10.12% and 16.14% of errors have positive values for ALOS and SRTM respectively. In general SRTM 30m DEM has better accuracy than ALOS and ASTER DEMs over the topography of this study area.

As in the previous study area, the shaded relief maps produced from ASTER, SRTM and ALOS DEMs show that SRTM and ALOS are better in representing the relief of the study area. Profile along 2.4 km long road was selected from all DEM including the reference DEM. The drown profile graph shows that SRTM and ALOS profile lines are closer to that of Reference line and thus, have better accuracy than ASTER DEM which shows higher deviation from the reference line. This profile graph also confirms that ASTER under-represented the terrain of this area because in the profile graph ASTER values are well under the reference line.

In this study area, the relationship between terrain elevation (and slope) and DEM errors are investigated. The result shows that SRTM and ASTER mean error values increased from below 2 m to over 20 m as terrain elevation increases from lower(below 1110 m) to higher (above 1450 m). DEM errors over different slope zones also shows that SRTM and ALOS mean error are relatively stable, while ASTER DEM mean error is higher in flat slope(below 2.5 degree). ALOS DEM showed better quality in terms of derived surface slope which more resembles that of reference dataset.

Drainage network extracted from these three DEM were compare with drainage network derived from reference DEM. The result show that ALOS and SRTM derived stream networks are more similar to that of reference and ASTER derived stream lines are more deviated from the reference stream lines.

In general ALOS (AW3D30) DEM has shown better quality in derivatives surface quality than the other two DEM and closely followed by SRTM 30 DEM dataset.

Chapter 6

6 Conclusions and Recommendations

6.1 Conclusions

This thesis focused on vertical accuracy of three global open source DEMs(ASTER GDEM2, SRTM-30M and ALOS-AW3D30) over Ethiopia in two study areas- Addis Ababa and Dire Dawa- by using GCP points measured by DGPS and Reference DEM as reference data. The research used conventional method to calculate RMSE of elevation differences between these DEMs and reference elevation datasets. Based on the results presented in this thesis the following conclusions can be made:

The vertical accuracy assessment of these three DEMs showed that the RMSE of ASTER GDEM2 is almost twice higher than the RMSE of SRTM-30m and ALOS (AW3D30) in both study areas.

When assessed by both GPS points and Reference DEM the accuracy of ASTER is better in Dire Dawa than in Addis Ababa. When assessed by GPS points ASTER scored RMSE of 13.66 m in Addis Ababa and 11.7 m in Dire Dawa. When assessed by Reference DEM (image differencing) ASTER has RMSE of 17.19 m in Addis Ababa and 9.51 in Dire Dawa.

The RMSE of SRTM and ALOS DEMs is better in Addis than in Dire by all means, though the difference is small. The RMSE values for SRTM in Addis are 5.13 m when assessed by GPS points and 4.45 m when assessed by Ref. DEM. These same values for Dire are 5.8 m and 5.33m. RMSE of ALOS in Addis is 5.28 m and 4.56 m for GPS points and Reference DEM, and for Dire this same values are 5.13 m and 5.64 m. This RMSE value for SRTM and ALOS in both study area for both method is far better than that of ASTER and the accuracy of SRTM is better than that of ALOS in general.

The investigation of vertical accuracy of these DEMs by derivative has confirmed the under-representation of ASTER DEM for the topography of the study area, which can be seen cleanly from the profile analysis for these DEMs. It was also confirmed that SRTM and ALOS has 2m to 6m overestimation of these two areas topography. In general, ALOS DEM has better of derived surfaces over these study areas, followed by ALOS (AW3D30) DEM, which differ from SRTM by smaller error magnitude.

This study has answered the search questions as:

- The elevation difference between terrain heights of these two study area as represented by test datasets and the three Global DEMs ranges from 0 meter to 14.5 maters for ASTER GDEM2 and from 0 m to 5 m for STRM 30m and ALOS (W3D30m) DEMs.
- SRTM 30m DEM has better accuracy over these two study area.
- ALOS DEM has better quality of derivative surfaces.

6.2 Recommendations

The following recommendations are set forth based on the results and discussions of this thesis:

- SRTM 30m DEM has showed batter vertical accuracy over Addis Ababa and Dire Dawa regions. Therefore this DEM can be used keeping in mind that this DEM can overestimation terrain topography by 2 to 6 meters.
- ALOS DEM can be the best alternative source of DEM based applications
- ALOS DEM has showed better quality of derived slope and drainage networks. Particularly the slope derive from this DEM is almost similar to that of reference datasets. Therefore this DEM can be used for classification of slope for land use planning agricultural land use planning and similar applications.
- ASTER GDEM has showed higher underestimation of height of these two study areas on average by up to 14 meters. Therefore users should be aware of this lower vertical quality of ASTER when using for applications that relatively require higher elevation precisions.

6.3 Feature Work Recommendations

The following recommendations are set forth for feature investigation

- DEM accuracy varies from region to region, accuracy assessment over different regions are required.
- The accuracy of DEM varies for different land use and land cover areas and to assess accuracy of DEM over differing land cover type reliable land use data is required
- Terrain morphology is one of the factors that influence the accuracy of DEM thus accuracy shall be assessed for difference in terrain morphologies.

Appendix A

Dire Dawa GPS data postprocessing and adjustment report

Project Summary

Adjustment
Project name: DIRE DAWA DATA
Created by: ABDI IBRAHIM
Linear unit: Meters
Angular unit: DMS
Projection: UTMNorth-Zone_37 : 36E to 42E
Datum: WGS84
Time Zone: (UTC+03:00)

Control Tie Analysis: Success

Adjusted Subnetworks Count: (Horz+Vert):9

Subnetwork Base LGDON, DDU, 275, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	10	2 + 1	0 + 0	29

Subnetwork Base DDU D3, COTON2, 281, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	10	2 + 1	0 + 0	29

Subnetwork Base DDU D4, COTON3, 302, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	10	2 + 1	0 + 0	29

Subnetwork DIREDU1, coton1, DD2Base1, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	9	2 + 1	0 + 0	21

Subnetwork BUBA D6, CONTROL, 297, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	8	2 + 1	0 + 0	19

Subnetwork Base LGDON1, DDU1, 274, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	6	2 + 1	0 + 0	15

Subnetwork DIREDU, coton, DD1Base1, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	6	2 + 1	0 + 0	15

Subnetwork 242, CUBA1, 249, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	5	1 + 1	0 + 0	7

Subnetwork Base1, Base12 (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	2	2 + 1	0 + 0	1

Control Points			
Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)
BUBA D6	9.60890864	41.8218685	1168.123
Base1	9.62489134	41.8434053	1120.893
Base12	9.59811844	41.8888117	1203.844
Base DDU D3	9.62489134	41.8434053	1120.081
Base DDU D4	9.62489134	41.8434053	1120.083
Base LGDON	9.59811844	41.8888117	1203.844
Base LGDON1	9.59811844	41.8888117	1203.829
CONTROL	9.59811844	41.8888117	1203.844
COTON2	9.59811844	41.8888117	1203.844
COTON3	9.59811844	41.8888117	1203.844
CUBA1	9.60890865	41.8218685	1168.973
DDU	9.62489135	41.8434053	1120.875
DDU1	9.62489135	41.8434053	1120.875
DIREDU	9.62489134	41.8434053	1120.131
DIREDU1	9.62489134	41.8434053	1120.077
coton	9.59811844	41.8888117	1203.844
coton1	9.59811844	41.8888117	1203.844

GPS Observations										
Name	dN (m)	dE (m)	dHt (m)	Horz RMS (m)	Vert RMS (m)	Solution Type	PDOP	HDOP	VDOP	Orbit
223–271	-486.006	68.495	8.026	0.004	0.005	Fixed	1.975	1.169	1.592	Precise
223–BM27O	-476.362	277.495	10.476	0.006	0.009	Fixed	2.233	1.284	1.828	Precise
223–DD1Base1	73.429	682.346	0.047	0.011	0.014	Fixed	2.062	1.212	1.668	Precise
223–DIREDU	4034.401	-1490.37	-90.667	0.006	0.007	Fixed	1.858	1.096	1.501	Precise
223–coton	1112.558	3522.555	-6.924	0.005	0.007	Fixed	1.869	1.105	1.507	Precise
224–259	1493.593	-617.413	-35.413	0.016	0.02	Fixed	3.133	1.958	2.446	Precise
224–274	1960.208	1740.46	-45.952	0.014	0.019	Fixed	2.779	1.634	2.248	Precise
224–BM299	-98.515	1412.014	22.436	0.021	0.023	Fixed	2.671	1.741	2.026	Precise
224–Base LGDON1	1679.553	2994.448	-17.642	0.009	0.011	Fixed	2.349	1.453	1.846	Precise
224–DDU1	4601.389	-2018.48	-100.64	0.01	0.013	Fixed	2.351	1.454	1.847	Precise
226–269	-1167.776	136.739	29.625	0.002	0.003	Fixed	2.374	1.25	2.018	Precise
226–273	613.398	874.57	-1.598	0.025	0.035	Fixed	2.087	1.071	1.791	Precise
226–275	-120.714	490.715	0.956	0.003	0.004	Fixed	2.128	1.092	1.826	Precise
226–Base LGDON	-223.272	1690.09	18.989	0.02	0.028	Fixed	1.932	0.986	1.662	Precise
226–DDU	2698.565	-3322.833	-63.985	0.023	0.032	Fixed	1.933	0.986	1.663	Precise
232–256	-398.12	1204.384	5.811	0.004	0.007	Fixed	2.08	0.904	1.873	Precise
232–288	-300.429	270.424	-9.502	0.005	0.006	Fixed	2.978	1.402	2.627	Precise
232–BM244	202.139	579.251	-9.534	0.004	0.009	Fixed	2.205	0.963	1.983	Precise

232–Base DDU D3	2310.071	-403.474	-57.528	0.004	0.006	Fixed	2.09	0.913	1.88	Precise
232–COTON2	-611.775	4609.454	26.276	0.004	0.007	Fixed	2.089	0.912	1.879	Precise
235–253	-751.015	-265.879	17.208	0.022	0.051	Fixed	2.43	0.915	2.251	Precise
235–254	-823.773	-118.547	18.525	0.008	0.01	Fixed	2.37	0.969	2.163	Precise
235–BM258	-955.288	-1215.953	21.75	0.004	0.008	Fixed	1.988	0.783	1.828	Precise
235–Base DDU D4	1674.025	-146.255	-42.39	0.003	0.006	Fixed	1.963	0.777	1.803	Precise
235–COTON3	-1247.814	4866.682	41.39	0.004	0.009	Fixed	1.964	0.777	1.804	Precise
239–BUBA D6	455.798	-5707.109	-4.567	0.021	0.031	Fixed	1.924	0.907	1.697	Precise
239–CONTROL	-677.336	1656.941	31.161	0.013	0.021	Fixed	1.924	0.906	1.698	Precise
242–247	259.137	517.129	-7.439	0.008	0.012	Fixed	2.929	1.573	2.471	Precise
242–249	-564.71	-781.177	15.765	0.011	0.014	Fixed	1.902	1.078	1.567	Precise
242–BM248	-442.446	-748.214	13.71	0.021	0.014	Fixed	1.87	1.066	1.536	Precise
242–CUBA1	60.829	-735.837	2.099	0.071	0.048	Fixed	1.786	1.014	1.47	Precise
247–249	-823.857	-1298.306	23.175	0.005	0.007	Fixed	2.364	1.267	1.996	Precise
247–BM248	-701.609	-1265.296	21.152	0.008	0.012	Fixed	2.602	1.394	2.196	Precise
249–BM248	122.246	32.985	-2.061	0.018	0.026	Fixed	1.682	0.901	1.421	Precise
250–267	-394.602	4182.824	24.953	0.006	0.008	Fixed	2.089	1.166	1.733	Precise
250–272	1317.178	4386.496	-9.03	0.01	0.013	Fixed	2.422	1.346	2.013	Precise
250–BM234	1619.189	267.032	-31.009	0.012	0.015	Fixed	4.301	2.427	3.551	Precise
250–Base LGDON	401.437	5255.578	12.866	0.005	0.007	Fixed	1.845	1.038	1.525	Precise
250–DDU	3323.276	242.655	-70.105	0.005	0.007	Fixed	1.844	1.038	1.524	Precise
253–254	-72.757	147.332	1.348	0.019	0.041	Fixed	2.983	1.257	2.705	Precise
253–BM258	-204.271	-950.074	4.558	0.014	0.029	Fixed	2.144	0.853	1.967	Precise
253–Base DDU D4	2425.034	119.629	-59.585	0.017	0.036	Fixed	2.14	0.85	1.964	Precise
253–COTON3	-496.801	5132.564	24.184	0.017	0.035	Fixed	2.14	0.85	1.964	Precise
254–BM258	-131.512	-1097.412	3.245	0.006	0.01	Fixed	1.863	0.821	1.672	Precise
254–Base DDU D4	2497.804	-27.711	-60.908	0.006	0.009	Fixed	1.845	0.816	1.655	Precise
254–COTON3	-424.039	4985.226	22.876	0.006	0.011	Fixed	1.844	0.816	1.654	Precise
256–288	97.683	-933.994	-15.375	0.008	0.014	Fixed	2.509	1.202	2.203	Precise
256–BM244	600.249	-625.127	-15.312	0.005	0.011	Fixed	1.974	0.832	1.79	Precise
256–Base DDU D3	2708.189	-1607.857	-63.325	0.003	0.007	Fixed	1.789	0.755	1.622	Precise
256–COTON2	-213.654	3405.069	20.469	0.003	0.006	Fixed	1.789	0.755	1.622	Precise
257–301	-431.835	445.985	3.744	0.005	0.007	Fixed	1.62	0.873	1.365	Precise
257–302	-512.362	196.962	5.28	0.005	0.006	Fixed	1.799	1.037	1.47	Precise
257–BM232	-325.921	487.886	3.381	0.006	0.009	Fixed	1.535	0.845	1.281	Precise
257–Base DDU D4	2716.113	767.019	-66.549	0.005	0.007	Fixed	1.457	0.797	1.22	Precise
257–COTON3	-205.726	5779.951	17.241	0.004	0.006	Fixed	1.458	0.797	1.22	Precise
259–274	466.663	2357.882	-10.603	0.01	0.016	Fixed	2.239	1.105	1.948	Precise
259–BM299	-	2029.444	57.809	0.005	0.009	Fixed	1.871	0.854	1.665	Precise

	1592.068									
259–Base LGDON1	185.991	3611.88	17.729	0.004	0.007	Fixed	1.802	0.812	1.608	Precise
259–DDU1	3107.821	-1401.057	-65.243	0.005	0.009	Fixed	1.803	0.813	1.609	Precise
260–281	-1150.233	-188.095	14.796	0.02	0.032	Fixed	1.956	0.933	1.719	Precise
260–283	-1134.188	-334.735	9.518	0.01	0.013	Fixed	2.028	1.094	1.707	Precise
260–BM 282	-519.714	-411.144	0.619	0.005	0.007	Fixed	2.498	1.435	2.044	Precise
260–Base DDU D3	3341.168	-1401.598	-73.199	0.007	0.011	Fixed	1.599	0.79	1.391	Precise
260–COTON2	419.33	3611.334	10.58	0.011	0.017	Fixed	1.598	0.789	1.39	Precise
267–272	1711.802	203.635	-34.088	0.008	0.011	Fixed	1.988	1.073	1.674	Precise
267–BM234	2013.801	-3915.804	-55.988	0.015	0.018	Fixed	2.571	1.653	1.968	Precise
267–Base LGDON	796.042	1072.727	-12.139	0.006	0.008	Fixed	1.477	0.812	1.234	Precise
267–DDU	3717.884	-3940.198	-95.102	0.006	0.008	Fixed	1.477	0.812	1.234	Precise
269–273	1781.178	737.845	-31.194	0.007	0.011	Fixed	2	0.989	1.738	Precise
269–275	1047.051	353.964	-28.65	0.005	0.008	Fixed	1.934	0.954	1.683	Precise
269–Base LGDON	944.517	1553.368	-10.598	0.006	0.01	Fixed	1.956	0.961	1.704	Precise
269–DDU	3866.358	-3459.558	-93.562	0.008	0.012	Fixed	1.957	0.961	1.705	Precise
271–BM27O	9.65	208.991	2.444	0.006	0.01	Fixed	1.972	1.032	1.681	Precise
271–DD1Base1	559.438	613.844	-7.982	0.007	0.01	Fixed	1.882	1	1.595	Precise
271–DIREDU	4520.408	-1558.869	-98.689	0.004	0.006	Fixed	1.762	0.933	1.495	Precise
271–coton	1598.565	3454.055	-14.948	0.003	0.004	Fixed	1.762	0.933	1.495	Precise
272–BM234	302.016	-4119.467	-21.913	0.016	0.021	Fixed	2.957	1.743	2.389	Precise
272–Base LGDON	-915.752	869.095	21.923	0.004	0.006	Fixed	1.679	0.926	1.4	Precise
272–DDU	2006.093	-4143.83	-61.042	0.006	0.008	Fixed	1.678	0.926	1.4	Precise
273–275	-734.128	-383.881	2.538	0.005	0.007	Fixed	1.74	0.867	1.509	Precise
273–Base LGDON	-836.668	815.524	20.582	0.003	0.004	Fixed	1.576	0.789	1.364	Precise
273–DDU	2085.169	-4197.404	-62.384	0.005	0.008	Fixed	1.577	0.789	1.365	Precise
274–BM299	-2058.745	-328.457	68.378	0.007	0.012	Fixed	2.103	1.062	1.815	Precise
274–Base LGDON1	-280.673	1253.989	28.341	0.004	0.006	Fixed	1.901	0.953	1.645	Precise
274–DDU1	2641.164	-3758.947	-54.655	0.006	0.009	Fixed	1.903	0.954	1.647	Precise
275–Base LGDON	-102.54	1199.405	18.047	0.004	0.006	Fixed	1.739	0.838	1.524	Precise
275–DDU	2819.298	-3813.523	-64.92	0.006	0.008	Fixed	1.739	0.838	1.524	Precise
278–BUBA D6	1400.416	-5427.967	-21.831	0.008	0.012	Fixed	2.181	1.036	1.919	Precise
278–CONTROL	267.286	1936.084	13.877	0.012	0.019	Fixed	2.182	1.036	1.92	Precise
280–296	-412.666	-569.537	7.131	0.006	0.008	Fixed	1.878	1.057	1.552	Precise

280–297	-564.034	-563.567	11.035	0.011	0.016	Fixed	1.676	0.918	1.402	Precise
280–BM308	-192.698	25.742	4.289	0.004	0.006	Fixed	1.479	0.781	1.256	Precise
280–BUBA D6	-760.3	-2800.738	23.988	0.003	0.004	Fixed	1.448	0.762	1.231	Precise
280–CONTROL	-1893.428	4563.312	59.713	0.003	0.005	Fixed	1.447	0.762	1.231	Precise
281–283	16.052	-146.632	-5.343	0.013	0.02	Fixed	2.168	1.102	1.867	Precise
281–BM 282	630.514	-223.044	-14.173	0.026	0.035	Fixed	2.804	1.579	2.317	Precise
281–Base DDU D3	4491.399	-1213.494	-88.038	0.009	0.015	Fixed	1.829	0.862	1.613	Precise
281–COTON2	1569.564	3799.433	-4.231	0.011	0.019	Fixed	1.827	0.861	1.611	Precise
283–BM 282	614.426	-76.375	-8.833	0.024	0.029	Fixed	4.059	2.333	3.322	Precise
283–Base DDU D3	4475.35	-1066.887	-82.721	0.004	0.007	Fixed	1.781	0.977	1.489	Precise
283–COTON2	1553.509	3946.045	1.075	0.004	0.006	Fixed	1.78	0.977	1.488	Precise
288–BM244	502.557	308.845	-0.031	0.01	0.019	Fixed	3.013	1.51	2.608	Precise
288–Base DDU D3	2610.496	-673.888	-48.014	0.003	0.004	Fixed	2.655	1.33	2.298	Precise
288–COTON2	-311.345	4339.041	35.783	0.004	0.006	Fixed	2.657	1.331	2.3	Precise
291–DD5226	116.905	-431.371	-9.47	0.014	0.02	Fixed	4.565	2.313	3.936	Precise
291–DIREDU1	4903.231	-2481.344	-113.943	0.019	0.028	Fixed	2.694	1.261	2.381	Precise
291–coton1	1981.339	2531.578	-30.218	0.019	0.03	Fixed	2.711	1.276	2.392	Precise
294–295	75.378	150.562	4.531	0.009	0.016	Fixed	1.855	0.933	1.603	Precise
294–BM300	347.143	124.207	-17.552	0.021	0.036	Fixed	1.88	0.995	1.595	Precise
294–DD2Base1	183.732	-442.187	-20.608	0.006	0.011	Fixed	2.249	1.13	1.944	Precise
294–DIREDU1	5030.72	-3195.11	-138.132	0.004	0.007	Fixed	1.803	0.906	1.558	Precise
294–coton1	2108.87	1817.819	-54.37	0.006	0.01	Fixed	1.803	0.906	1.559	Precise
295–DD2Base1	108.359	-592.747	-25.118	0.004	0.008	Fixed	1.972	0.978	1.713	Precise
295–DIREDU1	4955.336	-3345.666	-142.667	0.003	0.006	Fixed	1.663	0.795	1.461	Precise
295–coton1	2033.49	1667.258	-58.9	0.002	0.004	Fixed	1.664	0.794	1.462	Precise
296–297	-151.359	5.976	3.925	0.007	0.011	Fixed	2.281	1.256	1.904	Precise
296–BM308	219.972	595.275	-2.842	0.008	0.012	Fixed	1.93	1.075	1.603	Precise
296–BUBA D6	-347.631	-2231.203	16.86	0.005	0.007	Fixed	1.86	1.038	1.544	Precise
296–CONTROL	-1480.757	5132.851	52.579	0.006	0.008	Fixed	1.858	1.037	1.542	Precise
297–BM308	371.333	589.3	-6.745	0.008	0.015	Fixed	1.74	0.952	1.456	Precise
297–BUBA D6	-196.266	-2237.17	12.944	0.007	0.011	Fixed	1.673	0.915	1.401	Precise
297–CONTROL	-1329.397	5126.877	48.682	0.007	0.012	Fixed	1.673	0.915	1.401	Precise
301–302	-80.534	-249.024	1.536	0.01	0.014	Fixed	1.884	1.027	1.579	Precise
301–BM232	105.913	41.896	-0.378	0.004	0.007	Fixed	1.616	0.852	1.373	Precise
301–Base DDU D4	3147.953	321.037	-70.304	0.005	0.009	Fixed	1.499	0.786	1.276	Precise
301–COTON3	226.114	5333.965	13.472	0.006	0.011	Fixed	1.499	0.786	1.276	Precise
302–BM232	186.446	290.926	-1.913	0.005	0.007	Fixed	1.724	0.956	1.435	Precise

302−Base DDU D4	3228.487	570.063	-71.836	0.005	0.008	Fixed	1.711	0.947	1.425	Precise
302−COTON3	306.647	5583	11.959	0.005	0.007	Fixed	1.711	0.947	1.425	Precise
BM27O−DD1Base1	549.777	404.859	-10.413	0.007	0.01	Fixed	1.766	0.875	1.534	Precise
BM27O−DIREDU	4510.755	-1767.853	-101.131	0.006	0.01	Fixed	1.679	0.824	1.463	Precise
BM27O−coton	1588.914	3245.075	-17.373	0.005	0.008	Fixed	1.687	0.828	1.47	Precise
BM232−Base DDU D4	3042.041	279.133	-69.934	0.002	0.004	Fixed	1.441	0.773	1.216	Precise
BM232−COTON3	120.199	5292.071	13.863	0.003	0.004	Fixed	1.441	0.773	1.216	Precise
BM234−Base LGDON	-1217.759	4988.547	43.896	0.034	0.026	Fixed	2.062	1.296	1.604	Precise
BM234−DDU	1704.083	-24.385	-39.113	0.03	0.041	Fixed	2.051	1.289	1.595	Precise
BM244−Base DDU D3	2107.935	-982.727	-47.996	0.004	0.009	Fixed	1.921	0.813	1.74	Precise
BM244−COTON2	-813.913	4030.202	35.811	0.006	0.012	Fixed	1.92	0.812	1.74	Precise
BM258−Base DDU D4	2629.314	1069.701	-64.158	0.002	0.004	Fixed	1.588	0.657	1.446	Precise
BM258−COTON3	-292.526	6082.641	19.636	0.002	0.005	Fixed	1.588	0.657	1.446	Precise
BM299−Base LGDON1	1778.061	1582.435	-40.087	0.004	0.008	Fixed	1.587	0.735	1.407	Precise
BM299−DDU1	4699.896	-3430.502	-123.074	0.006	0.011	Fixed	1.587	0.735	1.407	Precise
BM300−DD2Base1	-163.411	-566.359	-3.064	0.012	0.021	Fixed	2.017	1.063	1.714	Precise
BM300−DIREDU1	4683.582	-3319.303	-120.613	0.013	0.021	Fixed	1.648	0.842	1.416	Precise
BM300−coton1	1761.707	1693.619	-36.774	0.025	0.042	Fixed	1.648	0.842	1.417	Precise
BM308−BUBA D6	-567.603	-2826.48	19.699	0.003	0.005	Fixed	1.455	0.763	1.24	Precise
BM308−CONTROL	-1700.733	4537.575	55.419	0.003	0.005	Fixed	1.455	0.763	1.239	Precise
BM 282−Base DDU D3	3860.875	-990.458	-73.832	0.006	0.007	Fixed	2.32	1.338	1.896	Precise
BM 282−COTON2	939.033	4022.462	9.967	0.008	0.011	Fixed	2.322	1.339	1.897	Precise
BUBA D6−CONTROL	-1133.128	7364.055	35.715	0.003	0.005	Fixed	1.587	0.744	1.402	Precise
Base1−Base12	-2921.845	5012.925	82.982	0.003	0.005	Fixed	1.658	0.779	1.463	Precise
Base268−DD5226	-1079.209	-1407.424	13.264	0.036	0.037	Fixed	30.029	23.32	18.92	Precise
Base268−DIREDU1	3707.052	-3457.405	-91.217	0.016	0.018	Fixed	3.346	2.004	2.68	Precise
Base268−coton1	785.202	1555.507	-7.467	0.016	0.019	Fixed	3.346	2.005	2.679	Precise
Base DDU D3−COTON2	-2921.842	5012.93	83.785	0.002	0.004	Fixed	1.619	0.737	1.442	Precise
Base DDU D4−COTON3	-2921.843	5012.938	83.79	0.002	0.004	Fixed	1.502	0.688	1.336	Precise
Base LGDON−DDU	2921.843	-5012.932	-82.972	0.003	0.004	Fixed	1.545	0.744	1.355	Precise
Base LGDON1−DDU1	2921.838	-5012.939	-82.999	0.002	0.005	Fixed	1.444	0.656	1.286	Precise
DD1Base1−DIREDU	3960.972	-2172.711	-90.711	0.007	0.011	Fixed	1.629	0.818	1.408	Precise
DD1Base1−coton	1039.127	2840.219	-6.962	0.007	0.011	Fixed	1.646	0.827	1.423	Precise
DD2Base1−DIREDU1	4846.98	-	-117.54	0.006	0.01	Fixed	1.801	0.907	1.555	Precise

		2752.917								
DD2Base1−coton1	1925.134	2260.005	-33.779	0.005	0.008	Fixed	1.801	0.907	1.556	Precise
DD5226−DIREDU1	4786.297	-2049.98	-104.474	0.007	0.013	Fixed	2.484	1.197	2.177	Precise
DIREDU−coton	-2921.844	5012.927	83.737	0.003	0.005	Fixed	1.55	0.767	1.347	Precise
DIREDU1−coton1	-2921.846	5012.925	83.765	0.002	0.004	Fixed	1.552	0.75	1.358	Precise

Adjusted Points						
Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)	Std Dev e (m)	Std Dev n (m)	Std Dev u (m)
223	9.58833452	41.8566656	1210.779	0.021	0.012	0.033
224	9.58317292	41.8614294	1221.498	0.037	0.043	0.074
226	9.60026345	41.8734458	1184.834	0.016	0.016	0.036
232	9.60399284	41.846903	1177.58	0.014	0.012	0.033
235	9.60975786	41.8446098	1162.456	0.017	0.015	0.047
239	9.60436279	41.8737821	1172.674	0.076	0.058	0.143
242	9.60830438	41.8285619	1166.875	0.076	0.027	0.054
247	9.61060683	41.8332886	1159.444	0.076	0.027	0.055
249	9.60326103	41.8214089	1182.626	0.076	0.027	0.055
250	9.5948883	41.8409455	1190.982	0.017	0.015	0.033
253	9.60299344	41.8421329	1179.654	0.059	0.056	0.171
254	9.60232507	41.8434685	1180.973	0.022	0.025	0.055
256	9.60030599	41.8578355	1183.392	0.014	0.012	0.037
257	9.6004123	41.8362182	1186.621	0.017	0.019	0.038
259	9.59671139	41.8559228	1186.109	0.022	0.018	0.054
260	9.59460353	41.8559103	1193.279	0.027	0.023	0.054
267	9.59100905	41.8789875	1215.972	0.018	0.016	0.035
269	9.58970421	41.8746015	1214.453	0.015	0.016	0.036
271	9.58393904	41.8572523	1218.804	0.015	0.01	0.028
272	9.60645673	41.8809716	1181.915	0.018	0.015	0.034
273	9.60573828	41.8814531	1183.259	0.014	0.01	0.031
274	9.60074907	41.8774198	1175.508	0.025	0.015	0.052
275	9.59913582	41.877903	1185.796	0.014	0.013	0.032
278	9.59585104	41.8711695	1189.956	0.038	0.045	0.092
280	9.61556747	41.8474197	1144.132	0.013	0.011	0.029
281	9.584227	41.8541112	1208.107	0.035	0.034	0.081
283	9.58438298	41.8527778	1202.784	0.022	0.014	0.039
288	9.60125862	41.8493418	1168.067	0.014	0.014	0.033
291	9.58041172	41.8656196	1234.027	0.046	0.067	0.128
294	9.57920613	41.8721061	1258.216	0.019	0.015	0.043
295	9.57987567	41.873482	1262.745	0.012	0.011	0.028
296	9.6118823	41.8422042	1151.263	0.019	0.015	0.039
297	9.61051449	41.8422472	1155.175	0.024	0.019	0.051

301	9.59647797	41.8402452	1190.373	0.02	0.019	0.046
302	9.59576906	41.8379724	1191.902	0.02	0.02	0.041
BM27O	9.58401052	41.8591552	1221.244	0.019	0.014	0.039
BM232	9.59743161	41.8406345	1189.996	0.014	0.013	0.032
BM234	9.60949542	41.8434981	1159.976	0.035	0.039	0.064
BM244	9.60577538	41.8521909	1168.061	0.017	0.016	0.047
BM248	9.60436292	41.8217185	1180.589	0.076	0.027	0.056
BM258	9.60121905	41.8334697	1184.225	0.012	0.011	0.034
BM299	9.58217668	41.8742735	1243.919	0.021	0.02	0.057
BM300	9.58233262	41.8732628	1240.683	0.047	0.043	0.105
BM308	9.6138248	41.8476394	1148.422	0.012	0.011	0.031
BM 282	9.58993958	41.8521288	1193.901	0.025	0.024	0.05
BUBA D6	9.60890864	41.8218685	1168.123	0	0	0.028
Base1	9.62489134	41.8434053	1120.893	0	0	0.131
Base268	9.59114344	41.8745942	1211.306	0.081	0.037	0.102
Base DDU D3	9.62489134	41.8434053	1120.081	0	0	0.025
Base DDU D4	9.62489134	41.8434053	1120.083	0	0	0.027
Base LGDON	9.59811844	41.8888117	1203.844	0	0	0.023
Base LGDON1	9.59811844	41.8888117	1203.829	0	0	0.039
DD1Base1	9.58894654	41.8628818	1210.827	0.023	0.017	0.046
DD2Base1	9.5808992	41.8680954	1237.622	0.016	0.015	0.039
DD5226	9.58150034	41.8617025	1224.556	0.033	0.044	0.092
DIREDU	9.62489134	41.8434053	1120.131	0	0	0.032
DIREDU1	9.62489134	41.8434053	1120.077	0	0	0.027

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Project Summary

Adjustment

Project name: DIRE DAWA DATA2

Created by:

Linear unit: Meters

Angular unit: DMS

Projection: UTMNorth-Zone_37 : 36E to 42E

Datum: WGS84

Time Zone: (UTC+03:00)

Control Tie Analysis: Success

Adjusted Subnetworks Count: (Horz+Vert):9

Subnetwork Base1, DDA, 328, ... (Horizontal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	6	2 + 1	0 + 0	9

Subnetwork 390, Base DDA, BM 388, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	4	1 + 1	0 + 0	6

Subnetwork DD3Base1, DDA2, Base3, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	4	1 + 1	0 + 0	6

Subnetwork 369, ABDI2, BM 371, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	4	1 + 1	0 + 0	5

Subnetwork 346, 347, BM 372, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	4	1 + 1	0 + 0	6

Subnetwork DDA4, EBSA BM3, ER 7TH, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	4	1 + 1	0 + 0	5

Subnetwork 368, ABDI, BM 370 (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)

	Points	Points	Points	GPS
HORZ + VERT	3	1 + 1	0 + 0	2

Subnetwork 361, BM365, GCP 367 (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	3	1 + 1	0 + 0	3

Subnetwork 339, DDA3 (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	2	1 + 1	0 + 0	1

Control Points			
Name	**WGS84 Latitude**	**WGS84 Longitude**	**WGS84 Ell.Height (m)**
368	9.5874522	41.86355349	1208.658
369	9.58729165	41.86503616	1208.53
Base1	9.60345347	41.84032864	1184.777
Base DDA	9.60158817	41.86193371	1196.396
DDA	9.60158817	41.86193371	1196.396
DDA2	9.60158817	41.86193371	1196.396
DDA3	9.60158817	41.86193371	1196.396
DDA4	9.60158817	41.86193371	1196.396
GCP 367	9.59167726	41.86032922	1198.985
GCP 379	9.59778864	41.875917	1183.571

GPS Observations										
Name	**dN (m)**	**dE (m)**	**dHt (m)**	**Horz RMS (m)**	**Vert RMS (m)**	**Solution Type**	**PDOP**	**HDOP**	**VDOP**	**Orbit**
328–Base1	-516.476	-243.926	22.41	0.006	0.01	Fixed	2.553	1.368	2.155	Broadcast
328–DDA	-703.231	2131.22	34.029	0.011	0.019	Fixed	2.553	1.368	2.155	Broadcast
337A–Base1	571.643	-1289.829	8.885	0.008	0.015	Fixed	2.965	1.432	2.596	Broadcast
337A–DD6Base1	-17.965	-794.797	3.578	0.006	0.012	Fixed	2.967	1.433	2.599	Broadcast
339–DDA3	1304.25	442.976	-5.976	0.002	0.005	Fixed	2.289	1.171	1.966	Broadcast
346–347	65.494	-1320.408	-10.313	0.004	0.006	Fixed	2.016	0.943	1.781	Precise
346–BM 372	-37.337	-1161.326	-9.34	0.005	0.008	Fixed	2.073	1.008	1.811	Precise

346–GCP 379	496.87	-483.84	-13.896	0.009	0.01	Fixed	2.51	1.299	2.147	Precise
347–BM 372	-102.832	159.08	0.967	0.002	0.004	Fixed	1.826	0.852	1.615	Precise
347–GCP 379	431.375	836.557	-3.588	0.005	0.007	Fixed	2.273	1.182	1.941	Precise
361–BM365	-972.231	824.783	21.651	0.006	0.01	Fixed	1.921	0.976	1.654	Precise
361–GCP 367	-226.311	678.174	8.837	0.002	0.004	Fixed	1.812	0.862	1.594	Precise
368–ABDI	-563.224	8.67	8.834	0.006	0.006	Fixed	2.414	1.419	1.953	Precise
368–BM 370	-1064.598	687.569	42.764	0.012	0.017	Fixed	2.392	1.348	1.976	Precise
369–ABDI2	-600.252	-154.486	9.287	0.01	0.018	Fixed	2.159	0.975	1.927	Precise
369–BM 371	-854.561	463.46	24.128	0.017	0.027	Fixed	2.215	1.044	1.953	Precise
369–GCP 343	-726.906	514.383	24.842	0.009	0.017	Fixed	1.968	0.844	1.777	Precise
390–BM 388	474.413	1309.129	-11.7	0.002	0.003	Fixed	3.058	1.098	2.854	Broadcast
390–Base DDA	-1086.213	2918.295	47.615	0.002	0.003	Fixed	3.03	1.112	2.818	Broadcast
390–GCP 391	-541.6	730.858	18.759	0.001	0.003	Fixed	3.224	1.14	3.016	Broadcast
ABDI2–BM 371	-254.326	617.942	14.812	0.014	0.02	Fixed	2.351	1.125	2.064	Precise
ABDI2–GCP 343	-126.665	668.854	15.537	0.01	0.018	Fixed	1.967	0.876	1.762	Precise
BM365–GCP 367	745.924	-146.602	-12.811	0.006	0.009	Fixed	1.971	1.001	1.697	Precise
BM 372–GCP 379	534.203	677.467	-4.574	0.006	0.009	Fixed	2.195	1.055	1.924	Precise
BM 388–Base DDA	-1560.627	1609.164	59.315	0.001	0.003	Fixed	3.179	1.107	2.98	Broadcast
BM 388–GCP 391	-1016.01	-578.269	30.463	0.002	0.004	Fixed	3.468	1.148	3.273	Broadcast
Base1–Base2	-404.529	732.953	-13.574	0.002	0.003	Fixed	2.359	0.947	2.161	Broadcast
Base1–DD6Base1	-589.614	495.03	-5.319	0.002	0.005	Fixed	2.251	1.068	1.981	Broadcast
Base1–DDA	-186.754	2375.148	11.616	0.002	0.004	Fixed	2.372	0.994	2.154	Broadcast
Base2–DDA	217.78	1642.194	25.204	0.002	0.004	Fixed	2.183	0.91	1.984	Broadcast
Base3–DD3Base1	178.994	-62.649	-1.766	0.003	0.006	Fixed	3.169	1.194	2.935	Broadcast
Base3–DD7Base3	127.479	454.093	-1.141	0.002	0.003	Fixed	2.449	0.998	2.237	Broadcast
Base3–DDA2	932.254	2469.868	9.505	0.002	0.004	Fixed	2.432	0.992	2.22	Broadcast
Base DDA–GCP 391	544.615	-2187.431	-28.85	0.002	0.004	Fixed	3.495	1.164	3.296	Broadcast
DD3Base1–DD7Base3	-51.517	516.74	0.618	0.002	0.005	Fixed	3.173	1.198	2.939	Broadcast
DD3Base1–DDA2	753.259	2532.516	11.269	0.002	0.004	Fixed	3.098	1.182	2.864	Broadcast
DD6Base1–DDA	402.858	1880.117	16.914	0.004	0.009	Fixed	2.251	1.068	1.981	Broadcast
DD7Base3–DDA2	804.775	2015.774	10.644	0.002	0.004	Fixed	2.238	0.966	2.019	Broadcast
DDA4–EBSA BM3	707.279	-2895.357	-42.698	0.019	0.021	Fixed	3.075	1.276	2.798	Broadcast
DDA4–GCP 000	1335.223	-2990.038	-50.485	0.008	0.01	Fixed	2.486	1.137	2.211	Broadcast
EBSA BM3–ER 7TH	211.49	-66.794	-2.199	0.012	0.018	Fixed	3	1.286	2.711	Broadcast
EBSA BM3–GCP 000	627.952	-94.679	-7.805	0.026	0.024	Fixed	3.966	1.905	3.479	Broadcast
ER 7TH–GCP 000	416.462	-27.881	-5.613	0.009	0.012	Fixed	2.92	1.352	2.588	Broadcast

Adjusted Points

Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)	Std Dev e (m)	Std Dev n (m)	Std Dev u (m)
328	9.60810085	41.8425879	1162.367	0.005	0.004	0.01
337A	9.59819285	41.85202582	1175.889	0.004	0.004	0.011
339	9.58983962	41.85780289	1202.372	0.002	0.002	0.006
346	9.59326364	41.88028304	1197.473	0.003	0.002	0.005
347	9.59395508	41.86826992	1187.162	0.003	0.001	0.004
361	9.59377259	41.85417365	1190.148	0.001	0.001	0.003
390	9.61161944	41.8354524	1148.783	0.001	0.001	0.002
ABDI	9.58236371	41.8635897	1217.492	0.005	0.003	0.006
ABDI2	9.581881	41.86358461	1217.827	0.004	0.004	0.01
BM365	9.58492799	41.86160707	1211.796	0.003	0.002	0.005
BM 370	9.57778348	41.8697307	1251.422	0.01	0.006	0.017
BM 371	9.57953708	41.86918954	1232.646	0.007	0.006	0.013
BM 372	9.59301417	41.86971004	1188.131	0.003	0.001	0.005
BM 388	9.61580706	41.84740472	1137.082	0.001	0.001	0.002
Base1	9.60345347	41.84032864	1184.777	0	0	0.003
Base2	9.59974424	41.84696968	1171.197	0.001	0.001	0.003
Base3	9.59335187	41.83938224	1186.891	0.001	0.001	0.001
DD3Base1	9.59497352	41.83882547	1185.128	0.001	0.001	0.001
DD6Base1	9.59809011	41.8447901	1179.465	0.002	0.002	0.005
DD7Base3	9.59446953	41.84352503	1185.75	0.001	0.001	0.001
EBSA BM3	9.60819452	41.83563262	1153.71	0.004	0.002	0.005
ER 7TH	9.61011002	41.83504052	1151.518	0.003	0.002	0.005
GCP 000	9.61387426	41.83481807	1145.908	0.002	0.001	0.003
GCP 343	9.58068645	41.86966267	1233.366	0.004	0.004	0.01
GCP 391	9.6066722	41.84206427	1167.543	0.001	0.001	0.002

TOPCON

Project Summary

Adjustment
Project name: DIRE DAWA DATA3
Created by: ABDI
Linear unit: Meters
Angular unit: DMS
Projection: UTMNorth-Zone_37 : 36E to 42E
Datum: WGS84
Time Zone: (UTC+03:00)

Control Tie Analysis:Success

Adjusted Subnetworks Count:

(Horz+Vert):4

Subnetwork DDBM4Base1, NEWOFFOICE, POINT, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	7	1 + 1	0 + 0	13

Subnetwork HIGH, SAY, ROVER, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	6	1 + 1	0 + 0	8

Subnetwork Base1, DDBMBase1, DDBM11Base1, ... (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	5	1 + 1	0 + 0	4

Subnetwork Base2, DDBM3Base1, G GURAGE (Horizontal Minimal Constraint + Vertical Minimal Constraint)

Type	Adjusted	Fixed	Weighted	Equations (Used/Rejected)
	Points	Points	Points	GPS
HORZ + VERT	3	1 + 1	0 + 0	2

Control Points			
Name	**WGS84 Latitude**	**WGS84 Longitude**	**WGS84 Ell.Height (m)**
DDBM3Base1	9.58072962	41.858791	1235.378
DDBMBase1	9.60158783	41.8619	1193.166
DRBM	9.60336041	41.840283	1219.942
HIGH	9.58070811	41.858717	1230.996
NEWOFFICE	9.61287908	41.814444	1151.431
NEWOFFOICE	9.61290064	41.814501	1160.103
SABI	9.60348294	41.840259	1185.022

GPS Observations										
Name	**dN (m)**	**dE (m)**	**dHt (m)**	**Horz RMS (m)**	**Vert RMS (m)**	**Solution Type**	**PDOP**	**HDOP**	**VDOP**	**Orbit**
Base1–DDBMBa	356.237	-2952.522	-1.06	0.003	0.006	Fixed	2.116	1.416	2.775	Broadcast
Base1–GENDA	771.087	-1068.053	-22.56	0.012	0.022	Fixed	2.937	2.717	5.279	Broadcast
Base2–DDBM3Ba	-2455.635	-937.417	68.628	0.042	0.06	Fixed	3.093	2.817	4.243	Broadcast
Base3–DDBM2Ba	962.09	-1716.682	-2.208	0.004	0.008	Fixed	3.936	3.86	3.929	Broadcast
Base3–DDBM8Ba	452.803	1156.206	-1.909	0.01	0.014	Fixed	3.658	3.321	3.382	Broadcast
Base3–SAY	-263.53	2254.991	22.334	0.004	0.007	Fixed	2.526	2.928	2.314	Broadcast
DDBM2Bas–DDBM8Bas	-509.28	2872.9	0.313	0.004	0.006	Fixed	3.18	3.033	27.01	Broadcast
DDBM3Bas–G GURAGE	195.914	1584.645	-3.876	0.009	0.012	Fixed	0.091	2.369	4.507	Broadcast
DDBM4Bas–DDBM23Bas	1943.983	-6180.739	-74.22	0.009	0.015	Fixed	1.594	0.777	1.392	Precise
DDBM4Bas–DDBM24Bas	1897.844	-5901.061	-71.473	0.004	0.008	Fixed	1.816	0.792	1.635	Precise
DDBM4Bas–MAR2	1836.527	-2756.007	-59.591	0.005	0.008	Fixed	1.888	1.01	1.595	Precise
DDBM4Bas–NEWOFFOICE	1209.323	-5220.526	-34.076	0.002	0.004	Fixed	1.66	0.762	1.475	Precise
DDBM4Bas–P1	537.013	-3090.223	-36.635	0.007	0.01	Fixed	2.16	1.169	1.817	Precise
DDBM8Bas–SAY	-716.345	1098.773	24.247	0.031	0.05	Fixed	2.181	3.039	2.01	Broadcast
DDBM11Bas–DDBMBas	162.496	-648.179	19.948	0.008	0.016	Fixed	9.547	3.508	3.415	Broadcast
DDBM23Bas–MAR2	-107.456	3424.731	14.624	0.004	0.007	Fixed	1.931	1.036	1.629	Precise
DDBM23Bas–NEWOFFOICE	-734.659	960.215	40.144	0.006	0.011	Fixed	1.594	0.777	1.392	Precise
DDBM23Bas–P1	-1406.98	3090.526	37.549	0.011	0.015	Fixed	2.19	1.188	1.84	Precise
DDBM24Bas–NEWOFFOICE	-688.519	680.536	37.393	0.003	0.006	Fixed	1.816	0.792	1.634	Precise
DDBM24Bas–POINT	-1523.191	2735.334	45.419	0.005	0.009	Fixed	1.901	0.864	1.693	Precise
DDBMBas–LEGHARA	-1076.811	1577.472	8.026	0.039	0.032	Fixed	3.734	3.489	3.902	Broadcast
HIGH–ROVER	561.004	376.713	-27.506	0.018	0.025	Fixed	107.671	27.099	1.206	Broadcast
HIGH–SAY	1275.051	1922.514	-28.721	0.005	0.008	Fixed	3.335	1.819	3.934	Broadcast
MAR2–NEWOFFOICE	-627.206	-2464.516	25.517	0.005	0.007	Fixed	1.889	1.01	1.596	Precise
NEWOFFOICE–P1	-672.309	2130.303	-2.578	0.011	0.015	Fixed	2.16	1.169	1.817	Precise

NEWOFFOICE−POINT	-834.673	2054.8	8.036	0.005	0.008	Fixed	1.855	0.85	1.649	Precise
ROVER−SAY	714.047	1545.809	-1.206	0.016	0.023	Fixed	1.652	2.084	1.189	Broadcast

Adjusted Points						
Name	**WGS84 Latitude**	**WGS84 Longitude**	**WGS84 Ell.Height (m)**	**Std Dev e (m)**	**Std Dev n (m)**	**Std Dev u (m)**
Base1	9.59814642	41.888747	1194.225	0.003	0.002	0.006
Base2	9.60284186	41.86751	1166.75	0.034	0.024	0.06
Base3	9.59463182	41.855808	1179.942	0.003	0.003	0.007
DDBM2Bas	9.60345154	41.840255	1177.73	0.003	0.003	0.008
DDBM4Bas	9.60158587	41.86193	1194.178	0.001	0.001	0.002
DDBM8Bas	9.59863521	41.866366	1178.041	0.004	0.003	0.008
DDBM11Bas	9.60007107	41.867788	1173.218	0.006	0.006	0.016
DDBM23Bas	9.61960858	41.805815	1119.963	0.002	0.002	0.004
DDBM24Bas	9.61917104	41.808358	1122.709	0.001	0.001	0.003
G GURAGE	9.58238011	41.873229	1231.502	0.006	0.007	0.012
GENDA	9.60519292	41.879085	1171.665	0.01	0.007	0.023
LEGHARA	9.59174153	41.876177	1201.191	0.034	0.02	0.032
2-Mar	9.61838307	41.836982	1134.587	0.001	0.002	0.003
P1	9.60666868	41.833842	1157.531	0.003	0.002	0.005
POINT	9.6052076	41.833143	1168.134	0.001	0.002	0.004
ROVER	9.58574761	41.862189	1203.485	0.005	0.005	0.01
SAY	9.59208128	41.876312	1202.276	0.002	0.002	0.005

Appendix B

Geoid height (N) and Orthometric (H) Calculated from GPS measured WGS84 Ellipsoidal height (h) for Dire Dawa GPS data.

Name	Latitude	Longitude	Ell.Height (h)	Geoid Height(N)	Ortho.Height (H)
223	9.58833454	41.85666564	1214.248	-13.03	1227.278
224	9.58317292	41.8614294	1221.512	-13.03	1234.542
226	9.60026342	41.87344578	1184.832	-13.07	1197.902
232	9.60399285	41.84690304	1181.054	-13.04	1194.094
242	9.60830438	41.82856194	1166.875	-13.03	1179.905
247	9.61060683	41.83328861	1159.443	-13.04	1172.483
249	9.60326103	41.82140891	1182.624	-13.02	1195.644
250	9.59488831	41.84094548	1190.986	-13.02	1204.006
253	9.6029934	41.84213292	1183.124	-13.04	1196.164
254	9.6023251	41.84346854	1184.448	-13.04	1197.488
256	9.60030601	41.85783549	1186.861	-13.05	1199.911
257	9.60041231	41.8362182	1190.088	-13.03	1203.118
260	9.59460355	41.8559103	1196.741	-13.04	1209.781
264	9.6025232	41.87433495	1179.71	-13.07	1192.78
267	9.59100906	41.87898746	1215.972	-13.06	1229.032
269	9.58970418	41.87460144	1214.453	-13.06	1227.513
271	9.58393906	41.8572523	1222.273	-13.03	1235.303
272	9.60645673	41.88097162	1181.916	-13.08	1194.996
273	9.60573828	41.8814531	1183.259	-13.08	1196.339
274	9.60074907	41.87741978	1175.535	-13.07	1188.605
275	9.5991358	41.877903	1185.794	-13.07	1198.864
278	9.59585103	41.87116952	1193.44	-13.06	1206.5
280	9.61556747	41.84741965	1147.616	-13.06	1160.676
281	9.58422703	41.8541112	1211.568	-13.02	1224.588
283	9.58438299	41.85277783	1206.251	-13.02	1219.271
288	9.60125863	41.84934176	1171.545	-13.04	1184.585
291	9.58041175	41.86561964	1237.515	-13.03	1250.545
292	9.58083138	41.86740497	1240.898	-13.04	1253.938
294	9.57920616	41.87210613	1261.698	-13.04	1274.738
296	9.61188229	41.84220423	1154.745	-13.05	1167.795
297	9.61051449	41.84224717	1158.658	-13.05	1171.708
302	9.59576907	41.83797243	1195.371	-13.02	1208.391
BM27O	9.58401054	41.85915519	1224.715	-13.03	1237.745
BM232	9.59743162	41.84063455	1193.464	-13.03	1206.494
BM234	9.60949542	41.84349813	1159.98	-13.05	1173.03
BM248	9.60436293	41.82171846	1180.587	-13.02	1193.607
BM258	9.60121906	41.83346966	1187.69	-13.03	1200.72
BM299	9.58217668	41.87427349	1243.944	-13.05	1256.994
BM300	9.58233266	41.87326283	1244.16	-13.04	1257.2
BM308	9.61382479	41.84763939	1151.907	-13.06	1164.967
BUBA D6	9.60890864	41.82186846	1171.606	-13.03	1184.636
Base268	9.59114346	41.87459416	1214.784	-13.06	1227.844
DD1Base1	9.58894657	41.86288177	1214.289	-13.04	1227.329

DD2Base1	9.58089922	41.86809543	1241.102	-13.04	1254.142
DD5226	9.58150037	41.8617025	1228.037	-13.03	1241.067
315	9.58792956	41.85483919	1197.491	-13.03	1210.521
316	9.58136154	41.86559998	1222.057	-13.03	1235.087
318	9.60264936	41.84649266	1172.498	-13.04	1185.538
320	9.61846008	41.83434966	1136.7	-13.05	1149.75
321	9.6170828	41.8349557	1140.422	-13.05	1153.472
328	9.60809298	41.84259108	1162.375	-13.05	1175.425
337A	9.59818501	41.85202903	1175.905	-13.04	1188.945
337B	9.599272	41.85124083	1173.191	-13.04	1186.231
339	9.58983146	41.85780128	1199.478	-13.04	1212.518
340	9.59041561	41.85534743	1195.855	-13.03	1208.885
346	9.5932637	41.88028322	1197.499	-13.07	1210.569
347	9.59395514	41.8682701	1187.189	-13.05	1200.239
348	9.59171653	41.86728599	1193.793	-13.05	1206.843
352A	9.60396685	41.87762456	1172.533	-13.08	1185.613
353	9.58519341	41.85025956	1202.73	-13.02	1215.75
354	9.59043149	41.85107422	1180.738	-13.03	1193.768
355	9.58901294	41.8490942	1192.613	-13.03	1205.643
359	9.60322252	41.84471484	1173.16	-13.04	1186.2
361	9.59377273	41.85417161	1190.225	-13.04	1203.265
366	9.58572792	41.86226297	1210.541	-13.04	1223.581
368	9.58745237	41.86355382	1208.702	-13.04	1221.742
369	9.5872919	41.86503637	1208.572	-13.04	1221.612
372	9.60346415	41.87126642	1170.719	-13.07	1183.789
373	9.60882312	41.87548582	1158.545	-13.08	1171.625
376	9.60339111	41.8704012	1169.35	-13.07	1182.42
381	9.60297201	41.87708217	1169.66	-13.08	1182.74
382	9.6173917	41.86400229	1137.464	-13.08	1150.544
383	9.61536245	41.86438044	1141.817	-13.08	1154.897
387	9.61387082	41.835527	1146.053	-13.05	1159.103
390	9.61161452	41.83545684	1149.649	-13.04	1162.689
393	9.60251368	41.85715164	1173.343	-13.05	1186.393
394	9.60153602	41.85880871	1176.741	-13.05	1189.791
ABDI	9.58236391	41.86359008	1217.541	-13.03	1230.571
BM365	9.58492813	41.86160503	1211.875	-13.03	1224.905
BM 245	9.60608476	41.85108555	1164.086	-13.05	1177.136
BM 328	9.60821501	41.82655692	1162.15	-13.03	1175.18
BM 329	9.60920794	41.8271036	1159.042	-13.03	1172.072
BM 341	9.58450137	41.86206354	1212.898	-13.03	1225.928
BM 349	9.59454424	41.87167258	1184.551	-13.06	1197.611
BM 356	9.58745729	41.84940392	1195.678	-13.02	1208.698
BM 360	9.59355038	41.85479536	1187.537	-13.04	1200.577
BM 370	9.57778356	41.86973087	1251.424	-13.03	1264.454
BM 371	9.57953733	41.86918976	1232.688	-13.04	1245.728
BM 372	9.59301422	41.86971022	1188.159	-13.05	1201.209
BM 377	9.60533434	41.87228687	1167.017	-13.07	1180.087
BM 378	9.60684472	41.87200787	1162.193	-13.08	1175.273
BM 384	9.60853601	41.83437924	1153.848	-13.04	1166.888
BM 385	9.62567124	41.86193233	1122.725	-13.09	1135.815

BM 388	9.61580213	41.84740916	1137.947	-13.06	1151.007
Base1	9.6034456	41.84033183	1184.786	-13.04	1197.826
Base2	9.59973638	41.84697287	1171.208	-13.04	1184.248
Base3	9.59333702	41.83937992	1189.647	-13.02	1202.667
Base DDA	9.60158325	41.86193815	1197.262	-13.06	1210.322
DD1Base1	9.5962708	41.84153114	1185.561	-13.03	1198.591
DD2Base1	9.60449579	41.84502745	1171.675	-13.04	1184.715
DD3Base1	9.59495866	41.83882316	1187.883	-13.02	1200.903
DD5Base1	9.59047331	41.87742768	1203.798	-13.06	1216.858
DD6Base1	9.59808225	41.84479329	1179.476	-13.03	1192.506
DD7Base3	9.59445467	41.84352272	1188.506	-13.03	1201.536
DDA2	9.60157331	41.86193139	1199.151	-13.06	1212.211
DDA3	9.60158002	41.86193211	1193.496	-13.06	1206.556
EBSA BM3	9.60818906	41.83563106	1153.785	-13.04	1166.825
ER 7TH	9.61010458	41.835039	1151.584	-13.04	1164.624
GCP 000	9.61386879	41.83481652	1145.984	-13.05	1159.034
GCP 314	9.58678479	41.8533287	1194.119	-13.03	1207.149
GCP 317	9.58190679	41.86570982	1221.775	-13.03	1234.805
GCP 319	9.61861792	41.84356399	1132.859	-13.06	1145.919
GCP 338	9.59301077	41.85927595	1191.153	-13.04	1204.193
GCP 342	9.58069843	41.8704759	1237.414	-13.04	1250.454
GCP 343	9.58068669	41.86966288	1233.411	-13.04	1246.451
GCP 350	9.6082648	41.87788799	1168.553	-13.08	1181.633
GCP 352	9.60603243	41.87641493	1168.989	-13.08	1182.069
GCP 364	9.61848687	41.84665541	1130.649	-13.07	1143.719
GCP 367	9.5916774	41.86032718	1199.062	-13.04	1212.102
GCP 374	9.60793726	41.87665532	1162.824	-13.08	1175.904
GCP 379	9.59778869	41.87591718	1183.597	-13.07	1196.667
GCP 380	9.59995499	41.87525283	1180.507	-13.07	1193.577
GCP 386	9.62887482	41.86125112	1114.391	-13.09	1127.481
GCP 391	9.60666727	41.8420687	1168.409	-13.04	1181.449
GCP 445	9.59269053	41.87913233	1198.547	-13.06	1211.607
KEBLE 02 DAY1 S3	9.60344803	41.84032704	1184.886	-13.04	1197.926
GCP1	9.60794293	41.8506595	1163.659	-13.05	1176.709
BRIDGE	9.60288197	41.85015979	1167.893	-13.05	1180.943
Base1 MEKELAKEYA	9.59840774	41.85631802	1184.477	-13.05	1197.527
Base2	9.60284748	41.86752753	1166.04	-13.06	1179.1
Base3	9.59463184	41.85580772	1179.935	-13.04	1192.975
Base174	9.60796059	41.85069997	1172.318	-13.05	1185.368
DDBM1Bas	9.60161765	41.86186379	1196.578	-13.06	1209.638
DDBM2Bas	9.60345158	41.8402548	1177.718	-13.04	1190.758
DDBM4Bas	9.60158586	41.86192973	1194.178	-13.06	1207.238
DDBM5Bas	9.60156423	41.86187303	1185.526	-13.06	1198.586
DDBM7Bas	9.60084867	41.84508859	1153.691	-13.04	1166.731
DDBM8Bas	9.59863525	41.86636596	1178.03	-13.06	1191.09
DDBM11Bas	9.6000711	41.86778788	1173.219	-13.06	1186.279
DDBM18Bas	9.60446287	41.84643231	1171.725	-13.04	1184.765
DDBM19Bas	9.59839017	41.85627746	1175.862	-13.05	1188.912
DDBM20Bas	9.58138461	41.85498291	1214.564	-13.02	1227.584
DDBM21Bas	9.60230862	41.84342676	1151.978	-13.04	1165.018

DDBM23Bas	9.61960858	41.80581515	1119.963	-13.03	1132.993
DDBM24Bas	9.61917104	41.80835763	1122.708	-13.03	1135.738
DDBM25Bas	9.60353571	41.83381514	1164.671	-13.03	1177.701
G GURAGE	9.58238011	41.87322877	1231.501	-13.04	1244.541
GENDA	9.60519291	41.87908467	1171.668	-13.08	1184.748
GG	9.58384287	41.85726944	1218.794	-13.03	1231.824
JERBA1	9.60131035	41.8269334	1164.885	-13.02	1177.905
LEGHARA	9.59173154	41.8761777	1199.89	-13.06	1212.95
GCP MAR2	9.61838307	41.83698217	1134.587	-13.06	1147.647
N−ONE	9.59967833	41.86609479	1177.671	-13.06	1190.731
P1	9.60666868	41.83384214	1157.526	-13.03	1170.556
POINT	9.6052076	41.83314263	1168.132	-13.03	1181.162
ROVER	9.58574761	41.86218859	1203.485	-13.04	1216.525
SAY	9.59208129	41.87631237	1202.275	-13.06	1215.335
SHELL	9.58391171	41.85916683	1221.434	-13.03	1234.464
320_LHRE	9.59822201	41.85195574	1177.843	-13.04	1190.883
321_LHRE	9.58516999	41.85210815	1202.26	-13.02	1215.28
321G_LHRE	9.59974831	41.83760043	1160.199	-13.03	1173.229
321C_LHRE	9.59041951	41.85527787	1193.405	-13.03	1206.435
322D_LHRE	9.58746841	41.86347471	1203.288	-13.04	1216.328
322E_LHRE	9.5939756	41.86827545	1188.115	-13.05	1201.165
132G_LHRE	9.62050558	41.77305976	1114.624	-13	1127.624
326_LHRE	9.61769881	41.77365051	1119.761	-12.99	1132.751
327_LHRE	9.60178637	41.83827712	1170.298	-13.03	1183.328

Appendix C

Maps and Image results from DEM Vertical Accuracy Assessment

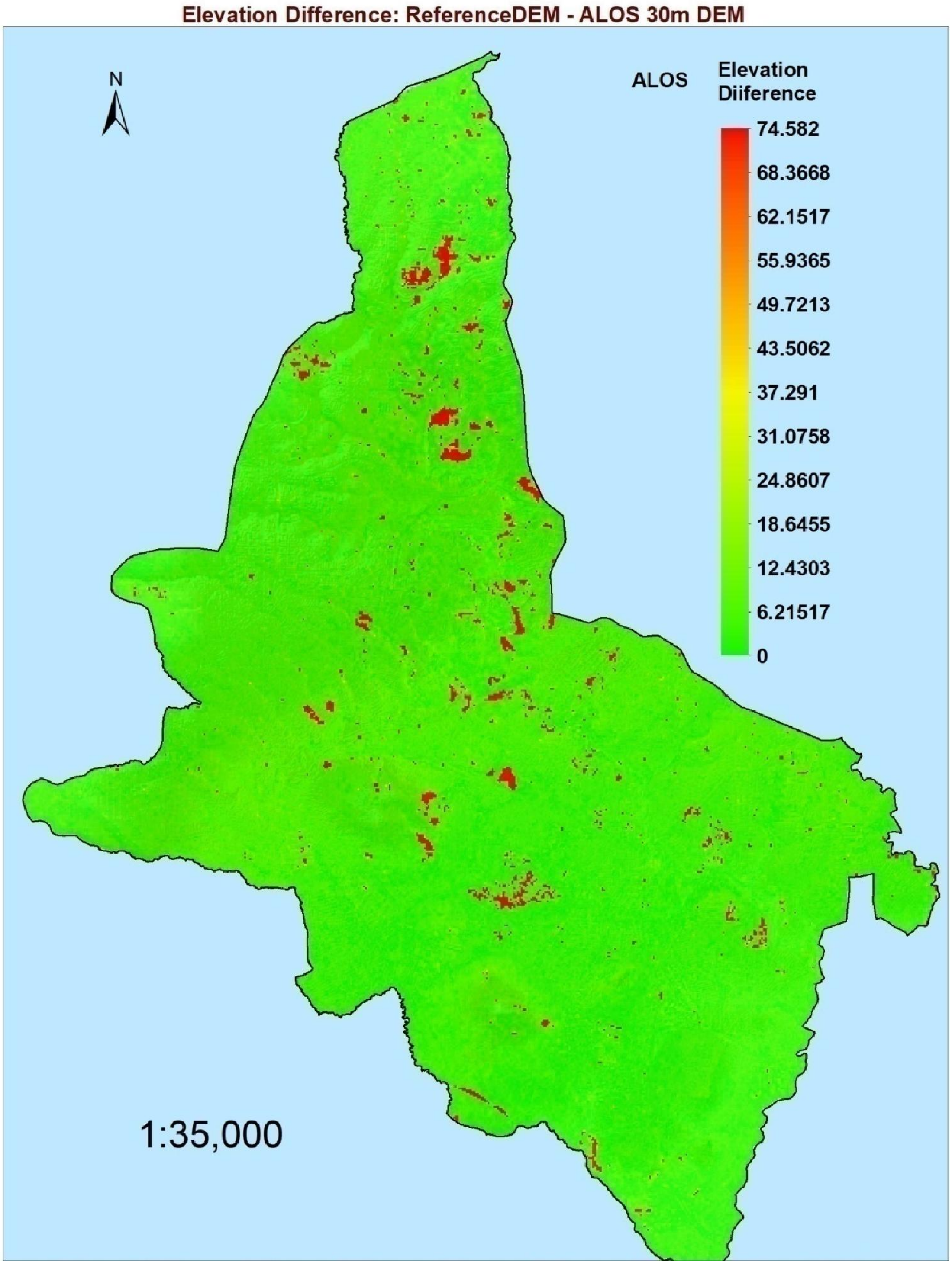

Figure1. ALOS DEM elevation differences with reference surface DEM in Addis Ababa (absolute value)

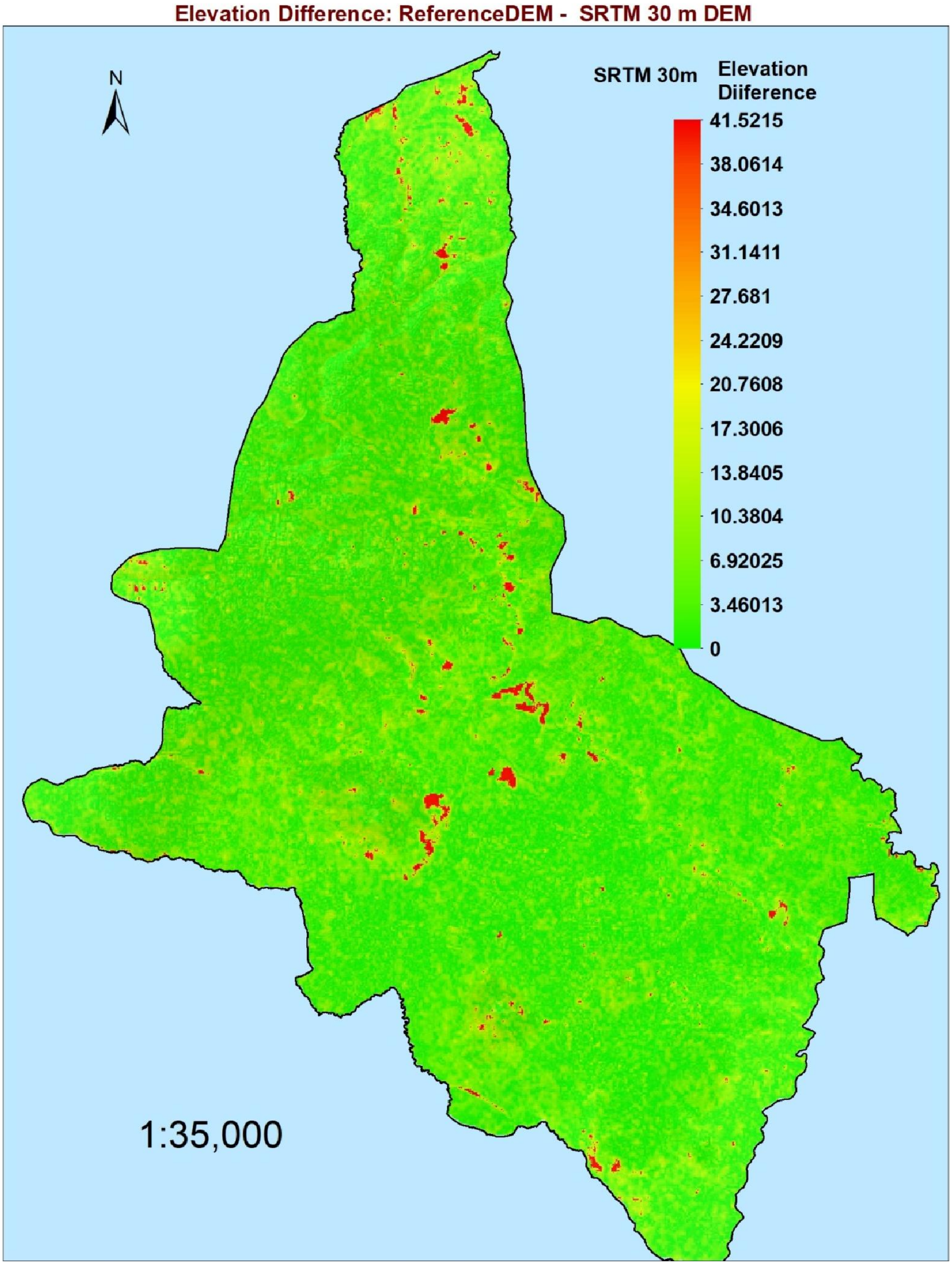

Figure 2: SRTM DEM elevation differences with reference surfac in Addis Ababa (absolute value)

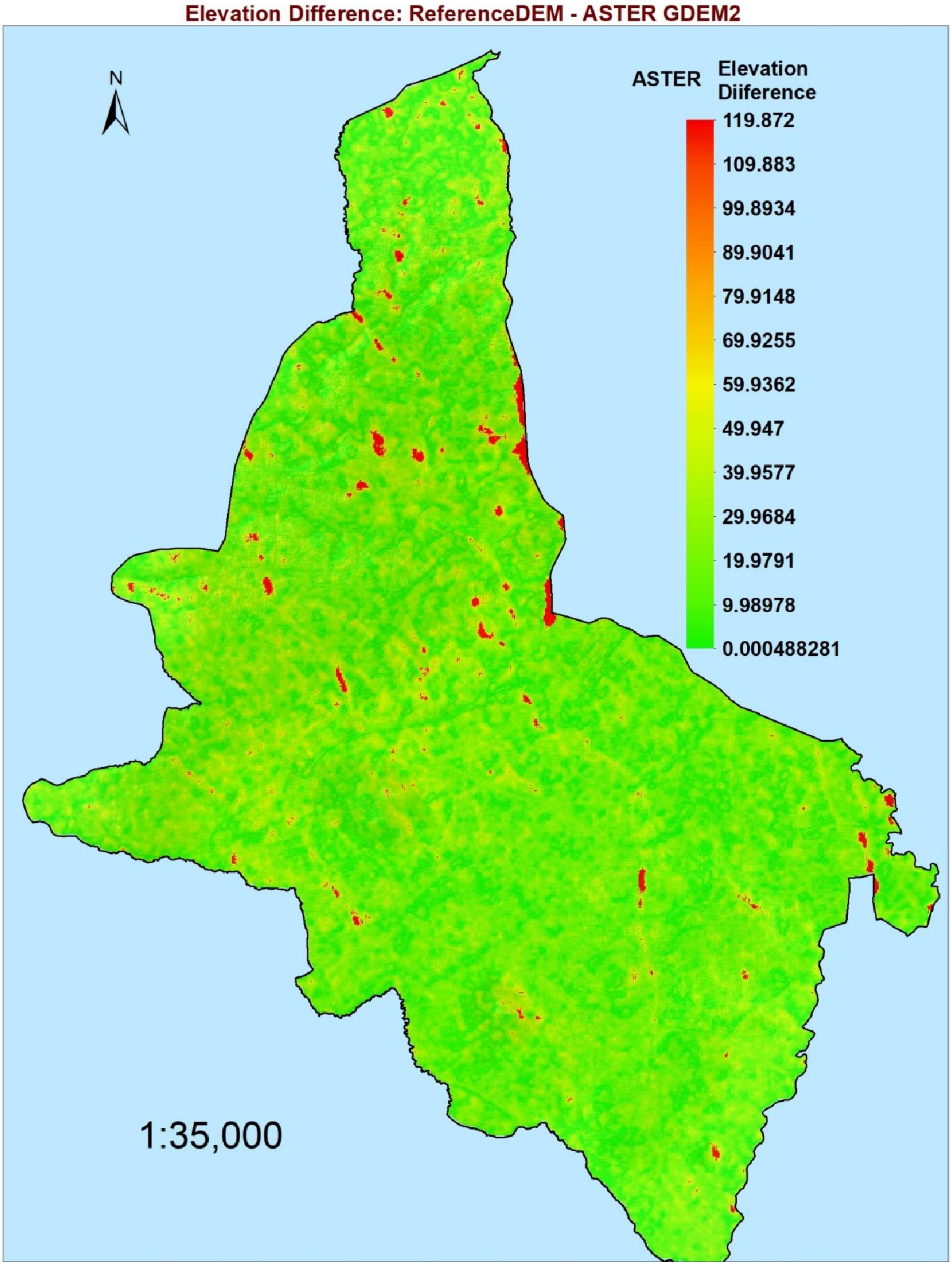

Figure 3: ASTER DEM elevation differences with reference surface in Addis Ababa (absolute value)

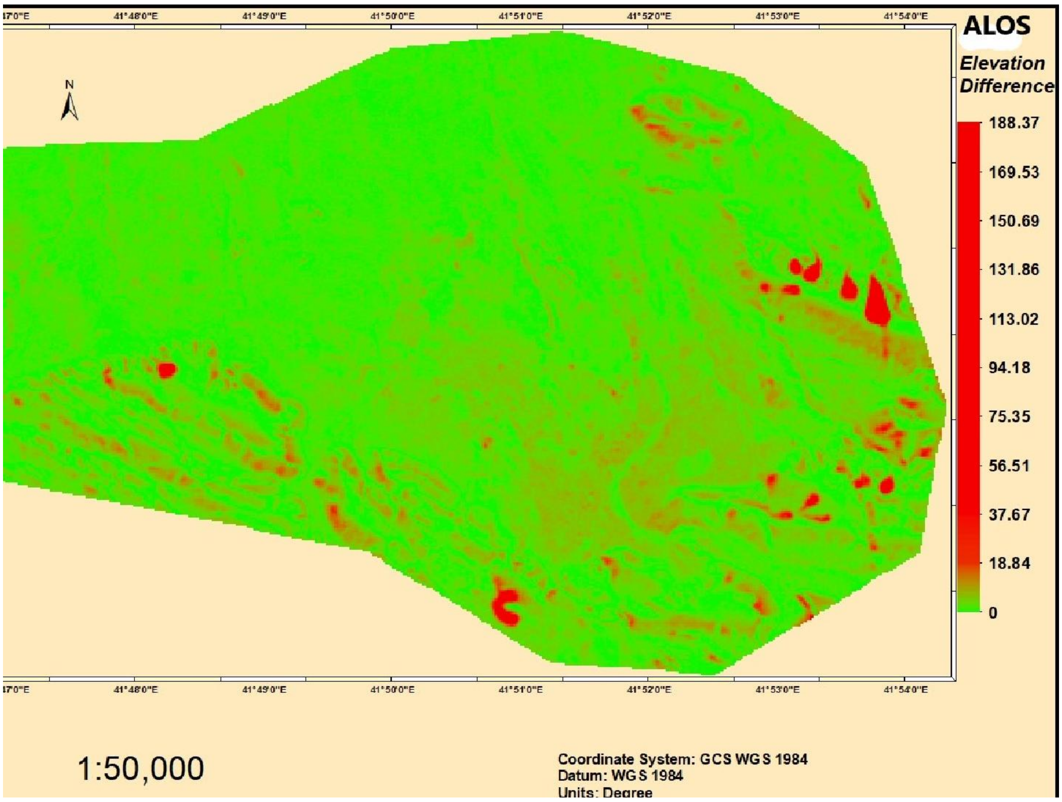

Figure 4: ALOS DEM elevation differences with reference surface in Dire Dawa (absolute value)

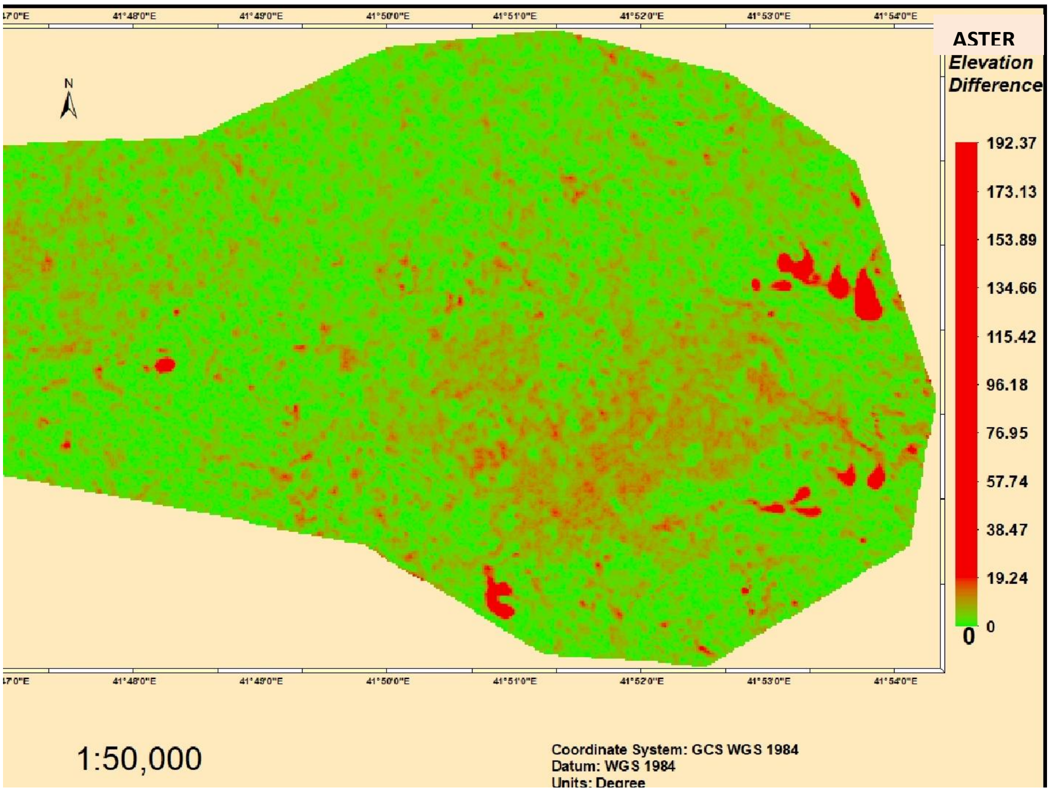

Figure 5: ASTER DEM elevation differences with reference surface in Dire Dawa (absolute value)

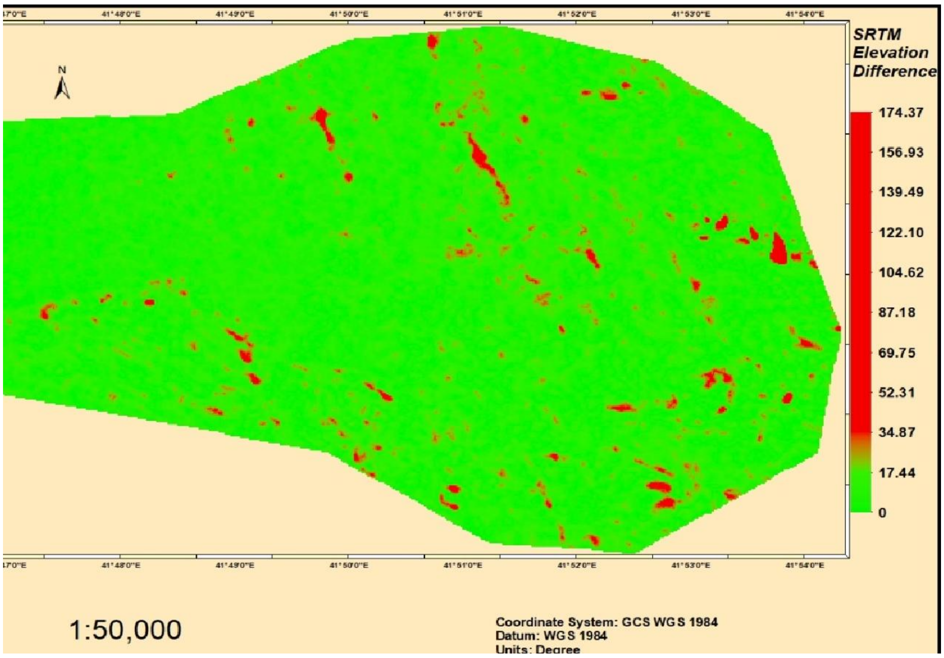

Figure 6: SRTM DEM elevation differences with reference surface in Dire Dawa (absolute value)

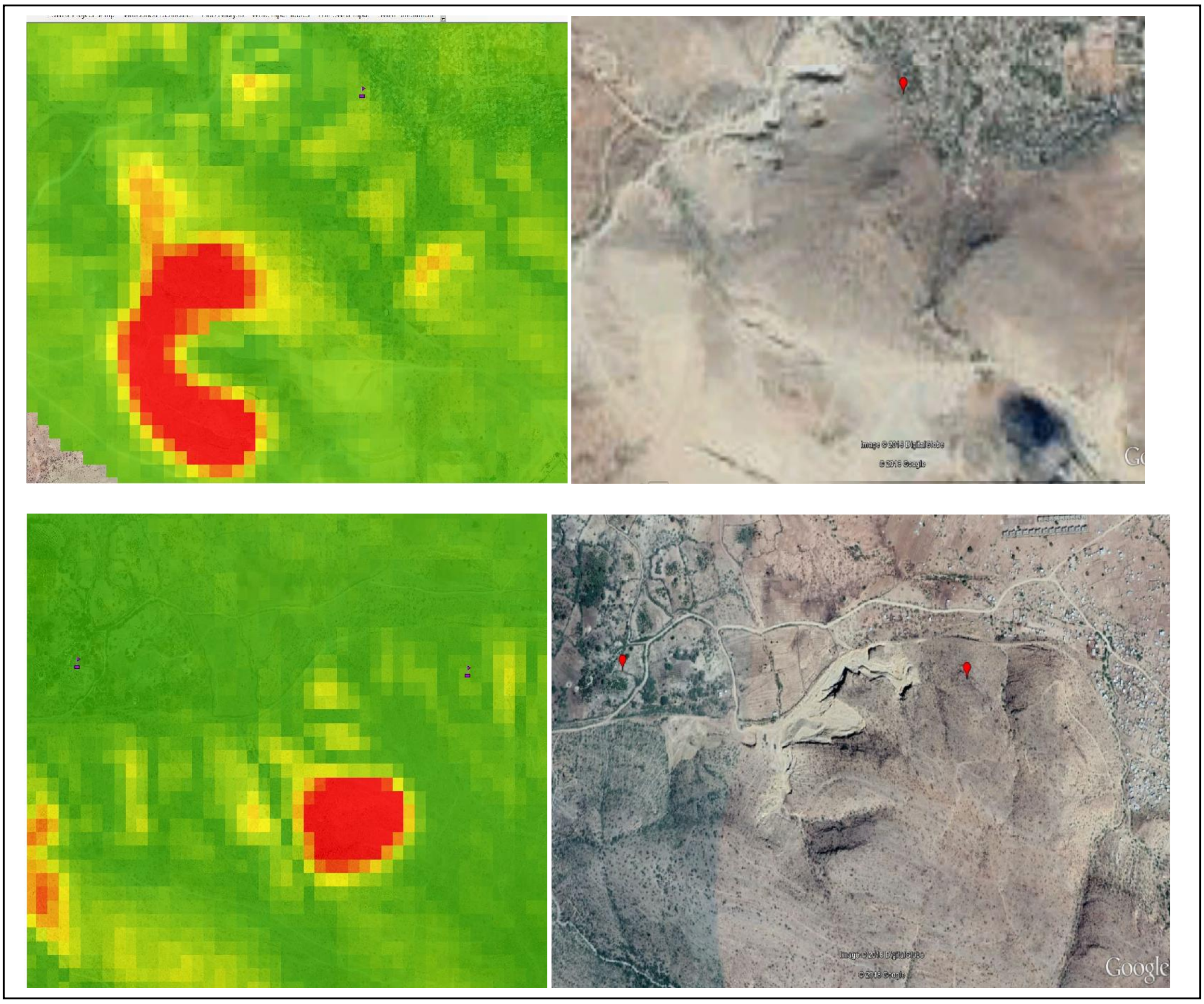

Figure 7: Locations of DEM extreme elevation differences on Google Earth image and DEM error map

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