Accuracy Assessment of Digital Terrain Models of Lowland Pedunculate Oak Forests Derived from Airborne Laser Scanning and Photogrammetry

Ivan Balenović, Mateo Gašparović, Anita Simic Milas, Alen Berta, Ante Seletković

Abstract

Digital terrain models (DTMs) present important data source for different applications in environmental disciplines including forestry. At regional level, DTMs are commonly created using airborne digital photogrammetry or airborne laser scanning (ALS) technology. This study aims to evaluate the vertical accuracy of DTMs of different spatial resolutions derived from high-density ALS data and existing photogrammetric (PHM) data in the dense lowland even-aged pedunculate oak forests located in the Pokupsko basin in Central Croatia. As expected, the assessment of DTMs' vertical accuracy using 22 ground checkpoints shows higher accuracy for ALS-derived than for PHM-derived DTMs. Concerning the different resolutions of ALS-derived (0.5 m, 1 m, 2 m, 5 m) and PHM-derived DTMs (0.5 m, 1 m, 2 m, 5 m, 8 m) compared in this research, the ALS-derived DTM with the finest resolution of 0.5 m shows the highest accuracy. The root mean square error (RMSE) and mean error (ME) values for ALS-derived DTMs range from 0.14 m to 0.15 m and from 0.09 to 0.12 m, respectively, and the values decrease with decreasing spatial resolution. For the PHM-derived DTMs, the RMSE and ME values are almost identical regardless of resolution and they are 0.35 m and 0.17 m, respectively. The findings suggest that the 8 m spatial resolution is optimal for a given photogrammetric data, and no finer than 8 m spatial resolution is required. This research also reveals that the national digital photogrammetric data in the study area contain certain errors (outliers) specific to the terrain type, which could considerably affect the DTM accuracy. Thus, preliminary evaluation of photogrammetric data should be done to eliminate possible outliers prior to the DTM generation in lowland forests with flat terrain. In the absence of ALS data, the finding in this research could be of interests to countries, which still rely on similar photogrammetric data for DTM generation.

Keywords: DTM, ALS, LiDAR, stereo-photogrammetry, aerial images, even-aged forest stands, Central Croatia

1. Introduction

Digital terrain models (DTMs) provide three-dimensional information of the Earth's bare surface excluding vegetation and man-made features (Li et al. 2005). DTMs present the important data source for different applications in environmental disciplines such as hydrology, geology, agronomy, and forestry. In forestry, DTMs can be used to support forestry operations (Stereńczak and Moskalik 2014), disaster risk analysis (Ristić et al. 2017), assessment of forest structure variables (Rahlf et al. 2015, Puliti et al. 2016, Balenović et al. 2017), etc. In particular, DTMs are used in combination with the digital surface models (DSMs) to obtain canopy height models (CHMs) or normalized point clouds, which are further used to estimate various forest variables at tree level (Rahlf et al. 2015) or area level (Puliti et al. 2016, Balenović et al. 2017).

A classical field survey by means of Global Navigation Satellite System (GNSS) receivers or total stations presents the most accurate method for acquiring data for DTM generation (Höhle and Potuckova 2011). However, for large areas, field surveys are expensive and time-consuming and, therefore, less efficient than the remote sensing methods. At regional level, DTMs are nowadays commonly created using airborne digital photogrammetry or airborne laser scanning (ALS) technology (Höhle and Höhle 2009). Currently, the most efficient remote sensing technology, in terms of accuracy, is ALS based on light detection and ranging (LiDAR) (Stereńczak et al. 2011). Namely, both technologies perform well in open areas, but as the laser beam can penetrate through the forest canopy and reach the ground, ALS is especially effective in forested and vegetated areas. National ALS campaigns have been performed or are still being performed in more and more countries worldwide, where ALS data now present the main source for DTM generation. However, a number of countries in Europe (e.g. Croatia, Greece, Hungary, Slovakia, etc.) and worldwide do not have a good ALS data coverage, and photogrammetrically derived data present the national standard for DTM generation.

The accuracy of DTMs, especially of ALS-derived DTMs, over different forest areas has been the focus of several studies. For example, Reutebach et al. (2003) investigated the accuracy of ALS-derived DTM of 1.52 m resolution over different stand densities of mountainous pine forests in western Washington, USA. The root mean square error (RMSE), mean error (ME) and standard deviation (SD) between DTM and ground checkpoints was 0.32 m, 0.22 m and 0.24 m, respectively. They found no significant differences in their results for different stand densities. Somewhat lower accuracy (RMSE≈0.55 m), but similar overestimation pattern (ME=0.20 m) for ALS-derived DTM, was obtained by Su and Bark (2006), whose research was conducted in aspen forests of different ages in Alberta, Canada. More recent research by Stereńczak et al. (2013) was focused on assessing the accuracy of ALS-derived DTMs of different spatial resolutions (0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 10 m) in pine forest stands at flat and steep terrain in western Poland. The RMSEs ranged between 0.09 m and 0.18 m for the flat terrain and 0.39 m and 1.34 m for steep terrain, whereas the MEs ranged between –0.12 m and 0.09 m for flat terrain, and –0.26 m and –1.16 m for steep terrain. Stereńczak et al. (2013) concluded that DTM had higher accuracy on flat terrains and that the DTMs' accuracy in general increases with the increase of spatial resolution. Furthermore, Stereńczak et al. (2016) evaluated the influence of various factors (forest structure, slope, off-nadir angle, understory vegetation and filtration and interpolation algorithm) on ALS-derived DTM accuracy in mixed mountainous forests in southwestern Poland. The RMSE and ME ranged from 0.19 m to 0.23 m, and from 0.13 m to 0.16 m, respectively. They identified the slope and particularly undergrowth vegetation as the most important factors influencing DTM accuracy. A direct relationship between the slope increments and DTM error has been recently confirmed by Aryal et al. (2017) within the study conducted in heterogeneous forest sites of Bavarian Forest National Park (southeastern Germany). Moreover, they obtained higher DTM errors for forest stands dominated by deciduous trees rather than for coniferous, mixed, and deadwood-dominated stands. From the above-mentioned studies, it is evident that DTM accuracy is affected by various factors, such as ALS data characteristics, forest and terrain characteristics. Thus, further research, which will include and encompass different ALS, forest and terrain characteristics, is needed. Contrary to ALS-derived DTM, the accuracy of photogrammetrically derived DTM has not attracted a lot of attention, especially within recent research. One of the rare exceptions is the research of Gil et al. (2013), which compared ALS and photogrammetrically derived DTMs in pine forests of Tenerife Island (Spain).

The aim of this study is to evaluate the vertical accuracy of DTMs of different spatial resolutions (0.5 m, 1 m, 2 m, 5 m, 8 m) derived from high-density ALS point clouds and existing photogrammetric data in dense lowland even-aged pedunculate oak (*Quercus robur* L.) forests. To the best of authors' knowledge, the DTM's accuracy in lowland pedunculated oak forests has not been the subject of similar studies. The results of this research could be of great interest to countries that still do not have ALS data, but have similar photogrammetric data for DTM generation.

2. Materials and methods

2.1 Study area

The study area, a part of the management unit Jastrebarski lugovi (991.50 ha), covers a portion of the forested area in the Pokupsko basin, located in Central Croatia, approximately 35 km southwest of Zagreb (Fig. 1). The management unit Jastrebarski lugovi is mainly covered with dense lowland even-aged pedunculate oak (*Quercus robur* L.) forests aged between 0 to 160 years, and even-aged narrow-leaved ash (*Fraxinus angustifolia* Vahl.) forests aged between 0 to 80 years. Oak and ash even-aged forest stands cover ≈77% and ≈20% of the total forest area, respectively. The oak stands are commonly mixed with other tree species, such as *Carpinus betulus* L., *Alnus glutinosa* (L.) Geartn., and *Fraxinus angustifolia* Vahl., while the ash stands are more homogenous and rarely mixed with tree species, such as *Alnus glutinosa* (L.) Geartn., and *Quercus robur* L. Two understory species, *Corylus avellana* L. and *Crataegus monogyna* Jacq., are common in the entire area. The forest stands are actively managed for sustained timber based on the 140-year (oak stands) and 80-year (ash stands) rotation cycles, having two or three regeneration fellings during the last 10 years of the rotation.

The study area is mostly flat, with ground elevations ranging from 105 to 118 m a.s.l. Soils are hydromorphic on clay parent material (Mayer 1996), and according to the World Reference Base for Soil Resources (WRB 2006), they are classified as luvic stagnosol. According to Köppen classification, the climate of the area is warm temperate with the mean annual temperature of 10.6°C and precipitation of 962 mm·y^{-1} (data from national Meteorological and Hydrological Service for the nearest meteorological station for the period 1981–2010).

2.2 Field reference data

The ground checkpoints recorded in the field by geodetic methods (e.g. total station, GNSS receivers) are

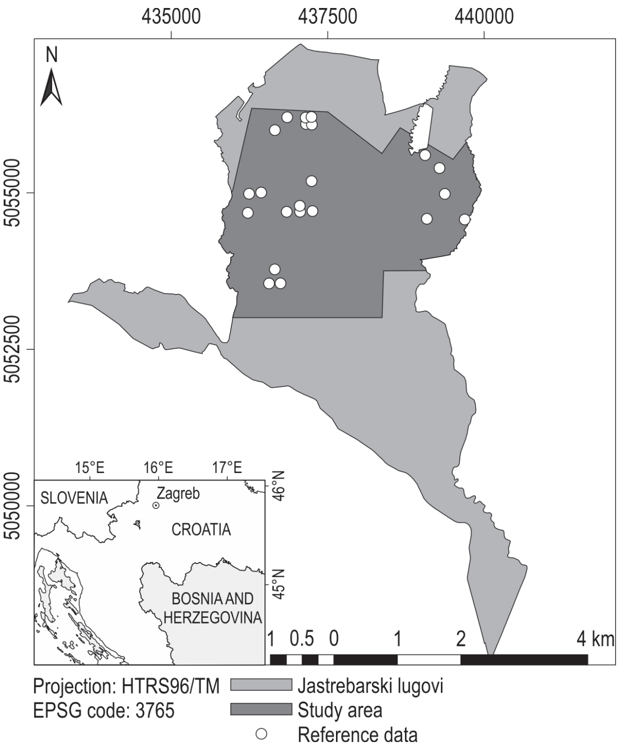

Fig. 1 Location of the study area (Jastrebarski lugovi) situated within the Pokupsko basin in Croatia with reference data (GNSS measured locations – white dots) for DTMs accuracy assessment

the most common reference data used for the accuracy assessment of DTM (Höhle and Höhle 2009). In order to obtain reliable accuracy measures, the ground checkpoints should have at least three times higher accuracy than DTM (Maune 2007). Besides high accuracy, the number of checkpoints should be sufficiently large, and they should be randomly distributed over the target area (Höhle and Höhle 2009). According to the American Society for Photogrammetry and Remote Sensing, for testing the vertical accuracy of DTM a minimum of 20 checkpoints should be collected in each of the major land cover categories of the area (ASPRS 2004).

Prior to the field work, the selection of potential ground checkpoints and pre-definition of their locations were done in the GIS environment (Global Mapper version 19 software; Blue Marble Geographics, Hallowell, Maine, USA). For that purpose, a regular grid with 100 m grid size was overlaid over the selected part of the study area. Four adjacent points were grouped in a quadrat and then numbered in the counter clockwise direction. From each quadrat, one point with the lowest numeration was selected as a ground checkpoint, given that the predefined condition of the minimum distance between the point and the forest edge and/or forest sub-compartment border was satisfied. The minimum distance was set to be 20 m, 30 m, and 50 m in the 21–60 year-old, 61–100 year-old, and 101–160 year-old forest stands, respectively. Namely, this approach was used because the recorded points would be used as the centers of the sample plots in the consequent research. In total, 114 points were selected as potential ground checkpoints.

The positioning (x, y, z) coordinates of the selected points were recorded using the GNSS receiver Stonex S9IIIN connected with the Croatian Positioning System (CROPOS), a network of reference stations which transmit corrections in real time directly to the GNSS receiver by mobile Internet. In this way, it is possible to obtain both horizontal and vertical positional accuracy from 2 to 5 cm (CROPOS – Users' Manual). To further increase the accuracy of the GNSS measurements, the data was collected with antenna receiver of 4 m in height during leaf-off conditions between 8 and 15 March 2017. The maximum time for measuring the positions was 30 minutes per location. During this time, an attempt was made to record the positions in FIXED receiver mode, which provided more accurate and more reliable results than the FLOAT mode (Brach and Zasada 2014). However, if the measurement with the FIXED mode were not realized during the 30 minutes, the point would be recorded with the FLOAT mode.

In order to obtain highly accurate and reliable reference data for the vertical accuracy assessment of

DTMs, only points recorded with FIXED receiver mode, and with vertical precision (standard deviation calculated by the receiver) ≤10 cm, were selected as ground checkpoints. Out of 114 recorded points, 22 points met these criteria. Due to limitations caused by dense forest conditions, the number of the selected ground checkpoints was not excessive, but it was relatively large under given conditions and also randomly distributed over the study area (Fig. 1).

2.3 Digital terrain models (DTMs) data and processing

2.3.1 ALS data and ALS-derived DTM

The ALS data were provided by the company Hrvatske vode, Zagreb, Croatia, a legal entity for water management, whereas the acquisition and processing were conducted by the Zavod za fotogrametriju d.d. and Mensuras d.d. under leaf-on conditions in several surveys between 29 June and 25 August 2016. The data were collected with an Optech ALTM Gemini 167 laser scanner mounted on the Pilatus P6 aircraft. The average flying height was 720 m above ground level with an average flying speed of 51 $m \cdot s^{-1}$. The laser pulse repetition frequency was 125 Hz, and field of view was ±25°. Resulting point densities for the study area, considering all returns and »last only«, were 13.64 $points \cdot m^{-2}$ and 9.71 $points \cdot m^{-2}$, respectively. According to the data provider, the horizontal accuracy of recorded points was 15 cm, and vertical accuracy was 8.3 cm. The stated accuracies were based on a much larger area than the one considered in this study, where forested and non-forested areas were included. The point data were classified into ASPRS Standard LiDAR Point Classes (ASPRS 2008) using TerraSolid (version 11) software (Terrasolid Ltd. 2012). In total, approximately 7% of all returns over the study area were classified as »ground«, resulting with an average ground point density of 0.91 $points \cdot m^{-2}$. Classification of the ground was based on the progressive triangulated irregular network (TIN) densification algorithm developed by Axelsson (2000). This procedure for LiDAR data classification for the purposes of defining ground data was used in several studies (Gobakken et al. 2014, Guan et al. 2014, Sánchez-Lopera and Lerma 2014, Torresan et al. 2014). From the classified ground returns, regular grids of various spacing (0.5 m, 1 m, 2 m, and 5 m) were generated and provided to us in .las format.

A raster DTMs with 0.5 m ($ALS\text{-}DTM_{0.5}$), 1 m ($ALS\text{-}DTM_1$), 2 m ($ALS\text{-}DTM_2$) and 5 m ($ALS\text{-}DTM_5$) resolution (pixel size) were generated from regular grids using the triangulated irregular network (TIN) and linear interpolation techniques of Global Mapper software.

2.3.2 Photogrammetric data and PHM-derived DTM

In this research, the digital terrain data used to generate photogrammetric DTMs (PHM-derived DTMs) were provided by the Croatian State Geodetic Administration (CSGA). These data present the Croatian national standard and, currently, they are the only available DTM data for most of Croatia, with the exception of several smaller areas surveyed with ALS, as shown in this study.

According to the rules of the CSGA (Product Specifications 301D150), the digital terrain data consisted of several three-dimensional vector data such as breaklines, formlines, spot heights and mass points. Breaklines are line strings (features) that describe the change of a slope declination, mostly ruptures as e.g. mountain ridges, incisions, dams, shores, and they are recognized as terrain fracture. Formlines are line strings that describe smooth terrain physical properties (e.g. the deepest line in a shallow ditch, the highest lines along the mountain ridge). Spot height presents the highest or lowest point of the characteristic landscape (e.g. peaks or sinks). Mass points are height points measured in irregular distribution that fill the area surrounded by breaklines and formlines.

The digital terrain data were collected by aerial stereo photogrammetry using digital aerial images of GSD≤30 cm (GSD – ground sample distance), supported with vectorization of existing maps and field data collection (especially for areas which were not visible from aerial images). Data density was dependent on terrain type, slope and surface roughness. The average distance between points in breaklines and formlines was recommended to be 25 meters. The average distance between mass points was considered to be 70–90 meters for open areas, whereas for flat areas or areas covered by vegetation, the distance was not more than 120 meters. For the flat terrain, which corresponds to the terrain type of Pokupsko basin, the required number of points in breaklines and formlines was 400–800 $points \cdot km^{-2}$, while the required number of mass points and spot heights was 100–150 $points \cdot km^{-2}$. The required absolute accuracy of digital terrain data (including both horizontal and vertical accuracy) validated with ground control points was <±1 m of the standard deviation for the well-defined details and <±2 m for not well-defined details. For this study area, the average number of points in breaklines and formlines was 455 $points \cdot km^{-2}$, while the average number of mass points and spot heights was 141 $points \cdot km^{-2}$, which corresponds to the recommendations of Product Specification 301D150 of CSGA.

Table 1 Results of Shapiro-Wilk test for normality of errors distribution

Parameter	Digital terrain models								
	ALS-DTM$_{0.5}$	ALS-DTM$_1$	ALS-DTM$_2$	ALS-DTM$_5$	PHM-DTM$_{0.5}$	PHM-DTM$_1$	PHM-DTM$_2$	PHM-DTM$_5$	PHM-DTM$_8$
W	0.92	0.97	0.98	0.97	0.95	0.95	0.95	0.95	0.95
p	0.11	0.77	0.97	0.80	0.28	0.28	0.28	0.29	0.30

Similar to ALS-DTMs generation, a photogrammetric raster DTMs with 0.5 m (PHM-DTM$_{0.5}$), 1 m (PHM-DTM$_1$), 2 m (PHM-DTM$_2$) and 5 m (PHM-DTM$_5$) resolution were generated from the national digital terrain data using the triangulated irregular network (TIN) and linear interpolation techniques. Additionally, a raster

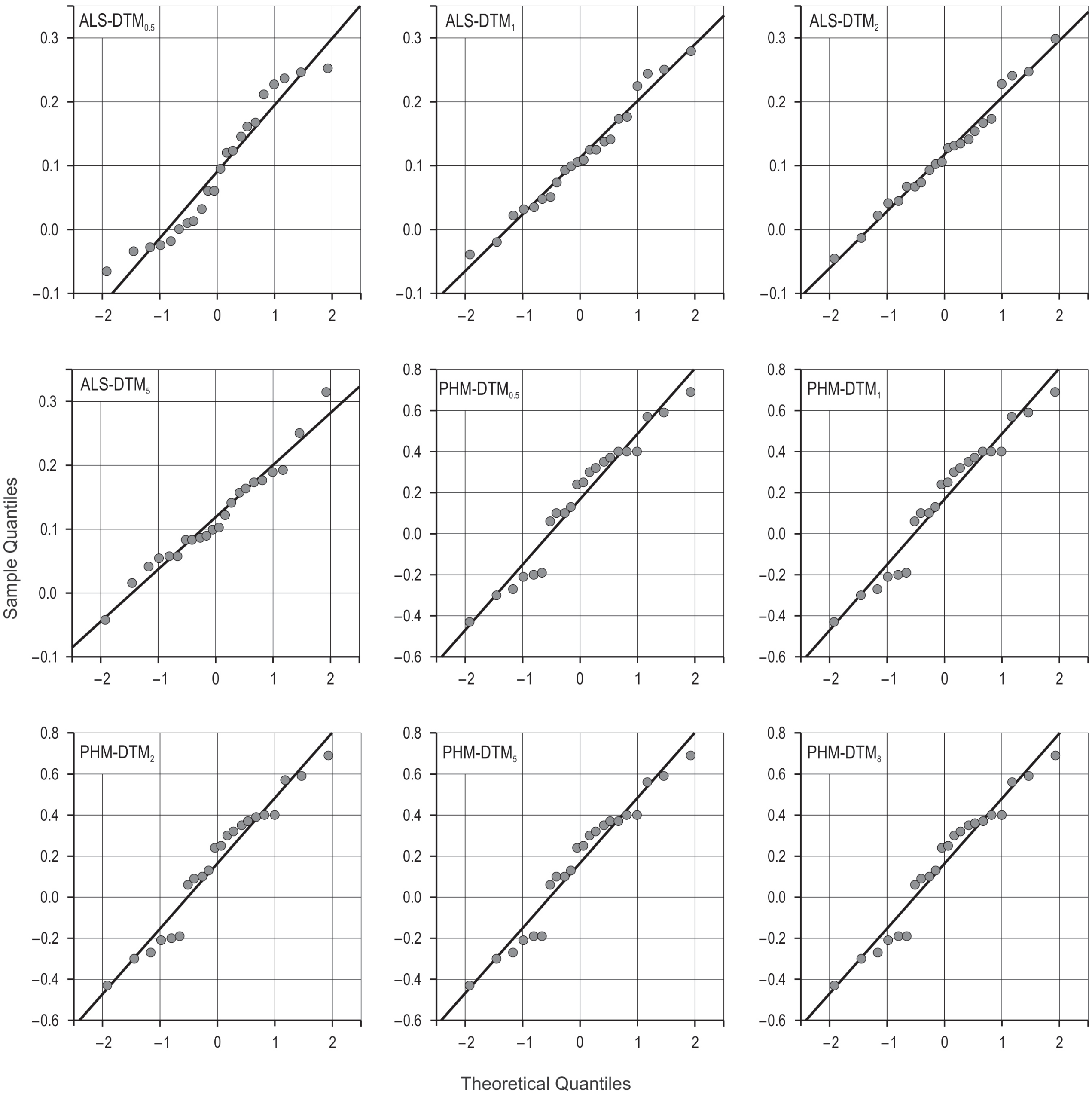

Fig. 2 Normal Q-Q plots

DTM with 8 m resolution (PHM-DTM_8) was generated based on optimal grid spacing (for used data) automatically determined by the Global Mapper software.

2.4 Accuracy assessment

The vertical accuracy assessments of the ALS-derived and PHM-derived DTMs of different resolutions were conducted by comparing elevations of the ground checkpoints and elevations of the planimetrically corresponding points extracted from raster DTMs. Since the different accuracy measures should be applied to DTMs with normal and those with non-normal error distribution (Höhle and Höhle 2009), the normality of the error distribution was tested for each DTM. Vertical errors between DTMs and checkpoints elevations were calculated, and the normality of errors distribution was analyzed using:

⇒ Shapiro-Wilk test (Shapiro and Wilk 1965) (Table 1)

⇒ normal Q-Q plots (Fig. 2).

All the statistical analyses were performed using the STATISTICA software (version 11; Hill and Levicki 2007).

Both tests, Shapiro-Wilk and normal Q-Q plots, revealed that vertical errors were normally distributed for each resolution of both ALS-derived and PHM-derived DTMs. Namely, *p* values of Shapiro-Wilk test were greater than 0.05 (Table 1) for each DTM, whereas only slight deviations of points from straight lines were observed in each Q-Q plot (Fig. 2). Therefore, as suggested by Höhle and Höhle (2009), the following measures were used for DTMs accuracy assessment with reference data (ground checkpoints): vertical error at point *i* (Δz_i), root mean square error (*RMSE*), mean error (*ME*), and standard deviation error (*SD*):

$$\Delta z_{\mathrm{i}} = z_{\mathrm{DTMI}} - z_{\mathrm{GCPi}} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{\mathrm{i=1}}^{\mathrm{n}} \Delta z_{\mathrm{i}}^2} \quad (2)$$

$$ME = \frac{1}{n}\sum_{\mathrm{i=1}}^{\mathrm{n}} \Delta z_{\mathrm{i}} \quad (3)$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{\mathrm{i=1}}^{\mathrm{n}} (\Delta z_{\mathrm{i}} - ME)^2} \quad (4)$$

Where:

z_{DTMi} the elevation of DTM calculated from point *i*,

z_{GCPi} the elevation of ground checkpoints measured in the field on point *i*, and *n* is the number of points.

To further evaluate the accuracy of PHM-derived DTM, the comparison between ALS- and PHM-derived DTMs of the highest accuracy (according to the evaluation with ground checkpoints) was conducted using the difference raster model (Gil et al. 2013). The difference raster model was generated for the entire study area by subtracting ALS- from PHM-derived DTM. In this case, the elevations from ALS-derived DTM were considered as reference data and the above-mentioned accuracy measures (Δz_i, *RMSE*, *ME*, *SD*) were calculated.

3. Results and discussion

As expected, the assessment of DTMs vertical accuracy in dense lowland pedunculated oak forests, conducted using 22 ground checkpoints, shows higher accuracy for ALS-derived DTMs than for PHM-derived DTMs (Fig. 3). The RMSE values for ALS-derived DTMs range from 0.14 m to 0.15 m, while for PHM-derived DTMs they amount to 0.35 m for all resolutions. This suggests that the ALS data provide more accurate DTM values and are more suitable remote sensing data for dense forested areas (Höhle and Potuckova 2011, White et al. 2013). Furthermore, the *ME* values are positive for both ALS- and PHM-derived DTMs indicating that elevations extracted from DTMs on average overestimate elevations of the ground checkpoints. The overestimations for ALS-derived DTMs range from 0.09 m to 0.12 m, whereas PHM-derived DTMs produce slightly greater overestimations with the value of 0.17 m for all resolutions. This is in agreement with other similar studies (Reutebuch et al. 2003, Su and Bork 2006, Gil et al. 2013, Stereńczak et al. 2016), which reported that due to near ground vegetation (e.g. grass, litter, woody debris) in the forest, ALS-derived DTMs had a tendency to overestimate the real reference terrain elevations.

Among all evaluated DTMs, the ALS-derived DTM (ALS-$DTM_{0.5}$) with the highest resolution (0.5 m) shows the highest accuracy (*RMSE*=0.14 m, *ME*=0.09 m, *SD*=0.10 m). All other ALS-derived DTMs with resolutions of 1 m, 2 m and 5 m produce just slightly larger errors (Fig. 3). Although the differences between the errors are small, it is evident that the accuracy of DTM slightly decreases with the decrease of resolution, which is in accordance with findings of Stereńczak et al. (2011, 2013).

Differences between the results for all PHM-derived DTM resolutions are almost negligible (Fig. 3). The results (errors) differ in the third decimal place only. However, among all PHM-derived DTMs, the DTM with the coarser spatial resolution of 8 m

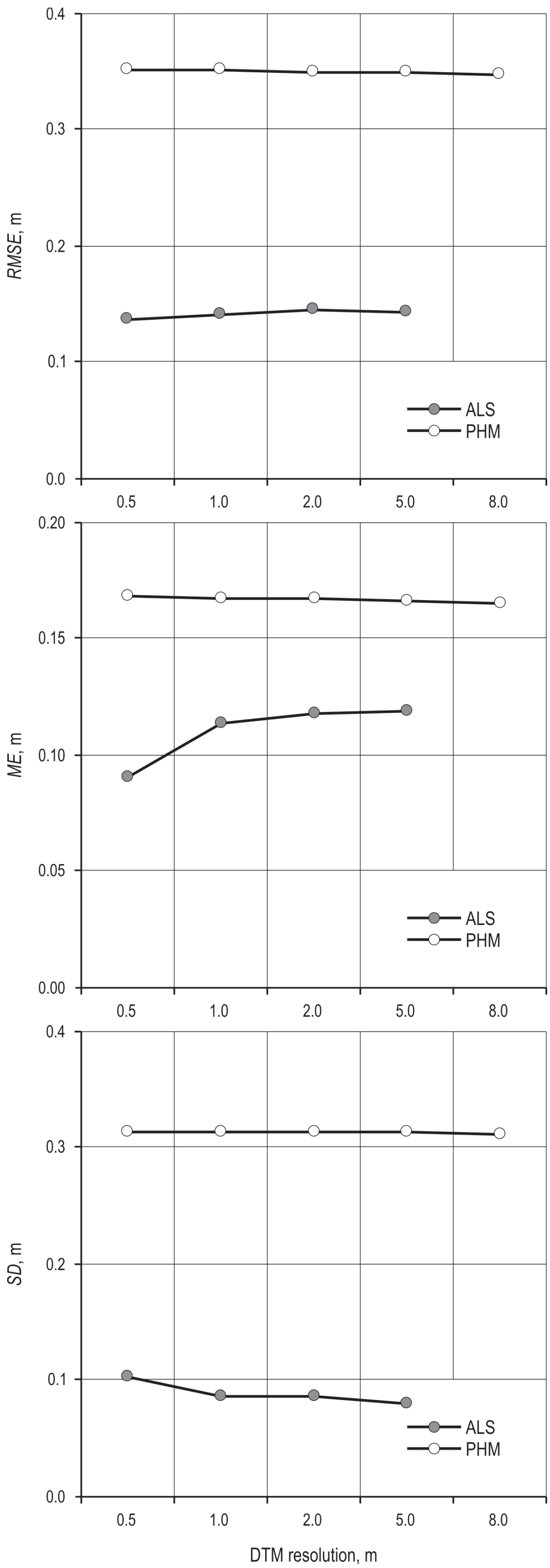

Fig. 3 Vertical accuracy (*RMSE, ME, SD*) of ALS- and PHM-derived DTMs of different resolutions assessed with ground checkpoints

($PHM\text{-}DTM_8$) exhibits the highest accuracy (*RMSE*=0.35 m, *ME*=0.17 m, *SD*=0.31 m) This suggests that this spatial resolution can be considered as optimal for given source data and that there is no need for finer spatial resolution for a given photogrammetric data. Moreover, keeping the coarser spatial resolution especially for larger areas, the processing of raster data is faster.

The vertical errors (Δz_i; differences between DTM and checkpoint elevations) of the most accurate PHM- and ALS-derived DTMs at each ground checkpoint are shown in Fig. 4. At each checkpoint, the errors of $PHM\text{-}DTM_8$ are considerably larger ranging from –0.43 m to 0.69 m than errors of $ALS\text{-}DTM_{0.5}$, which range from –0.06 m to 0.25 m. Furthermore, it can be seen that elevation values of $PHM\text{-}DTM_8$ vary noticeably from the underestimation to the overestimation, whereas $ALS\text{-}DTM_{0.5}$ elevation values mostly overestimate checkpoints elevations. Only elevations of 5 checkpoints are slightly underestimated by $ALS\text{-}DTM_{0.5}$. The common overestimation of the ALS-derived DTMs in forest areas caused by near ground vegetation has been already discussed above. Another possible reason for the overestimation may arise from field measurements of ground checkpoints. Namely, due to weather and terrain conditions (e.g. moist soil) during the field measurements, some sinking of the posts used to hold the GNSS antenna receiver is possible, causing changes in the level and inclination of posts and ultimately the overestimation of ALS-derived values. Finally, as already mentioned, the vertical precision (*SD*) of the selected ground checkpoints ≤10 cm, may also slightly influence the differences.

The obtained accuracies for ALS-derived DTMs in this study are in agreement with the other studies (Kraus and Pfeifer 1998, Reutebuch et al. 2003, Su and Bork 2006, Spaete et al. 2011, Stereńczak et al. 2011, 2013, 2016, Gil et al. 2013), although the direct comparison of the results is not fully justified due to a number of differences between studies regarding the used ALS data (e.g. point density, scanning angle, acquisition period), forest/vegetation type and structure (e.g. species composition, canopy and stem density, presence and density of low vegetation) and terrain characteristics (e.g. slope).

For further comparison between the PHM- and ALS-derived DTMs, a difference raster model of 0.5 m resolution was generated by subtracting $ALS\text{-}DTM_{0.5}$ from $PHM\text{-}DTM_8$ (Difference Model A, Fig. 5a) to detect the areas of greater elevation differences between the $PHM\text{-}DTM_8$ and $ALS\text{-}DTM_{0.5}$ (Gil et al. 2013). Further analysis revealed that the discrepancies were caused by photogrammetric data such as mass or

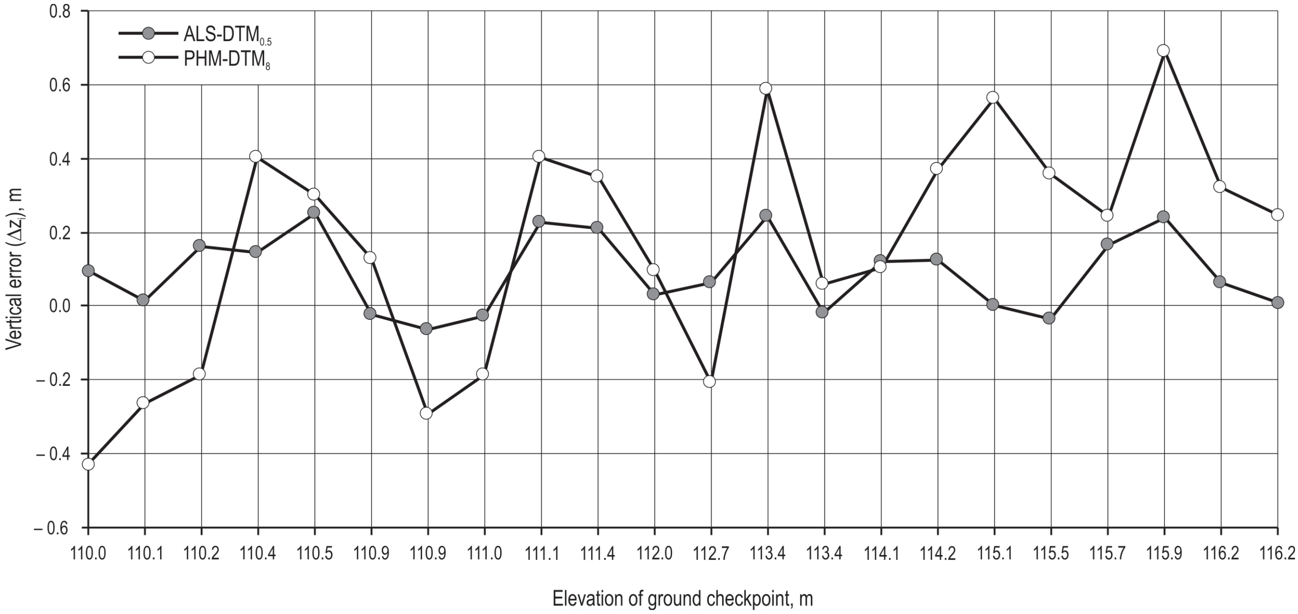

Fig. 4 Vertical errors (Δz_i; differences between DTM and checkpoint elevations) of ALS-DTM$_{0.5}$ and PHM-DTM$_8$ for each of 22 ground checkpoints

height points used for PHM-DTM$_8$ generation, which elevations considerably differed from elevations of all surrounding points (Fig. 5c). Therefore, all points for which elevation differed for more than 1 m from elevations of four surrounding points were removed, and new, improved PHM-DTM$_8$, as well as new Difference Model B, were generated (Fig. 5b, d). Out of 21 removed points (outliers), only one has greater negative elevation values compared to the elevations of surrounding points. The improvements of PHM-DTM$_8$ by eliminating 21 points can be observed even visually in Difference Model B (Fig. 5b, d). To validate the outliers, additional field observations were conducted, and the absence of the outlier was confirmed. The removed points present gross errors (outliers) that most likely occurred during photogrammetric measurements (restitution). Based on the authors' field experience, the threshold of 1 m for removing outliers is applicable in this study.

Descriptive statistics calculated for the entire area (54,687,600 pixels) for both difference models are presented in Table 3. Compared to Difference Model A, both the *RMSE* and *SD* values for Difference Model B are decreased by 0.02 m. On the other hand, *ME* is increased by 0.01 m because of 20 removed points (outliers) with positive values and only one point with a negative value. Opposite to the validation with ground checkpoints, where PHM-DTM$_8$ produce larger *ME* value than ALS-DTM$_{0.5}$ indicating that PHM elevations on average overestimate ALS elevations by 0.06 m, the comparison based on the Difference Model B for the entire research area shows that PHM elevations underestimate ALS elevations by –0.15 m on average. It should be noted that the ground checkpoints are placed in the north part of the research area (Fig. 1) where, according to Difference Model B (Fig. 5b), PHM values mostly overestimate ALS values, while PHM values mostly underestimate ALS values in the remaining area. Similarly, Gil et al. (2013) reported a tendency of PHM-derived DTM to underestimate the terrain elevations compared to ALS-derived DTM over the different conditions (e.g. flat and open terrain, hilly area covered by dense pine forest). Due to a large area (a large number of pixels used in calculations), the improvement of the PHM-DTM$_8$ by eliminating outliers seems to be negligible in terms of *RMSE* and *SD*, but Figs. 5c, 5d, and 5e, show that the improvement is considerable. For the exemplary area, vertical differences between ALS-DTM$_{0.5}$ and PHM-DTM$_8$ (i.e. vertical error of PHM-DTM$_8$) decrease up to 4 m (Fig. 5e).

4. Conclusions

This research first provided comparative accuracy assessment of ALS- and PHM-derived DTMs in dense lowland even-aged pedunculated oak forests. In accordance with recent studies, the results of this research confirmed that ALS was highly suitable remote sensing technology for accurate terrain modelling in dense forested areas. More precisely, the comparative

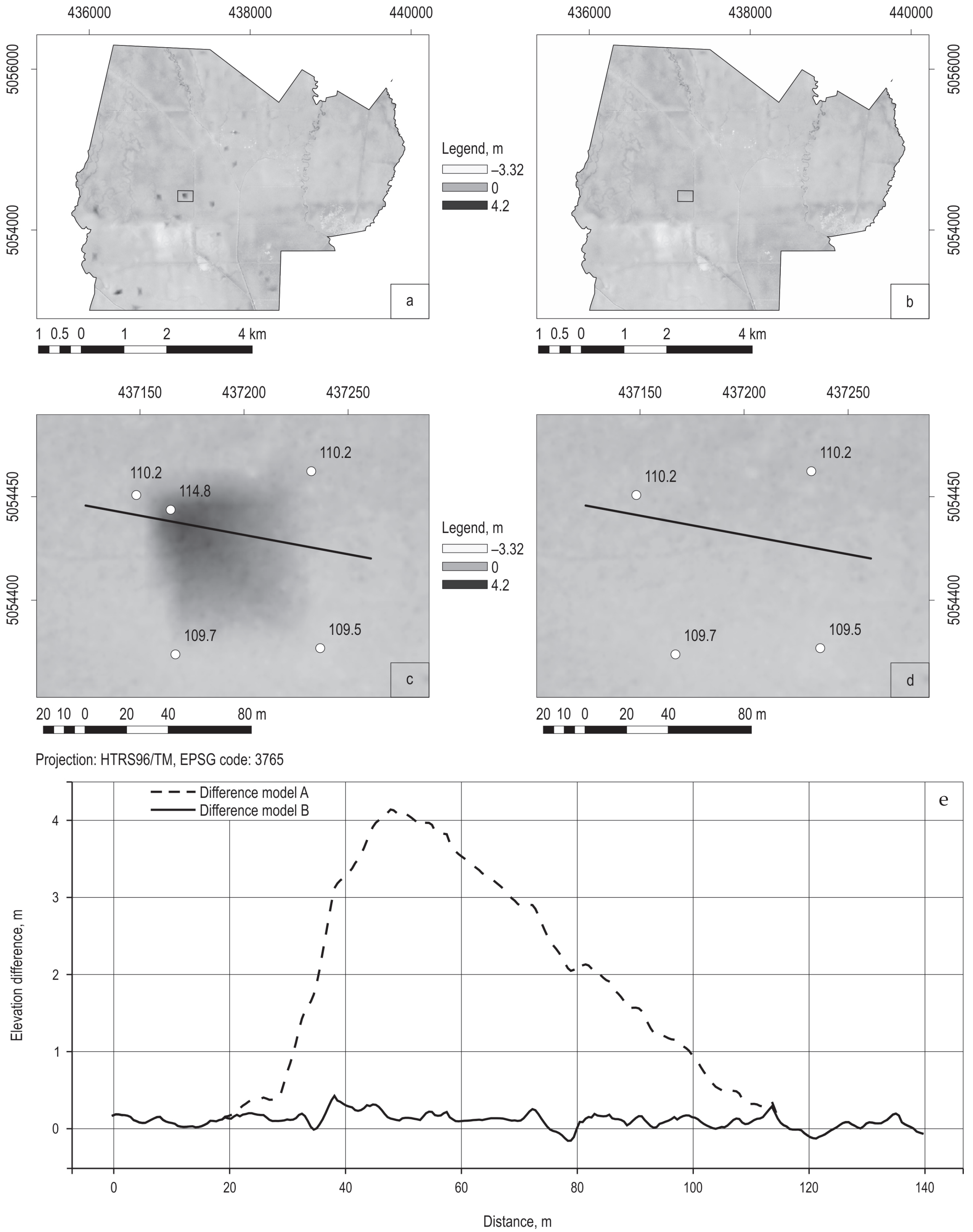

Fig. 5 (a) Difference Model A of 0.5 m resolution generated by subtracting ALS-DTM$_{0.5}$ from PHM-DTM$_8$; (b) Difference Model B of 0.5 m resolution generated by subtracting ALS-DTM$_{0.5}$ from improved PHM-DTM$_8$; (c) the exemplary area of Difference Model A; (d) the exemplary area of Difference Model B; (e) vertical profile of Differences models A and B across the exemplary area

Table 2 Descriptive statistics for Difference Model A and B

Difference Model	*RMSE*, m	*ME*, m	*SD*, m	*Max.*, m	*Min.*, m
A	0.51	–0.14	0.49	4.25	–3.68
B	0.49	–0.15	0.47	3.10	–3.68

accuracy assessment confirmed that ALS-derived DTM had higher accuracy then PHM-derived DTM. Concerning different resolutions of ALS-derived DTMs (0.5 m, 1 m, 2 m, 5 m) and PHM-derived DTMs (0.5 m, 1 m, 2 m, 5 m, 8 m) compared in this research, the ALS-derived DTM with the finest resolution of 0.5 m showed the highest accuracy. While the accuracy of ALS-derived DTMs slightly decreased with the decrease of its resolution, the differences between the obtained results for all PHM-derived DTM resolutions were almost negligible. Among all PHM-based DTMs, the DTM with the coarser spatial resolution (8 m), which is defined as optimal for given source data, showed the highest accuracy. This suggested that, for a given photogrammetric data, no finer than 8 m spatial resolution was needed. Regardless of the spatial resolution, both ALS- and PHM-derived DTMs on average overestimated elevations of the ground checkpoints, which was in agreement with findings of other recent studies based on ALS. Due to dense near ground vegetation present in the forest, ALS-derived DTMs tended to overestimate the real terrain elevations.

Additionally, this research revealed that the national digital photogrammetric data for forest areas contained specific errors (outliers), which considerably affected the DTM accuracy. Visual assessment of the difference raster model enabled detection of the areas of greater elevation differences between the PHM- and ALS-derived DTMs. The elimination of the outliers from photogrammetric data was successfully managed with the improved PHM-derived DTM. The occurrence of outliers is not uncommon for PHM-derived DTMs and their detection presents a challenge for scientists. Thus, in the absence of ALS data, the photogrammetric terrain data could be used for DTM generation in lowland forests with flat terrain but with the greatest caution.

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