Accuracy Assessment of DEMs Using Modern Geoinformatic Methods

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Abstract

Digital Elevation Models (DEMs), which can come in the form of digital surface models or digital terrain models, are key tools in land analyses and other purposes. Classical methods such as field surveying and photogrammetry can yield high-accuracy terrain data, but they are time consuming and labor-intensive. Nowadays, different modernistic height-finding methods have emerged, including Global Positioning System (GPS) and airborne methods. In contrast to the airborne ways that are suited to gain highly precise, fine-resolution DEMs at a local scale. The airborne ways are complementary to their space-borne matches, such as Light Detection and Ranging (LiDAR), Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer- Global Digital Elevation Model (ASTER GDEM) and Advanced Land Observing Satellite (ALOS). LiDAR data acquisition has become the standard approach for collecting point data to interpolate high-resolution ground and aboveground surface. In this study, we assessed elevation accuracy of three modern geoinformatic methods (STRM, ASTER GDEM and ALOS); by comparing standard deviations of elevation differences for these methods versus more than 6,000,000 points from LiDAR. From case study results, standard deviations of elevation differences between LiDAR points vs ASTER DEM equal 9.09 m, LiDAR points vs STRM DEM equal 5.28 m and LiDAR point's vs ALOS DEM equal 2.08 m, based on these results, ALOS DEM shows a good agreement with LiDAR data.

Keywords: DEMs, LiDAR, ASTER, SRTM, ALOS, Height Measurement, Vertical Accuracy.

1. INTRODUCTION

Current and accurate elevation data play an important role in studying the dynamics of the Earth's surface, such as volcanic flows, avalanches, landslides, rock falls, beach erosion and accretion, and glacier melting. Traditional methods to obtain surface height is determined using the levelling method, height differences between two points are determined by a theodolite or total station. These methods able to yield accurate height measurements, but these methods are very slow, especially over steep terrain or around tall buildings or trees where the view between the points is likely to be blocked [1].

Digital Elevation Model (DEM) is an introduction of persistent elevation values over a topographic surface by orderly array z-values, referenced to a common datum [2, 3]. Concurrently, it is a computer representation of the earth's surface [4]. The generation of DEMs can be achieved through three main methods [5, 6]: data from digitized topographic maps, field data "direct survey" (e.g. topographical survey by GPS or total station) and remote sensing (e.g. LiDAR, SRTM, ASTER or ALOS). Recently, surveying engineers considerably use remote sensing rather than classical methods to get DEMs. At present, DEMs data becomes one of important geographic data in topographic mapping and thematic mapping, and is used widely in layout and planning of city, construction of road and railway, selection of area for factory and mining, the navigation and so on.

LiDAR can be an exporter of data for generating accurate and directly georeferenced spatial information about the shape and surface characteristic of the earth. LiDAR is an instituted method for gathering very dense and precise elevation data across landscapes, shallow-water areas and project sites. It is a kind of an active remote sensing technicality, which is like to radar but uses laser light pulses instead of radio waves for capturing 3D point clouds of the earth surface [7]. In recent years, LiDAR has become the main data source for producing high-resolution digital elevation model (DEM) or digital terrain model (DTM) [8-12]. Typically, a spatial resolution of 1 meter or higher can be obtained from various sources for example high density airborne LiDAR and high-resolution aerial photogrammetry. Moreover, point's levels from LiDAR can have ±0.5 cm vertical and ±0.5 cm horizontal accuracy, and point densities typically between 0.5–50 points per square meter [13]. LiDAR points information are interpolated into a DEM, with typical spatial resolutions of <1 m. Interpolation methods can be classified according to the following criteria [14]: The compatibility between the interpolated elevations at the sampled points and the true elevations (exact and inexact interpolation methods), the spatial extent of the utilized sample for the estimation of the elevation at a given interpolation point (global and local interpolation methods) and the utilized terrain and data characteristics within the interpolation mechanism (stochastic and deterministic interpolation methods).

Many interpolation processes for DEM production, including deterministic ways such as Inverse Distance Weighted (IDW), geo-statistical ways such as Kriging, and polynomial-based processes such as Local Polynomial (LP). The diversity of obtainable interpolation processes has led to questions about which is most appropriate in different contexts and has stimulated several comparative studies of relative accuracy [15]. To assess the achievement of some ordinarily used interpolation methods, an assortment of empirical studies has been conducted to evaluate the effects of different methods of interpolation on DEM accuracy.

The typical way for the evaluation of the accuracy of a DEM produced by interpolation is to compare the generated DEM with a "true" terrain surface. These types of "true" terrain surfaces are not obtainable in practice. Using a DEM of comparatively higher accuracy as reference is an option, but access to such a DEM cannot be supposed when a new DEM- production project is being implemented [16]. Validation and cross-validation methods can be used to evaluate the accuracies of DEMs produced from different interpolation algorithms. For validation method, whole dataset is separated to training and test datasets. Test data are used as checkpoints while the training data are then used to generate DEMs with different interpolators. Differences between elevations of test data and corresponding elevations from DEMs are computed to evaluate the accuracies of DEMs [13]. In the current study, IDW will used to DEMs interpolation as [15] recommended.

In the 2003, public shot of the Shuttle Radar Topography Mission (SRTM) DEM which was leaded by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) of the United States [17] ushered in a new age of near-global digital topographic analysis [18, 19, 20]. SRTM has formed an unparalleled information set of global elevations that is freely obtainable for modeling and environmental applications [21]. The global availability of SRTM data supplies baseline data for many kinds of the worldwide research. With the 2009 appearance of the global digital elevation model dataset, which uses data gained by the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM (ASTER GDEM), by NASA and the Ministry of Economy, Trade and Industry (METI), Japan, and a second version was released in 2011 [22, 23].

A recent GDEM dataset using the information obtained by the Panchromatic Remote Sensing Instrument for Stereo Mapping (PRISM) onboard the Advanced Land Observing Satellite (ALOS, nicknamed "Daichi") was prefaced by the Japan Aerospace Exploration Agency (JAXA) in collaboration with commercial partners NTT DATA Corp. and Remote Sensing Technology

Centre of Japan. This project is named “ALOS World 3D”, and the dataset created consists of fine resolution DEM (0.15 arc sec approx. 5 m) and Ortho Rectified Image (ORI) of PRISM in global terrestrial area [24].

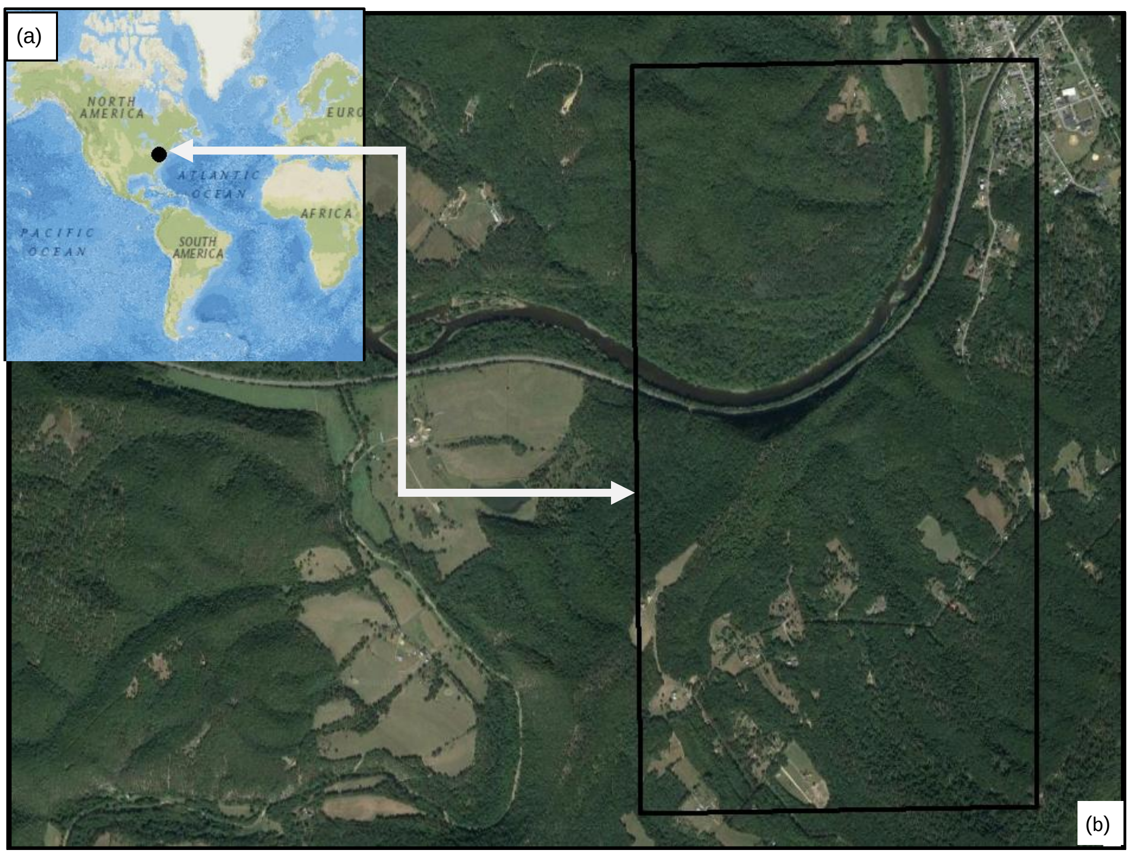
A DEM generation by the modern geoinformatic methods (ASTER, STRM and ALOS) can be found in a raster data format, which is an array of square cells (i.e., pixels) with a height estimate related with each pixel.

The main objective of this contribution is to evaluate the potential for DEMs from the most up-to-date and freely obtainable global digital elevation models (STRM, ASTER GDEM and ALOS), this objective was achieved by comparing these DEMs against the main data source for producing high-resolution digital elevation model (LiDAR).

2. STUDY AREA AND DATA DESCRIPTION

2.1 Study Area

The study area is in Morgan County, West Virginia, USA, (38° 55′ 12″ N, 80° 51′ 0″ W),, with an area of 1.5 km by 2.55 Km (two tiles, each tile’s extent is 1.5 km by 1.5 km with 30% average overlap), and the elevations in this area based on North American Datum (NAD) 1983 is ranging from 151 m to 400 m, the study area is view through Google Earth (Figure 1).



FUGURE 1: (a) Overview of the study area in Morgan County, West Virginia, USA.
(b) Focus on study area.

2.2 LiDAR Data

LiDAR data were collected for the Tug Notch project; this project was collected 19 Dec 2011 and is composed of 125 working segments, covering 63,846.64 acres. The major objective of this LiDAR data gathering was to facilitate more precise terrain pattern impersonation for the implementation of a series of environment related projects. LiDAR data was collected by the Optech ALTM-3100 100k Hz Multi-pulse LiDAR system mounted in a Piper Navajo PA-31.

The ALTM-3100 collects up to four returns per pulse, as well as backscatter reflectance (intensity) data. The data of LiDAR have been classified into ground and non-ground points by using data filter algorithms across the project area (in the present study we use more than 6000000 ground points, where point densities in the current study is 3.2 points per square meter). The data collected was flown back to the WVU NRAC office in Morgantown, WV, extra cited, viewed, and quality controlled such that immediate re-flights could be performed if necessary. Ground GPS data collected via two TOPCON HiPER GD dual-frequency, 12-channel geodetic quality receivers. The LiDAR dataset was tested to 0.1207m vertical accuracy at 95% confidence level based on consolidated RMS Ez (0.04m x 1.960) when compared to GPS static checkpoints. Locations occupied for collection either are registered National Geodetic Survey (NGS) control monuments, or created Online Positioning User's Service (NGS OPUS) control points [25].

2.3 SRTM Elevation Model

A DEM from SRTM 1 arc second database was taken away over the study area. SRTM digital elevation information sets are the common endeavor of NASA, NGA and the German Aerospace Center (DLR) and the Italian Space Agency (ASI). The SRTM elevations are based on interferometric evaluations of observations of the dual radar antennas (sensitive for C- and X-band) on board of the Shuttle Radar Topography Mission's spacecraft, which flew in February 2000 [17]. All landmass between 56 degrees south and 60 degrees north (that is around 80% of the Earth's total landmass) are covered by SRTM observations and are contained in SRTM DEMs [26, 27]. STRM quality has often been evaluated. Its performance has fundamentally consisted in the evaluation of its position accuracy founded on theoretical considerations concerning SAR interferometry capabilities and on ground control points [27].

The impact of resolution on accuracy and on the achievement of topographic derivations, are known [28]. In coarse resolution, elevation information are probable to produce reduced results in topographic derivations due to the larger horizontal distances applied in their calculations. The geometric expression of the pixel structure is also enhanced at coarse resolution, allowing the occurrence of unrealistic features in the DEM. These effects motivated the refinement of SRTM data from 3" to 1" by different authors using diverse techniques [29, 30]. These refinement techniques do not represent a real improvement on DEM resolution, but considered as a recommendable care to partially overcome resolution effects due to the lack of high resolution data.

2.4. ASTER-GDEM2 Elevation Model

The joint Japanese–US Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 was released in October 2011 (three years after its predecessor, version 1) by the Ministry of Economy, Trade and Industry (METI) of Japan together with the United States National Aeronautics and Space Administration (NASA). Since 2000 the Japanese ASTER instrument, payload on NASA's Terra satellite, acquires stereo image data with its two nadir- and backward viewing telescopes, which are sensitive in the near infrared spectral band. The Sensor Information Laboratory Corporation (SILC) has developed an automatic processing methodology for the generation of the GDEM from ASTER's a long track stereoscopic sensors measurements. The Terra spacecraft's near-polar orbit covers the Earth's land surfaces between ± 83 degree latitude and the nominal ground sampling distance is 15 m. The GDEM heights refer to the WGS84/EGM96 geoid and are provided as 1 x 1 degree tiles in Geo-TIFF format with geographic latitude/longitude coordinates sampled to a one arc second (approximately 30 m) grid. In total 22,600 tiles, each of 24.7 MB size (accounting for almost 560 GB in total) can be downloaded free of charge, e.g. at the Earth Remote Sensing Data Analysis Center (ERSDAC) of Japan [31].

In an epitomizing research by the joint Japan–US ASTER Science Team comprising a total of four separated effectiveness researches, the vertical accuracy of ASTER GDEM2 is evaluated to be around 17 m at a confidence interval of 95%. The main obstacle of ASTER is that it is an optical sensor and thus constant cloud cover over confirmed areas may drive to data gaps ("holes") or artefacts in the GDEM. Moreover, it is significant to recall that ASTER maps the surface of the Earth including all buildings and plant canopy, so heights do not reflect the bare ground where the ground is covered. When validated versus different height information sets, ASTER largely offered higher offsets in the canopy, exceeding even SRTM elevations in forested areas, and negative offsets were measured over low- or non-vegetated areas. Compared to version 1, the updates in the algorithm to generate version 2 lead to a finer horizontal resolution, a correct detection of water bodies as small as 1 km2, and the global adjustment of an elevation offset of –5 m [31, 32]. Over and above, two additional years of measurements are integrated in GDEM2, decreasing the information voids and artefacts in areas of scattered measurements. The information of STRM and ASTER GDEM2 were gained from [33].

2.5. ALOS Elevation Model

A new global DEM dataset was produced from the 2.5 m spatial resolution information obtained by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) onboard the ALOS. The AW3D project extended the DEM with a suitable resolution of 0.15 arc sec (approximate 5 m), which is presently the most accurate global-scale elevation. The primary version of the AW3D DEM was distributed to commercial bases by the NTT DATA and RESTEC in March 2016 [34]. In 2015, the Japan Aerospace Exploration Agency (JAXA) released a free-of-charge DSM named the AW3D– 30 m, which was a global DSM dataset with a horizontal resolution of approximately 30 m (1 arc sec). In fact, these data were a resampled version of the 5 m mesh version of the AW3D. A recent study performed by Takuku et al. reported a 3.28 m vertical RMSE worldwide and a 3.69 m vertical RMSE for Turkey [35]. Data of ALOS were obtained from [36]. Figure (2) shows that the 3D view of ground surface for DEMs generation by modern geoinformatic methods (LiDAR, ASTER, STRM GDEM and ALOS).

3. RESULTS AND DISCUSSION

In this study, Inverse Distance Weighted (IDW) was used to interpolate elevation for Lidar point from the STRM, ASTER, ALOS DEMs. IDW is an exact local deterministic interpolation technique, which is one of the most widely used methods for scattered data. IDW is an interpolation technique that estimates cell values from a set of weighted sample points with measurement values. As it is seen in the Eq. 1, the interpolated values of unsampled points are estimated as a function of sampled point values $u_i = u(x_i)$ and weights, $w_i(x)$ [32]. N denotes the total number of sampled points.

$$u(x) = \sum_{i=0}^{N} \frac{w_i(x)\, u_i}{\sum_{j=0}^{N} w_j(x)} \tag{1}$$

Weights are determined for each sampled point as a function of distance between known (x) and unknown (xi) points, d, and power parameter, p that is a positive real number (see Eq.2). The choice of amount for p is thus a function of the degree of smoothing desired in the interpolation, the density and distribution of samples being interpolated, and the maximum distance over which an individual sample is allowed to influence the surrounding ones. In this study, power number is considered as 2 in practice so applied methodology is abbreviated as IDW2. It is possible to imply that as the distance between sampled and unsampled point's increases, less weight is calculated for that point, so that this method assumes that each measured point has a local influence that diminishes with distance [37, 38].

$$w_i(x) = \frac{1}{d(x, x_i)^p} \tag{2}$$

In this research, ArcGIS 10.1 with the spatial analysis and the 3D analyst extensions will be used in creating the DEMs from the modern geoinformatic methods (see figure 2). To assess DEM vertical accuracy, we interpolated elevation of Lidar points from STRM, ASTER, and ALOS

DEMs. The interpolated points (6605109 points) are used. In the present study, we are interested in the mean and the Standard Deviation (SD) of statistics results. Figures (3, 4 and 5) ASTER, STRM and ALOS DEMs versus LiDAR height plotted histograms of uncertainty distribution were normalized by their respective mean offsets so the SD could be visually compared. From table 1, which shows statistics of the results, one can show that, the most convenient DEM with LiDAR data is the ALOS, which gives minimum absolute elevation difference between elevation from LiDAR, and the interpolated elevation from ALOS DEM reaches to 15.4 m. In addition, gives maximum absolute elevation difference between elevation from LiDAR and the interpolated elevation from ALOS DEM reaches to 19.9 m, and mean elevation difference is 62 cm, finally ALOS offers the smallest standard deviation 2.08 m.

Criteria	ASTER vs Lidar	STRM vs Lidar	ALOS vs Lidar
Number of interpolated points	6605109	6605109	6605109
Min. difference (m)	- 51.547	- 30.003	- 19.914
Max. difference (m)	72.851	30.678	15.399
Mean difference (m)	9.454	4.43	-0.626
Standard deviation (m)	9.09	5.28	2.082

TABLE 1: statistics of interpolated elevations for LiDAR points from ASTER, STRM, and ALOS DEMs.

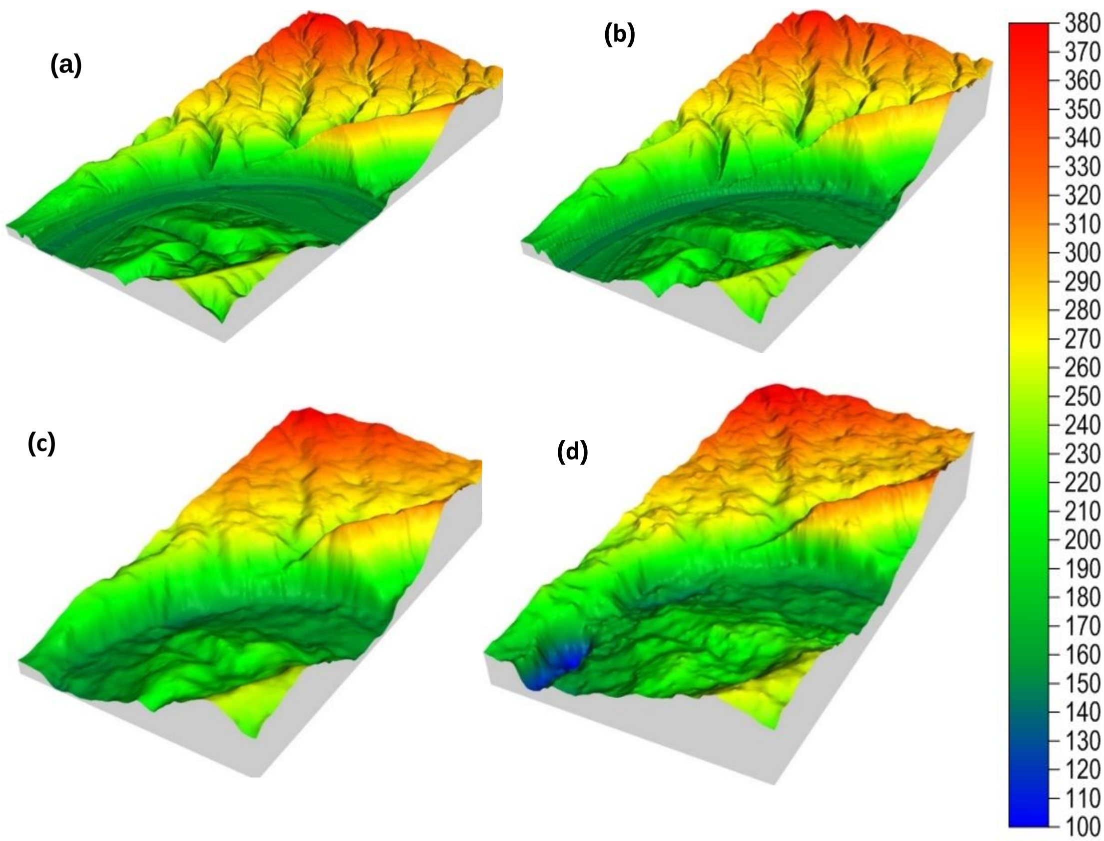


FIGURE 2: 3D view of ground surface for DEMs generation by modern geoinformatic methods (a) LiDAR, (b) ASTER GDEM, (c) STRM, and (d) ALOS.

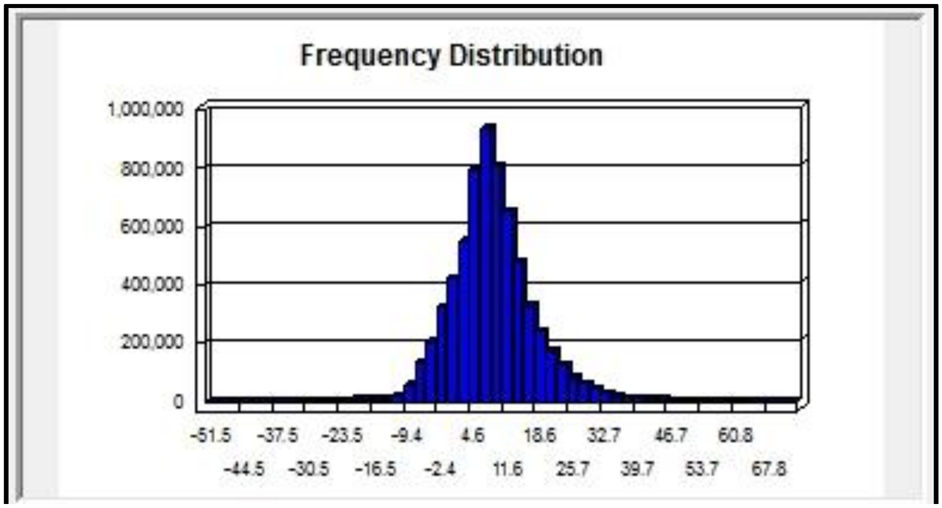


FIGURE 3: ASTER GDEM vs LiDAR DEM absolute vertical accuracy for ground points.

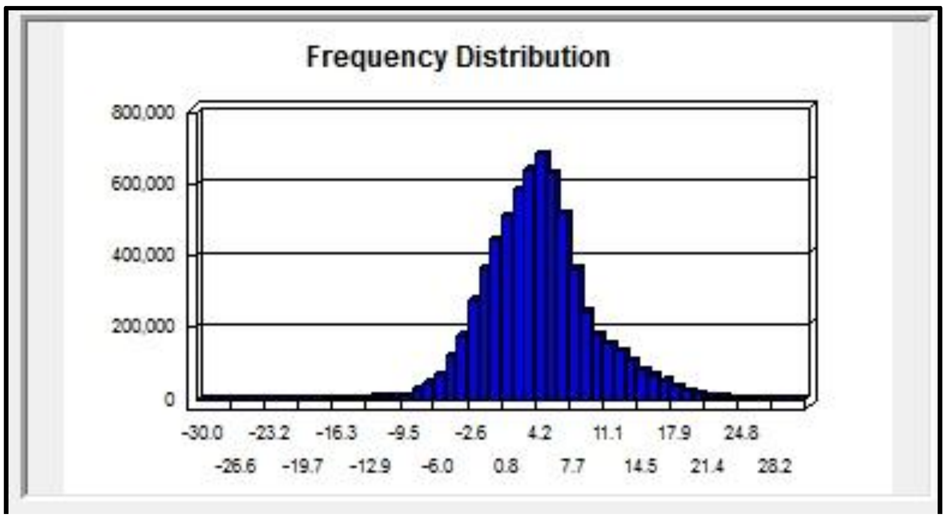


FIGURE 4: STRM GDEM vs LiDAR DEM absolute vertical accuracy for ground points.

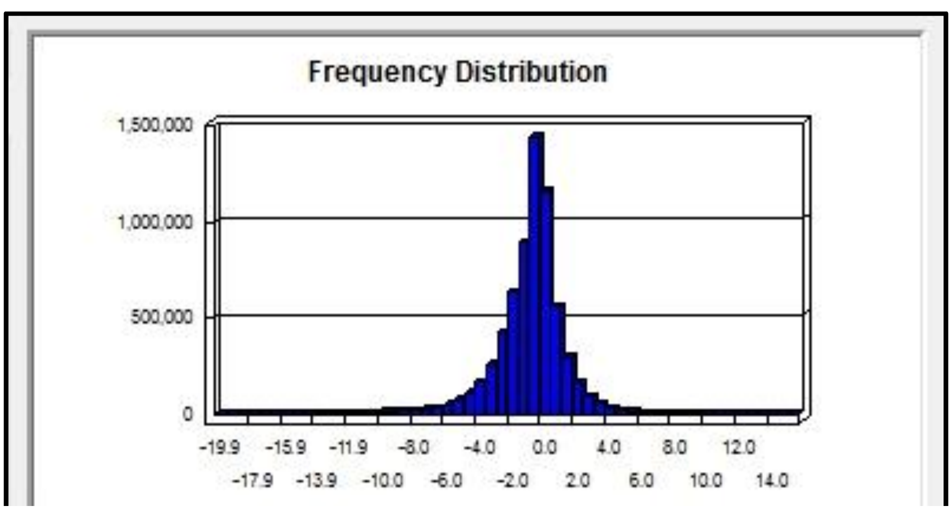


FIGURE 5: ALOS DEM vs LiDAR DEM absolute vertical accuracy for ground points.

4. CONCLUSION

Today, studies mostly use DEMs obtained by modern geoinformatic (remote sensing) methods instead of direct measurement techniques due to the increased number of observation satellites with stereo capabilities and increased spatial and temporal resolution, as well as the reduced cost of the production of new DEMs. Airborne LiDAR is one of the most significant technology introduced in mainstream topographic mapping in the last decade and the Using LiDAR data for DEM generation is becoming a standard practice in spatial related areas.

In this research, DEMs obtained from a variety of satellite sensors were compared to analyze their vertical accuracy and performance. For this purpose, three of the most up-to date freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM), and Advanced Land Observing Satellite (ALOS) DEMs data have been inter-compared and evaluated externally by more than six million points from main data source for producing high-resolution digital elevation model “LiDAR”.

From the results of this study, the comparison generally shows a good agreement between both ALOS DEM and LiDAR DEM (as indicated by the smaller values of mean = 0.626 m and standard deviation (SD) = 2.082m).

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