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Evaluation of the accuracy of open-source DEMs using GPS data

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Abstract

The DEM is often required for flooding or drainage modeling, land use studies, and geological or other applications. A variety of DEMs, such as the Advanced Space Thermal Emission Radiometer (ASTER GDEM) and the Radar Topography Mission (SRTM) are currently available to the public free of charge. However, these DEMs remain a representation of reality, which requires, before any application, their evaluation using high-precision reference data. The objective of this study is to assess the quality of the two DEMs, ASTER GDEM and SRTM, in Morocco. The methodology adopted for this validation is based on two approaches: internal validation and external validation. The first validation consists of a comparison of the versions of each product with each other. This processing showed that version 2 and version 3 (1 arcsecond) are the best versions of ASTER and SRTM respectively. For the second validation, the vertical precision of DEMs is evaluated by 3551 GPS control points. The overall vertical accuracy attests to a ″ RMSE ″ mean square error of 8.17 and 10.15 respectively for ASTER and SRTM, compared to the GPS elevation points. These ″ RMSE ″ values are the lowest compared to the other versions of these two products, which confirms the quality of version 2 of ASTER GDEM and that of version 3 (1 arcsecond) of SRTM. An in-depth analysis of SRTM version 3 data (1 arcsecond) and ASTER GDEM v2, shows the presence of outliers associated with the slope, which shows the degradation of the performance of these DEMs with the increase of the slope.

Keywords: DEM, ASTER GDEM, SRTM, accuracy assessment, Morocco.

Introduction

Synonymous with the digital elevation model (DEM), a digital terrain model (DTM), "is simply, a statistical representation of the continuous surface of the ground by a large number of selected points with known XYZ coordinates in an arbitrary coordinate field" (Miller a Laflamme, 1958). It is a generic term presenting the digital data of the topography (altimetry for emerging sectors or bathymetry for submerged sectors) of a terrestrial zone, in all the forms adapted to its use by a digital calculator (computer), as well as by all possible methodologies (adaptation of (Maune, 2001)). Being manipulated by GIS software, the importance of DEMs comes from the possibility of transforming the initial plane of the altitudes (Z) into multiple associated products. This involves derivations (slopes, orientation, curvatures), analyse of local or extensive topography and geomorphology, analyses of visibility, 3D representations, potential insolation, or the search for water flow directions (drainage networks) for an introduction into mathematical models that use altitude or its transforms (Alpar, et al., 2004; Dietrich and Perron, 2006).

These examples of applications related to DEM, clearly show the importance of this product as a valuable source of information. However, according to (Carter, 1988), a DEM, even with better accuracy, remains an approximation of the reality on the ground. Therefore, it always contains errors. These errors inevitably propagate in the different applications that use it and can significantly influence the final results (Huang and Lees, 2005; Oksanen and Sarjakoski, 2005; Gazioğlu, et al., 2014; Kılıç et al., 2022). This requires an evaluation at local scale of the accuracy of these products before any application, in order to understand the potential and limitations of using this data for a specific area.

Many studies have used inter-comparison techniques to determine the most accurate DEM in a given region. Most of these studies compare elevation accuracies between available DEMs. Accurate ground control points (GCPs) obtained from the global positioning system (GPS) (Athmania and Achour, 2014; Hirt et al., 2010; Mouratidis et al., 2010; Zhao et al., 2010; Yaman et al., 2019) or high quality altimetry measurements (Carabajal, 2011; Ensle et al., 2012; Satgé et al., 2015; Zhao et al., 2010) are used as references to compute the elevation errors of DEMs. Other studies have focused on the errors of the eight neighboring pixels to study the quality of the Earth's surface shape. This quality is used for geomorphology and hydrology applications (El Hage et al., 2012). This latter type of study will be the subject of further work.

All the above-mentioned studies emphasized the fact that the accuracy of these DEMs differs from an area to

another. From this point comes the need of local accuracy assessment for these open-source products. Except a work of (Tahiri et al., 2011), no validation study of open source DEMs has concerned the Moroccan territory. With this perspective, the present work aims to assess the accuracy of open-source DEMs for Morocco, specifically "Ain Leuh" area, using GPS collected data.
The methodology adopted for this validation is based on two approaches: internal validation and external validation. The first validation consists of a comparison between versions for each DTM. As for the second validation, 3551 GPS control points were used to assess the vertical precision of the DEMs. The basic processing is carried out in a geographic information system (GIS), namely ArcGIS. Section 2 presents the study area and the essential information on the evolution of SRTM and ASTER GDEM and their properties. The methods used to perform the inter-comparisons are described in section 3. Then, the results and discussion are detailed in section 4. Finally, the conclusions and recommendations are presented in section 5.

Study area and data set

Study area

The region studied (Figure 1) is located in the central Middle Atlas, about 40 km SW of the city of Azrou, precisely the town of Aïn Leuh. It is bounded by the geographic coordinates Lat. 33° 20' N to 33° 18' N and long. 5° 24' W to 5° 20' W. This sector covers an area of 5 km2. This area is crossed by Oued Aïn Leuh in a west-east direction.

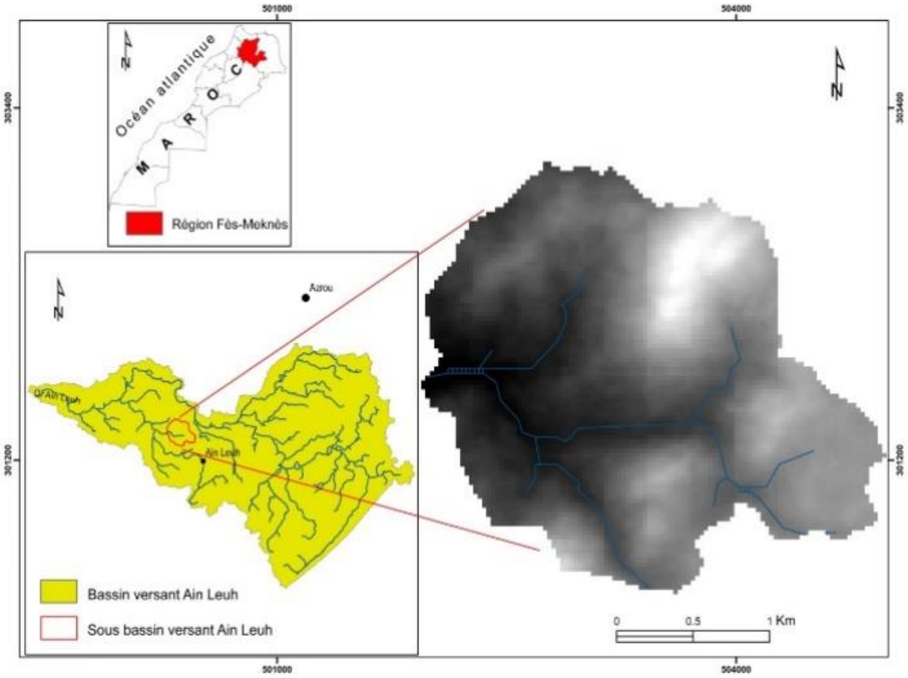

Fig. Study area location.

Data Set

<u>SRTM versions</u>: The Shuttle Radar Topography Mission (SRTM) of February 2000 (SRTM) has provided for the first time a high-quality DEM with resolutions of 1 and 3 arcseconds, using Interferometric Synthetic Aperture Radar (INSAR) in a single pass. SRTM (van Zyl, 2001) was a collaboration between the National Aeronautics and Space Administration (NASA) and the National Imaging and Mapping Agency (NIMA which changed its name in November 2003 to the National Geospatial-Intelligence Agency: NGA). The absolute and relative vertical accuracy specifications of this DEM are respectively defined as ± 16 m for 90% of the data on the whole mission and ± 6 m for some 50–100 km scale regions, (Farr and Kobrick, 2000; Rabus et al., 2003).

Four NASA SRTM versions are available for free download from the USGS websites (v1) consists of the original digital elevation model and was published between 2003 and 2004. These data are unedited and contain spurious data points in areas of low radar backscatter such as water bodies. This dataset includes a 1 arcsecond DEM (NASA-SRTM-1), released for the United States, and a 3 arcseconds DEM covering the rest of the world between latitudes 56 ° S and approximately 60 ° N. In 2005, version 2 (v2) was released. It is the result of an improvement from version 1 (v1). Such as the identification, delineation, and determination of the height of coasts and water bodies exceeding the specified dimensions, as well as the removal of spikes and wells (Single pixel error) and the filling of small voids (Slater et al., 2006). Either way, v2 is a higher product than v1 and is recommended for most users (www2.jpl.nasa.gov/srtm/). In 2009, the NASA Jet Propulsion Research Laboratory (JPL) released version 2.1 with only 3 arc seconds DEM, by averaging the full-resolution edited data" to correct some ″occasional artefacts″ of version 2.0, in particular, a slight vertical banding above latitude 50° N and below latitude 50° S.

The latest NASA SRTM products, publicly released in 2015, are version 3.0 (a.k.a. SRTM Plus). It includes a near-global 1-arcsecond product and two 3 arcseconds datasets, created respectively by sub-sampling and by averaging the 1-arcsecond product. The averaged 3 arc seconds DEM is identical to NASA version 2.1 in non-void areas. The latter, however, were filled in the version 3.0 products, using non-commercial DEMs, such as the ASTER GDEM version 2.

Apart from these original NASA SRTM versions, two other versions were provided by Consultative Group for International Agricultural Research – Consortium for Spatial Information (CGIAR-CSI): version 3 (2004) and version 4.1 (2008).

Version 3 (v3) is the result of NASA data post-processing (version 2.0) to fill in the data voids using interpolation techniques. But the latter suffered a ½ grid pixel shift compared to SRTM v2 (Jarvis et al., 2006). This error has been recognized, but not resolved. The version (v4.1) compensated for this ½ pixel shift.

The latest (and only) currently available CGIAR-CSI SRTM product for free from the http://srtm.csi.cgiar.org/ website is version 4.1, which was released in August 2008 (Jarvis et al., 2008). Void-filling of NASA version 2.0 was performed using the techniques described in (Reuter et al., 2007). This product is available from the CGIAR-CSI server 2008 (Jarvis et al., 2008), as well as from several mirror sites.

ASTER GDEM: In 2009, a new global DEM was produced. The Advanced Space Thermal Emission Radiometer (ASTER) was jointly developed by the Ministry of Economy, Trade and Industry (METI) of Japan and NASA. The approach used to construct the DEM is a pair correlation of stereoscopic images (Shapiro and Stockman, 2001). ASTER GDEM covers land surfaces between 83° S and 83° N, which is an improvement over SRTM coverage. During an observation period of more than seven years (2000-2007), a total of approximately 1260000 scenes of stereoscopic DEM data of 60 km x 60 km terrain were collected, thus the topography of most areas has been sampled several times (Zhao et al., 2010). The overall vertical precision of ASTER elevations is specified to vary between 10 m and 25 m (ASTER GDEM Validation Team, 2009). Like SRTM, ASTER GDEM refers to WGS84 and the EGM96 geoid.

ASTER GDEM v2 and v3 data are freely available to the public on the NASA website: https://earthdata.nasa.gov.
The initial version of the ASTER Global Digital Elevation Model (GDEM v1) with a resolution of 1-arcsecond (about 30 m), was published in June 2009 (Abrams et al., 2010). The user's community widely embraced this product even though NASA and METI acknowledged it to be a "research-grade" dataset that contains anomalies and artifacts that may limit its usefulness for some applications. Several validation efforts carried out on GDEM v1 concluded that in most cases, the dataset met its stated accuracy goal (± 20 meters at 95% confidence), but that some characteristics of the dataset affect how the terrain is represented and how the DEM performs in applications (ASTER GDEM Validation Team, 2009; Miliaresis and Paraschou, 2011; Slater et al., 2011).

To address the limitations of GDEM v1, NASA and METI jointly developed GDEM version 2 (v2) (ASTER GDEM Validation Team 2011) and released it to the user's community in October 2011. In addition to the correction of the altitude offset of approximately -5 m detected in version 1, improvements in GDEM v2 processing include 260,000 additional individual ASTER scenes to improve coverage. Moreover, a smaller correlation window (5x5 versus 9x9 for GDEM1) was used to enhance spatial resolution, and ameliorate water masking (ASTER GDEM Validation Team, 2011).

In 2016, the ASTER team published GDEM version 3 (Abrams, 2016). In addition to the Digital Elevation Models for each tile, a separate dataset of water bodies was included. An auxiliary data plan identified water bodies as a river, lake, or ocean. The AWBD (Aster water body dataset) was used as a mask while creating the DEM, so shorelines and lake boundaries were integrated. In addition, rivers have descending elevations from their headwaters to their junction with other rivers, or junction with the ocean. The methodology used to identify water is described in detail by (Fujisada et al., 2005).

Kinematic GPS data collection: In November and December 2017, a five-day kinematic GPS campaign was carried out in Aïn Leuh regions (figure 1), using three Leica 1200 dual-frequency GPS receivers, one fixe and two mobiles. This kinematic mode ensures a vertical precision of 20 mm + 1 ppm and a horizontal precision of 10 mm + 1 ppm (Leica Geosystems, 2006). However, the accuracy of the GPS itself depends on various factors. According to (Rey, 1997), the GDOP (Geometric Dilution Of Precision) indicator is the most important factor to be observed in order to obtain the accuracy of measurements in kinematic mode. The importance of this indicator is the integration of PDOP (Position DOP) and TDOP (Time DOP). The minimum number of visible satellites must be four. If the GDOP is good enough (<4) already with 4 satellites, it is theoretically useless to try to find more satellites. However, a higher number of satellites is a good guarantee against degradation of the GDOP and for the "recovery" of possible cycle jumps (cycle slips). In this study, the receivers picked up 11 satellites with a GDOP value of 1.6. The collection of the elevation data is preceded by the configuration of the GPS, and Lambert Conformal Conic (LCC) reference is selected for the horizontal datum, as well as Earth Gravitational Models 1996 (EGM96) for the vertical reference. The real-time kinematic mode is chosen for data acquisition, which provides a product that can be directly exploited without post-processing. To optimize the sampling, this data collection targeted ridges, thalwegs, and slope breaks. With the above considerations, 3551 points were collected, within approximately 20 hours, with a density of measurements of the order of 710 points / km2.

Data Processing

Before using GPS data to assess the absolute and relative vertical accuracy of SRTM and ASTER GDEM, a relative comparison of versions between them was performed for each DEM. These treatments were performed after converting the data to the same format, and the same geodetic datum.

SRTM and ASTER GDEM data are in raster format, while GPS data are in vector format. Comparing these datasets requires converting them to the same topological format. For this purpose, two methods are possible: either converting SRTM and ASTER GDEM raster data into vector format or converting GPS vector data into raster format. Although both conversions can be easily performed in the ArcGIS (Spatial Analyst) environment, the former is adopted in this study because it is more informative and practical for various manipulations in a GIS environment, and requires less computational effort.
The horizontal datum for SRTM and ASTER GDEM data is converted from the World Geodetic System 1984 (WGS84) to the Lambert Conformal Conic North Morocco and the vertical datum corresponds to the EGM96.

DEM versions comparison
The comparison of two raster versions of DEM is based on subtracting the values of two equivalent pixels in the two versions. This is done by the Map Algebra tool of the ArcGIS Spatial Analyst Tools module. The results of all subtractions are shown in Figure 2 and the statistics are summarized in Table 1.

Calculation of absolute and relative vertical precision
From a statistical point of view, the absolute vertical accuracy of the two DEMs was assessed by computing the absolute differences between the DEM pixel value and the corresponding GPS point. For each point, an elevation error (Ludwig and Schneider, 2006; Sun et al., 2003) was computed as the difference between the explored data and the reference data (Equation (1)) :

$$\boldsymbol{Z_{dif} = Z_{ex} - Z_{ref}} \qquad \text{(Eq.1)}$$

In equation (1), Zdif is the elevation error, Zex is the elevation of the explored DEM, and Zref is the elevation of the GPS points. Positive differences represent locations where the DEM elevation exceeds the GPS point elevation; and, conversely, negative errors occur at locations where the DEM elevation was below the GPS elevation.
In the second step, we looked at the relative elevation precision. Calculations were performed using the same GPS points, randomly selecting an analogous number of height differences. This can be translated as follows (Equation (2)):

$$\boldsymbol{MNT_{dif} = MNT_{pixel1} - MNT_{pixel2}}$$

$$\boldsymbol{GPS_{dif} = GPS_1 - GPS_2}$$

$$\boldsymbol{Z_{dif.r} = MNT_{dif} - GPS_{dif}} \qquad \text{(Eq.2)}$$

In equation (2), Zdif.r is the relative elevation error, MNTdif is the difference in the values of two pixels, and GPSdif is the difference in elevation between the two corresponding GPS points.
After that, the mean error (ME), standard deviation (STD), mean square error (RMSE), and the maximum (Max) and minimum (Min) error values were calculated as follows (Athmania and Achour, 2014; Lane et al., 2000; Liu and Mason, 2013) :

$$\boldsymbol{ME = \sum \frac{Z_{dif}}{n}} \qquad \text{(Eq.3)}$$

$$\boldsymbol{STD = \pm\sqrt{\frac{(Z_{dif} - ME)^2}{n-1}}} \qquad \text{(Eq.4)}$$

$$\boldsymbol{RMSE = \sqrt{\frac{\sum(Z_{dif})^2}{n}}} \qquad \text{(Eq.5)}$$

STD and RMSE are measures of surface quality and provide insight into the distribution of deviations on either side of the mean value.

Results and discussion
SRTM v1, v2.1, v3 and v4.1 comparison

From the analysis of Figure 2 and Table 1, v3 and v2.1 coincide by 100%. Thus, there is a remarkable similarity between v2.1 and v1 and between v3 and v1, as indicated by the standard deviation (0.27) and the fact that 93% of the pixels have the same elevation value. Despite the similarity between v2.1 and v1 on the one hand and v3 and v1 on the other hand, we note that the pixels exhibit differences of ± 1 m (a and e figure 1). These pixels represent only 0.02% (318 pixels) of the total number of pixels. Knowing that the study area does not contain water bodies, this can be explained by the voids that were filled in versions v2.1 and v3 compared to version 1. The comparison of SRTM v4.1 from CGIAR-CSI with the three SRTM versions (v1, v2.1, and v3) from NASA highlights low similarity, as confirmed by the standard deviation (over 7) and low percentage (about 9%) of the pixels with same values (Table 1). This comparison shows pixels with differences of the order of ± 30 m (c, d, and f figure 2) as well. To try to understand these important differences, visual analysis was performed at ArcMap. The latter consists of superimposing SRTM v4.1 from CGIAR-CSI with SRTM v2.1 from NASA, then we find a value of a given pixel (example pixel at value = 1364) in the two products with different colors. This visual prospecting allowed the observation of a shift of 1 pixel, for which the direction is not constant. Previous studies have compared CGIAR-CSI and NASA SRTM products. A comparison of several SRTM versions was performed in northern Greece (Mouratidis et al., 2010), including NASA version 2.0 and CGIAR-CSI version 4.1 (referred to as version 4 in the work of (Mouratidis et al., 2010)). Versions 2.0 and 4.1 were found to be identical in nonempty areas. On the other hand, a comparison of the DEMs throughout Australia (Rexer & Hirt, 2014), showed a relative geolocation shift of 1 pixel between latitudes 30.01 S and 29 S, by comparing NASA SRTM version 2.1 and CGIAR- CSI version 4.1, as well as an overall RMS elevation difference of 1.2m, including the band of latitude affected by the change in geolocation.

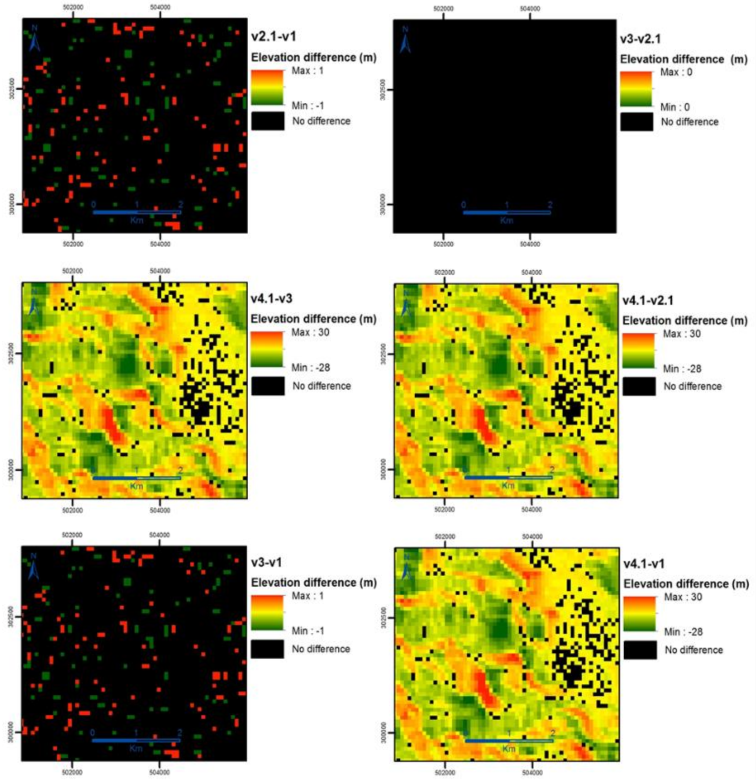

Fig. 2. Differences between the four SRTM versions by subtracting corresponding pixel values for each pair.

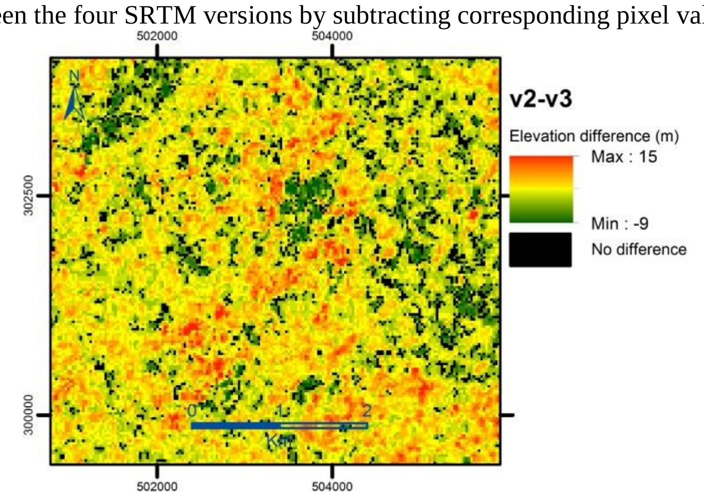

Fig. 3. Difference between the two ASTER GDEM versions by subtracting corresponding pixel values.

Table 1. Statistics of the comparisons between SRTM versions.

Subtraction operations between versions	**No. of pixels**	**Percentage of pixels with matching value (no. of pixels)**	**Min. (m)**	**Max. (m)**	**Mean (m)**	**Standard deviation (m)**
V2.1 – V1	4544	93 (4226)	-1	1	0,0	0,27
V3 – V2.1	4544	100 (4544)	0	0	0,0	0,0
V4.1 – V3	4544	9,15 (416)	-28	30	-0,74	7,57
V4.1 – V2.1	4544	9,15 (416)	-28	30	-0,74	7,57
V3 – V1	4544	93 (4226)	-1	1	0,0	0,27
V4.1 – V1	4544	9,11 (414)	-28	30	-0,74	7,58

Table 2. Statistics of the comparisons between ASTER GDEM versions.

Subtraction operations between versions	No. of pixels	Percentage of pixels with matching value (no. of pixels)	Min. (m)	Max. (m)	Mean (m)	Standard deviation (m)
V2 – V3	40068	8,23 (3299)	-9	15	2,76	2,23

ASTER v2 and v3 comparison

The comparison of the two ASTER GDEM versions (v2 and v3) shows a weak resemblance with a standard deviation of 2.23 and a percentage of 8.23% for the pixels with the same values (Table 2). Furthermore, this comparison shows pixels with differences that vary from -9 m to 15 m (Figure 3). These pixels represent approximately 92% of the total pixel count (40068).

Validation with GPS measurements

SRTM: Analysis of Figure 4 for the scatter plots of elevation differences, shows that the uniformity of the elevation accuracy between v1, v2.1, and v3 is evident. It is also clear that v4.1 deviates from the other three versions.

The results presented in Table 3 are relatively close to those presented by (Rodríguez et al., 2005) for Africa, with an exception of v4.1, whose standard deviation exceeds the expected values due to the 1 pixel shift of Grid. It is also important to note that v3 (1-arcsecond) gives even better results than all other versions.

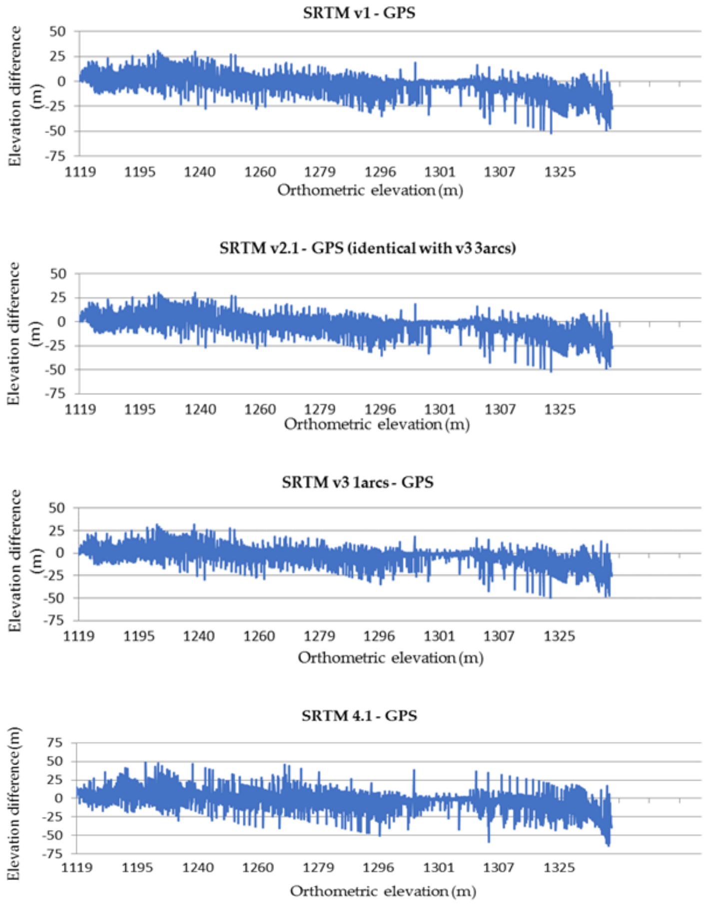

Fig. 4. Absolute elevation differences between GPS and SRTM versions against orthometric elevations.

Table 3. Statistics of SRTM v1, v2.1, v3, and v4.1 over GPS elevation data and comparison with results of Africa from (Rodríguez et al., 2005).

SRTM versions	Absolute elevation Error (m)				Relative elevation error (m)			
	Min.	Max.	Standard deviation		Min.	Max.	Standard deviation	
			This study	(Rodríguez et al., 2005)			This study	(Rodríguez et al., 2005)
v1	-51	30	10.4	5.6	-57	68	13.6	9.8
v2.1	-51	30	10.4	5.6	-57	68	13.6	9.8
v3 (3arcs)	-51	30	10.4	5.6	-57	68	13.6	9.8
v3 (1arcs)	-49	32	10.0	5.6	-56	67	13.2	9.8
v4.1	-63	48	13.6	5.6	-75	82	18.7	9.8

The results of the RMSE calculation, confirm the similarity of the three versions (v1, v2.1, and v3 all of them with 3 arcseconds) SRTM where RMSE = 10.9, with a slight performance improvement concerning the v3 1-arcsecond with RMSE = 10.5. However, v4.1 with an RMSE = 13.84, still shows an exception. A validation work of v4.1 carried out in Algeria and Tunisia using GPS data (Athmania and Achour, 2014), indicates an RMSE = 3.6 in Tunisia (Anaguid Saharan platform) and an RMSE = 8.3 in Algeria (Tebessa basin). In Saudi Arabia (Elkhrachy, 2017), a v3 validation study recorded an RMSE of ± 7.92, which can be improved to ± 5.94 by removing outliers. The slope impact on the altimetric accuracy of the SRTM data is obvious because as shown in Figure 4, with high elevations (> 1200 m), therefore larger slopes, the elevation error exceeds 25 m and increases proportionally with altitude until reaching a maximum of 51 m. The works of (Miliaresis and Paraschou, 2005; Gorokhovich and Voustianiouk, 2006) recognized and analyzed the effect of slope in determining the altimetric accuracy of SRTM data.

ASTER GDEM: The figure 5 relating to the scatter plots of the elevation differences shows a clear uniformity of the elevation accuracy between v2 and v3.

The results presented in Table 4, including the calculation of the RMSE, confirm the similarity of the two versions (v2 and v3) ASTER GDEM with RMSE = 8.17 for v2 and RMSE = 8.29 for v3. These results are in agreement with the results presented by de (Gesch et al., 2012) and (Gesch et al., 2016) for USA.

A v2 validation study carried out in Algeria and Tunisia using GPS data (Athmania and Achour, 2014), indicates an RMSE = 5.3 in Tunisia (Anaguid Saharan platform) and an RMSE = 9.8 in Algeria (Tebessa basin). Another work in Saudi Arabia (Elkhrachy, 2017), examining v2, shows an RMSE of ± 7.45, which can be improved to reach ± 5.07 by removing outliers.

The effect of the slope on the altimetric accuracy of the ASTER GDEM data is clear because as shown in figure 5, with high elevations (> 1190 m), and therefore larger slopes, the elevation error exceeds 25 m and increases proportionally with altitude until reaching a maximum of 39 m.

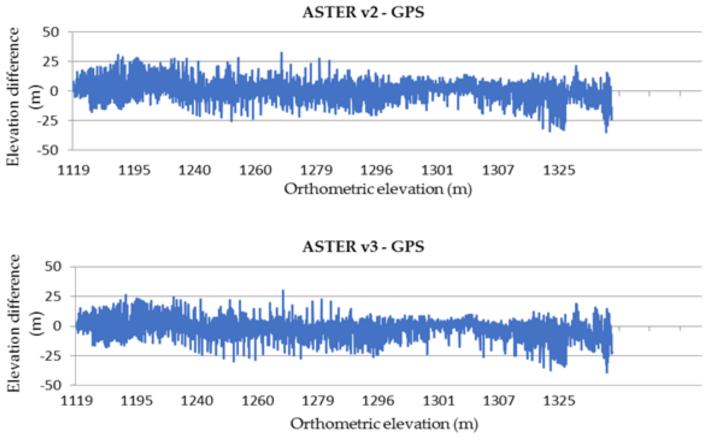

Fig. 5. Absolute elevation differences between GPS and ASTER GDEM versions against orthometric elevation.

Table 4. Statistics of ASTER GDEM v1 and over GPS elevation data and comparison with results for USA from (Gesch et al., 2012) and (Gesch et al., 2016).

ASTER GDEM versions	This study					USA (Gesch et al., 2012, 2016)				
	Min.	Max.	Mean	Standard deviation	RMSE	Min.	Max.	Mean	Standard deviation	RMSE
v2	-35	33	0.8	8.1	8.17	-137	64.9	-0.2	8.68	8.68
v3	-39	30	-2.16	8.0	8.29	-82	69.9	-1.2	8.44	8.52

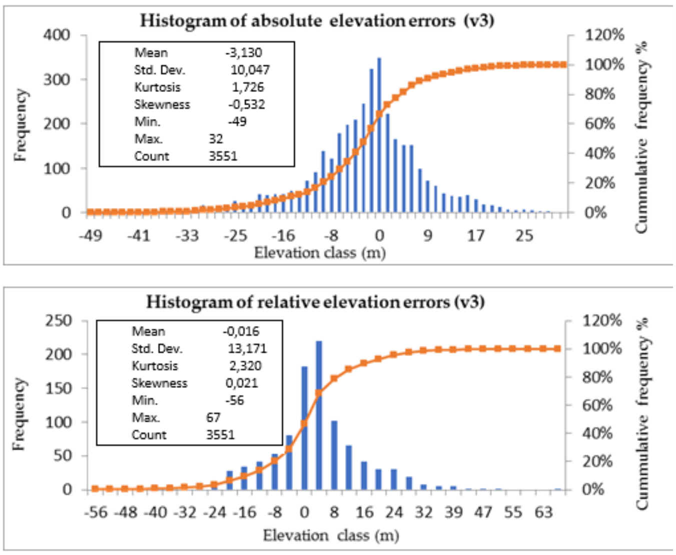

Figure 6. Histograms of elevation errors and relevant descriptive statistics for SRTM v3 (1-arcsecond). Absolute elevation errors (above) and relative elevation errors (below).

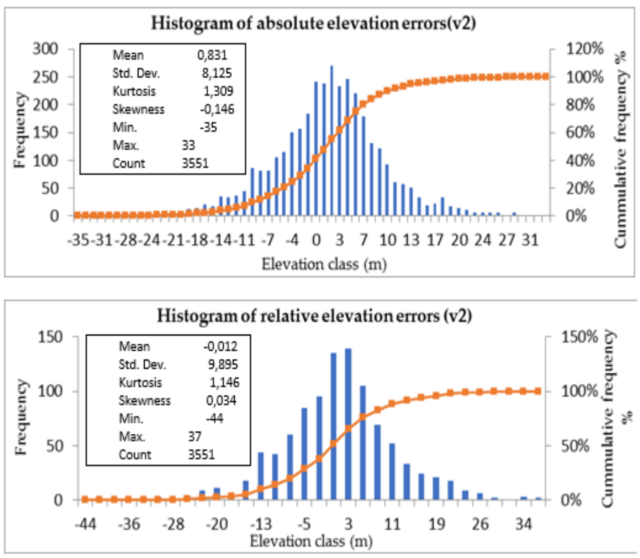

Fig. 7. Histograms of elevation errors and relevant descriptive statistics for ASTER GDEM v2. Absolute elevation errors (above) and relative elevation errors (below).

As it is shown so far, the SRTM v3 1-arcsecond and ASTER GDEM v2 are indeed the upgraded versions. Further analysis of slope and elevation influence in these versions will be highlighted in the paragraphs below. In addition, histograms and corresponding descriptive statistics for absolute and relative elevation errors (Figures 6 and 7) were computed. The value of the skewness coefficient different from zero indicates that the data is asymmetric. As for the kurtosis coefficient, it is less than 3 so the edges of the distribution are thin; this is a ″ Platikurtic ″ distribution, suggesting the presence of outliers.

To study the outliers in the two edges of distributions (Figures 6 and 7) and to interpret differences at high altitudes and even at low altitudes (Figures 4 and 5), all points with errors greater than ± 20m were identified. This process gave 271 points (7.6%) for SRTM v3 1-arcsecond and 90 points in the case of ASTER GDEM v2 (2.5%). The slope map was calculated for the two products and used to interpret the distribution of these outliers (Figures 8 and 9). For both products, all points were located in areas with variable slopes (between medium, high, and very high), and no points were associated with flat areas. However, for ASTER GDEM v2, 2 points out of 90 (2.2%) were associated with an area that has a slope <3°. Therefore, for these 2 points, the problems related to GPS should be considered as the most likely source of error.

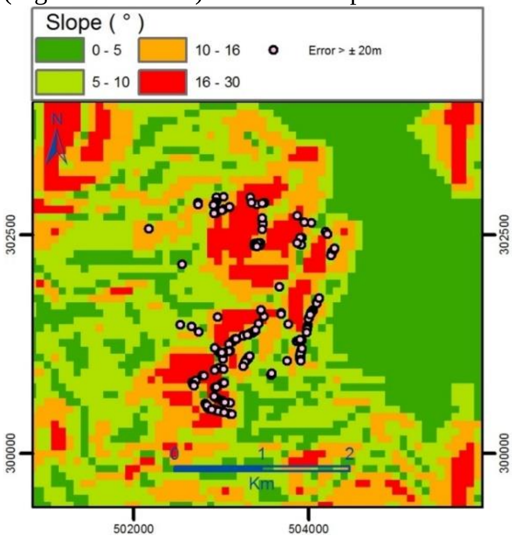

Fig. 8. Slope map (SRTM) of the study area for the interpretation of elevation error outliers.

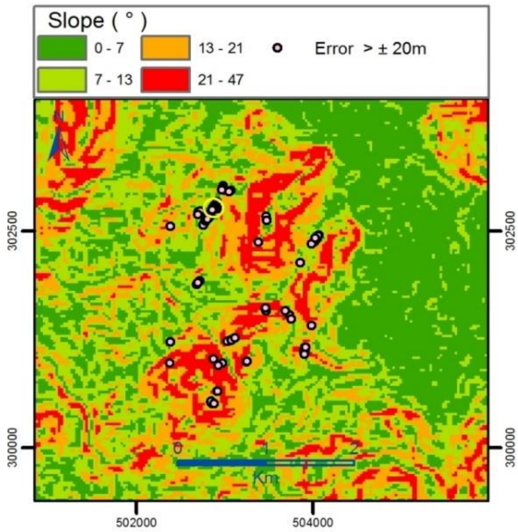

Fig. 9. Slope map (ASTER GDEM) of the study area for the interpretation of elevation error outliers. The yellow circle indicates the 2 errors not explained by the slope.

In addition to the slope effect as an explanation for the high deviations between the GPS data and those of SRTM and ASTER GDEM, it should also be noted that some of these points are located in populated rural areas, where buildings (14 houses) influence the performance of SRTM and ASTER GDEM data. In this context, it must be taken into account that SRTM DEM is in fact a digital surface model (DSM), therefore it includes the elevation of buildings, and trees (therefore the actual elevation is overestimated), while the KGPS data refer exclusively to the ground surface. In these cases, the result of subtracting the KGPS elevation data from SRTM should normally be a positive number, a theoretical assumption that applies to the points in question.

Conclusion

The interest of this study was the validation of ASTER GDEM and SRTM DEMs, by using a large amount of KGPS collected data in Ain Leuh, Morocco. Throughout the analysis of results, we find that the two versions of ASTER GDEM show a weak similarity of 8.23% for Ain Leuh area. As for SRTM, except CGIAR version 4.1, the three NASA versions display a perfect resemblance since the percentage of matching values goes from 93% to 100%. The 1 pixel shift of version 4.1 compared to version 2.1 induces errors in the DEM SRTM v4.1. This shift is not systematic but occurs in different directions, which makes this version inappropriate for use in this case as it is confirmed by other works mentioned above.
The use of GPS collected data shows that the absolute vertical accuracy of 16 m for the SRTM mission is respected, while the relative vertical accuracy of 10 m is not obtained with standard deviations of around 13 m for the 3 versions of NASA and 18.7 m for version 4.1 of the CGIAR. For the ASTER DEM, the absolute vertical accuracy is verified for both versions, so the relative vertical accuracy is acceptable with an RMSE of 8.17 m and 8.29 m respectively for versions 2 and 3.

Therefore, this study concluded that version 2.1 of SRTM, could be used in regions without large voids as for Ain Leuh. Alternatively, in areas with considerable voids, version 3 (1-arcsecond) would be ideal because voids are compensated while preserving the accuracy of the original data. Either way, version 3 (1-arcsecond) is the best SRTM DEM. Regarding the ASTER DEM, version 2 is slightly better than version 3.

Furthermore, the performed analysis on SRTM version 3 (1-arcsecond) and ASTER version 2 indicates that the presence of outliers and deviation from normality is observed due to the high slope values. More precisely, the accuracy of these DEMs decreases with increasing slope.

Finally, we recommend that further works should focus on:

- Studying the relation between DEM's accuracy and slope;
- Studying others Moroccan areas in order to confirm the results of this experiment.

References

Abrams, M. (2016). Aster Global Dem Version 3, And New Aster Water Body Dataset. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B4*, 107 110. doi.org/10.5194/isprsarchives-XLI-B4-107-2016

Abrams, M., Bailey, B., Tsu, H., Hato, M. (2010). The ASTER Global DEM. *Photogrammetric Engineering and Remote Sensing*, *76*(4), 344 348.

Alpar, B., Gazioğlu, C., Altınok, Y., Yücel, ZY., Dengiz, Ş. (2004). Tsunami hazard assessment in Istanbul using by high resolution satellite data (IKONOS) and DTM. *XXth Congress of the ISPRS,* Istanbul, 2004.

ASTER GDEM Validation Team. (2009). ASTER Global DEM Validation Summary Report. *ersdac.or.jp and* ci.nii.ac.jp

ASTER GDEM Validation Team. (2011). *ASTER Global Digital Elevation Model Version 2—Summary of validation results*. NASA. www.pubs.er.usgs.gov

Athmania, D., Achour, H. (2014). External Validation of the ASTER GDEM2, GMTED2010 and CGIAR-CSI- SRTM v4.1 Free Access Digital Elevation Models (DEMs) in Tunisia and Algeria. *Remote Sensing*, *6*(5), 4600-4620. doi.org/10.3390/rs6054600

Carabajal, C. C. (2011). ASTER GLOBAL DEM VERSION 2.0 EVALUATION USING ICESat GEODETIC GROUND CONTROL. *NASA Goddard Space Flight Center: Greenbelt, Maryland*, 47.

Carter, J. R. (1988). Digital Representations of Topographic Surfaces. *PHOTOGRAMMETRIC ENGINEERING*, 4.

Dietrich, W. E., Perron, J. T. (2006). The search for a topographic signature of life. *Nature*, *439*(7075), 411-418. doi.org/10.1038/nature04452

El Hage, M., Simonetto, E., Faour, G., Polidori, L. (2012). Evaluation of Elevation, Slope and Stream Network Quality of Spot DEMS. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *I-2*, 63-67. doi.org/10.5194/ isprsannals-I-2-63-2012

Elkhrachy, I. (2017). *Vertical accuracy assessment for SRTM and ASTER Digital Elevation Models : A case study of Najran city, Saudi Arabia*. 11.

Ensle, F., Heinzel, J., Koch, B. (2012). Evaluating Height Differences between Global Digital Surface Models and ICESat Heights at Footprint Geolocation. *GIS Ostrava 2012: Surface Models for Geosciences*, 37 48.

Farr, T. G., Kobrick, M. (2000). Shuttle radar topography mission produces a wealth of data. *Eos, Transactions American Geophysical Union*, *81*(48), 583. doi.org/10.1029/EO081i048p00583

Fujisada, H., Bailey, G. B., Kelly, G. G., Hara, S., Abrams, M. J. (2005). ASTER DEM performance. In *IEEE Transactions on Geoscience and Remote Sensing* (Vol. 43, Numéro 12, p. 7). doi.org/10.1109/TGRS.2005.847924

Gazioğlu, C., Aipar, B., Yücel, Z.Y., Müftüoğlu, A.E., Güneysu, C., Ertek, T.A., Demir, V., Kaya, H. (2014). Morphologic Features of Kapıdağ Peninsula and its Coasts (NW-Turkey) using by Remote Sensing and DTM. *International Journal of Environment and Geoinformatics*, 1(1), 48-63. doi.10.30897/ijegeo. 300739.

Gesch, D., Oimoen, M., Danielson, J., Meyer, D. (2016). *Validation of the Aster Global Digital Elevation Model Version 3 over The Conterminous United States*. 6-7.

Gorokhovich, Y., Voustianiouk, A. (2006). Accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. *Remote Sensing of Environment*, *104*(4), 409 415. doi.org/10.1016/j.rse.2006.05.012

Hirt, C., Filmer, M. S., Featherstone, W. E. (2010). Comparison and validation of the recent freely available ASTER-GDEM ver1, SRTM ver4.1 and GEODATA DEM-9S ver3 digital elevation models over Australia. *Australian Journal of Earth Sciences*, *57*(3), 337 347. doi.org/10.1080/ 08120091003677553

Huang, Z., Lees, B. (2005). Representing and reducing error in natural-resource classification using model combination. *International Journal of Geographical Information Science*, *19*(5), 603 621. doi.org/10.1080/13658810500032446

Jarvis, A., Guevara, E., Reuter, H. I., Nelson, A. D. (2008). *Hole-filled SRTM for the globe : Version 4 : data grid*.

Jarvis, A., Reuter, H. I., Nelson, A., Guevara, E. (2006). Hole-filled seamless SRTM data V3. *International Centre for Tropical Agriculture (CIAT)*

Kılıç, B., Gülgen, F., Çelen, M., Öncel, S., Oruç, H., Vural, S. (2022). Morphometric Analysis of Saz-Çayırova Drainage Basin using Geographic Information Systems and Different Digital Elevation Models. *International Journal of Environment and Geoinformatics*, 9(2), 177-186. doi.10.30897/ijegeo. 1079851

Lane, S. N., James, T. D., Crowell, M. D. (2000). Application of Digital Photogrammetry to Complex Topography for Geomorphological Research. *The Photogrammetric Record*, *16*(95), 793 821. doi.org/10.1111/0031-868X.00152

Leica Geosystems, G. (2006). Leica GRX 1200 Series : Technical Data. *Printed in Switzerland*.

Liu, J. G., Mason, P. (2013). *Essential Image Processing and GIS for Remote Sensing*. https://nbn-resolving.org/urn:nbn:de:101:1-201412208115

Ludwig, R., Schneider, P. (2006). Validation of digital elevation models from SRTM X-SAR for applications in hydrologic modeling. *ISPRS Journal of Photogrammetry and Remote Sensing*, *60*(5), 339 358. doi.org/10.1016/j.isprsjprs.2006.05.003

Maune, D. F. (2001). *Digital elevation model technologies and applications : The DEM users manual* (American Society for Photogrammetry and Remote Sensing, Éd.). American Society for Photogrammetry and Remote Sensing.

Miliaresis, G. Ch., Paraschou, C. V. E. (2005). Vertical accuracy of the SRTM DTED level 1 of Crete. *International Journal of Applied Earth Observation and Geoinformation*, *7*(1), 49 59. doi.org/10.1016 /j.jag.2004.12.001

Miliaresis, G. Ch., Paraschou, C. V. E. (2011). An evaluation of the accuracy of the ASTER GDEM and the role of stack number : A case study of Nisiros Island, Greece. *Remote Sensing Letters*, *2*(2), 127 135.doi.org/10.1080/01431161.2010.503667

Miller, C. L., Laflamme, R. A. (1958). The Digital Terrain Model—Theory & Application. *PHOTOGRAMMETRIC ENGINEERING*, 10.

Mouratidis, A., Briole, P., Katsambalos, K. (2010). SRTM 3″ DEM (versions 1, 2, 3, 4) validation by means of extensive kinematic GPS measurements : A case study from North Greece. *International Journal of Remote Sensing*, *31*(23), 6205 6222. doi.org/10.1080/01431160903401403

Oksanen, J., Sarjakoski, T. (2005). Error propagation of DEM-based surface derivatives. *Computers & Geosciences*, *31*(8), 1015 1027. doi.org/10. 1016/j.cageo.2005.02.014

Rabus, B., Eineder, M., Roth, A., Bamler, R. (2003). The shuttle radar topography mission—A new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing*, *57*(4), 241 262. doi.org/10.1016/S0924-2716(02)00124-7

Reuter, H. I., Nelson, A., Jarvis, A. (2007). An evaluation of void-filling interpolation methods for SRTM data. *International Journal of Geographical Information Science*, *21*(9), 983 1008. doi.org/10. 1080/13658810601169899

Rexer, M., Hirt, C. (2014). Comparison of free high resolution digital elevation data sets (ASTER GDEM2, SRTM v2.1/v4.1) and validation against accurate heights from the Australian National Gravity Database. *Australian Journal of Earth Sciences*, *61*(2), 213 226. doi.org/10.1080/ 08120099.2014.884983

Rey, J.-M. (1997). *Techniques GPS en mode cinématique* doi.org/10.5169/SEALS-235359

Rodríguez, E., Morris, C. S., Belz, J. E., Chapin, E. C., Martin, J. M., Daffer, W., Hensley, S. (2005). *An Assessment of the SRTM Topographic Products*. 143.

Satgé, F., Bonnet, M. P., Timouk, F., Calmant, S., Pillco, R., Molina, J., Lavado-Casimiro, W., Arsen, A., Crétaux, J. F., Garnier, J. (2015). Accuracy assessment of SRTM v4 and ASTER GDEM v2 over the Altiplano watershed using ICESat/GLAS data. *International Journal of Remote Sensing*, *36*(2), 465 488. doi.org/10.1080/01431161.2014.999166

Shapiro, L. G., Stockman, G. C. (2001). *Computer Vision* (1st edition). Pearson.

Slater, J. A., Garvey, G., Johnston, C., Haase, J., Heady, B., Kroenung, G., Little, J. (2006). The SRTM Data "Finishing" Process and Products. *Photogrammetric Engineering & Remote Sensing*, *72*(3), 237 247. doi.org/10.14358/PERS.72.3.237

Slater, J. A., Heady, B., Kroenung, G., Curtis, W., Haase, J., Hoegemann, D., Shockley, C., Tracy, K. (2011). Global Assessment of the New ASTER Global Digital Elevation Model. *Photogrammetric Engineering & Remote Sensing*, *77*(4), 335 349. doi.org/10.14358/ PERS.77.4.335

Sun, G., Ranson, K. J., Kharuk, V. I., Kovacs, K. (2003). Validation of surface height from shuttle radar topography mission using shuttle laser altimeter. *Remote Sensing of Environment*, *88*(4), 401 411. doi.org/10.1016/j.rse.2003.09.001

Tahiri, D., Alaoui, A., Zeddib, H., Rasmy, L. (2011). Évaluation Du Mnt Global Aster Gdem Sur Le Territoire Marocain. In *The 25th International Cartographic Conference*. French Committee of Cartography.

Yaman, A., Yılmaz, H. M., Bilgilioğlu, S. S. (2019). Comparison of Point Accuracies on Digital Elevation Model Obtained from Digital Air Photographs with Different Specifications. *International Journal of Environment and Geoinformatics*, 6(1), 131-134. doi. 10.30897/ijegeo.551722.

van Zyl, J. J. (2001). The Shuttle Radar Topography Mission (SRTM) : A breakthrough in remote sensing of topography. *Acta Astronautica*, *48*(5 12), 559 565. doi.org/10.1016/S0094-5765(01)00020-0

Zhao, G., Xue, H., Ling, F. (2010). Assessment of ASTER GDEM performance by comparing with SRTM and ICESat/GLAS data in Central China. *2010 18th International Conference on Geoinformatics*, 1 5. doi.org/10.1109/ GEOINFORMATICS.2010. 5567970.