The Accuracy Assessment of DTM Generated from LIDAR Data for Forest Area – a Case Study for Scots Pine Stands in Poland

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Stereńczak, K., Zasada, M. and Brach, M. 2013. The Accuracy Assessment of DTM Generated from LIDAR Data for Forest Area – a Case Study for Scots Pine Stands in Poland. *Baltic Forestry* 19(2): 252–262.

Abstract

The paper presents the analysis of the influence of various factors on the accuracy of the Digital Terrain Model (DTM) generated under forest conditions in pine stands. DTMs with 0.5, 1, 2, 3, 4, 5 and 10 meter pixel sizes have been evaluated. The accuracy assessment has been performed for 4 age classes (developmental stages) in flat terrain and on slopes. Additionally, the analysis of differences between values obtained from single pixels and from 3x3 pixels moving window for various DTM pixel size has been performed. The General Linear Model for repeated measures has been applied for the analyses. Only the overstocked young stands show different patterns of relationships between the DTM accuracy and resolution. On average, model error for slopes was 3 times larger than for the flat terrain. The height obtained from DTM created using direct pixel values of height is slightly more accurate than that obtained using values smoothed by 3x3 pixel windows, the difference, however, is not statistically significant. The use of percentiles is much more appropriate than mean-based measures, especially for not normally distributed and skewed data.

Key words: digital terrain model, airborne laser scanning, repeated measures ANOVA, error analysis, percentile, earth surface, Scots pine, slope, survey.

Introduction

The digital model of the earth is one of the most frequently used spatial data. In most cases, the term Digital Surface Model (DSM) represents the earth's surface and includes all objects on it. In contrast to a DSM, the Digital Terrain Model (DTM) represents the bare ground surface without any objects, like for example plants and buildings (Li et al. 2005). Accurate and reliable Digital Terrain Model is one of the most important sources of data for Geographic Information Systems (GIS) and photogrammetry workflows, analyses and studies. It can be used in a number of ways: to assess terrain parameters, to visualize and analyze the earth's surface, to rectify airborne and satellite imagery, to perform spatial analyses and to build other spatial models. The potential variation of this application allows it to be used as a base for numerous engineering and environmental analyses. One of the most commonly used digital models in forestry and in environmental study is the Crown Height Model (CHM). The CHM is created by subtracting the Digital Terrain Model "Z" (elevation) pixel values from the Digital Surface Model elevation pixel values. It can be used for the extraction of many forest parameters, for example stand density (Næsset et al. 2004), tree height (Næsset et al. 2004) and biomass or stand volume (Maltamo et al. 2004). The quality of DTM influences the excellence of CHM (Leckie et al. 2003, Maltamo et al. 2004, Næsset et al. 2004, Straub et al. 2006, Stereńczak et al. 2008, Zawiła-Niedźwiecki et al. 2008) and augments the dimension of topographic objects (Koch and Heipke 2006).

There are a few basic data sources for the DTM generation. The most traditional method is a classical field survey. Today this is usually done with the use of total station or GNSS receivers. This is a very accurate method, but also expensive and time consuming (Grala and Brach 2009, Yakar 2009). A more efficient and cost effective method is based on the processing of existing contour lines available on topographic maps (Yan et al. 2008). Alternatively we can utilize stereoscopic measurements on satellite radar imagery (Toutin and Gray 2000). There are also free DTM data available on the Internet, such as SRTM made from global radar interferometry data or ASTER derived from digital photogrammetry (http://www.jpl.nasa.gov/srtm, accessed 15 November 2012). Unfortunately, the spatial resolution of this data is low and is provided without any estimation of height error (Kervyn et al. 2008). Currently the best way to obtain a high spatial resolution and accuracy of the DTM is to use airborne LIDAR (Light Detection and Ranging) technique (Aguilar and Mills 2008).

The accuracy of the DTM in forested areas, particularly for projects of an engineering nature, can be a critical factor. The quality of the model depends on the accuracy and detail of the input data (Hassanin and Moshelhi 2003). Thanks to LIDAR it is possible to measure ground surface with very good height accuracy and in almost all kinds of land cover types. The overall accuracy of LIDAR data is about 10-15 cm (Baltsavias 1999), which means that although it is not the most accurate tool for DTM measurement, it is the only tool which allows good quality wide range DTM measurements. One of the most common methods of application of the LIDAR technology is airborne laser scanning (ALS).

The ALS, however, has a number of potential errors, which include: GNSS, INS, object characteristics, scanning angle, footprint size, flight altitude, processing and human errors (Baltsavias 1999). The lack of measurement points on the edge of the LIDAR swath causes the accuracy of the DTM height estimation to be reduced because of the irregular spacing of sample points (Lovell et al. 2005). The scanning angle is another factor affecting DTM quality (Lovell et al. 2005). Generally, in forested areas, a maximum angle of 10° should be used. Scan angles between 7° to 15° do not cause statistically significant differences in the generated terrain models (Ahokas et al. 2005). Previous studies on the effect of LIDAR data density on the DTM accuracy has proved, that even large reduction of original LIDAR datasets does not significantly change the results (Anderson et al. 2006).

The raw LIDAR point clouds are used as a base to create DTM using many algorithms (Hyyppä et al. 2004, Sithole and Vosselman 2004, Aguilar et al. 2005, Chaplot et al. 2006, Kobler et al. 2007). Various factors influence DTM accuracy. Slope is the most important factor affecting the quality of DTM (Aguilar et al. 2005, Hodgson et al. 2005, Hyyppä et al. 2005, Chaplot et al. 2006). This can cause large errors and misclassifications before DTM development starts, notably that the occurrence of random errors rises proportionally to the increase in slope (Hyyppä et al. 2005, Su and Bork 2006). Another important factor to be considered when analyzing model accuracy is the resolution of the DTM. For various purposes, different model resolutions are used. The highest resolution DSM does not always produce the highest accuracy (Wu et al. 2008). Generally, larger pixels of DTM give greater simplification of the area, so on the slopes it can cause larger errors. Yet another issue is flight altitude, which in general causes the decrease in the DTM accuracy with the increase in the flight height (Lovell et al. 2005, Yu et al. 2004, 2005). Apart from the technical aspects and flight conditions, objects existing on the earth surface can also affect DTM accuracy. Vegetation can also influence the terrain model production. It depends on its changing state throughout the vegetation season; therefore its influence varies over the year (Hyyppä et al. 2005, Stereńczak and Kozak 2011). Factors, such as species composition (Reutebuch et al. 2003, Yu et al. 2005, Stereńczak 2009), forest structure (Hodgson et al. 2005, Stereńczak 2009) and canopy density (Reutebuch et al. 2003, Hyyppä et al. 2005) influence LIDAR data density because they reduce the possibility of reaching the real ground surface by a laser beam. Therefore, it is very difficult to find an optimal structure parameter, which can characterize a forest. Segmentation into small regions, corresponding to either open areas (no vegetation above) or areas located under trees (Hyyppä et al. 2005), is not an optimal solution, because the scan angle varies from 0 degrees to at least 7 degrees in one direction, so generally most of the beam has to penetrate the top vegetation in order to reach the ground. This vegetation characteristic is very complex and difficult to model. Additionally, the presence of even low vegetation can cause an overestimation of real DTM values (Reutebuch et al. 2003, Hodgson et al. 2005). Small and dense foliage can imitate ground surface, because it is impermeable to laser beams. It has been proven that LIDAR data acquired during leaf-off time is the best for DTM generation (e.g. Hyyppä et al. 2005). Studies that have been published to date did not investigate the influence of pine stands, which are the main forest stands in Central Europe. Additionally, no wider comparison between pixel values and window mean values (3×3 pixels) were performed yet. It is not clear if slope causes large differences between this information. It is possible that pixel value can be distorted by slope. In such cases, it is suitable to use smoothened window values instead of pixel values. This will be evaluated in our research.

The most widely used global accuracy measurement for evaluating the performance of DEMs is the

Root Mean Square Error (RMSE). Other authors (e.g. Höhle and Höhle 2009), however, note that the DTM accuracy assessment has to take into account the fact that outliers may exist in the data sets and that errors may not follow the normal distribution. Consequently, various approaches to solve these problems have been proposed in available publications, such as robust estimators and non-parametric methods (e.g. Atkinson et al. 2005, Aguilar et al. 2007b). Aguilar et al. (2007a), for example, propose the use of the coefficient of variation of the sample variance. Höhle and Höhle (2009) focused on the use of sample error distribution quintiles as measures for the model accuracy.

Additional problems arise when comparing the performance of various DTMs. There are numerous approaches, using various statistical methods, to investigate the significance of errors of different models and conditions. Many papers describe and discuss differences in the model accuracy without using any formal statistical tests (e.g. Claessens et al. 2005, Hejmanowska et al. 2008, Tighe and Chamberlain 2009). Some authors apply various simple tests for means. For example, Reutebuch et al. (2003) tested the accuracy of the LIDAR-based terrain model under different conifer forest canopies. The authors employed a simple two-sample Z-test of the difference between the error means for various canopy classes and stated that there is an extremely small, but highly significant difference between the results obtained from various forest conditions. Chaplot et al. (2006) evaluated the effects of land form types, density of the data and interpolation techniques on the accuracy of DTM. These scientists characterized the accuracy of the models by means of the mean error and RMSE. The authors noted that the datasets to be compared are not independent, and therefore, differences between estimated and observed height values have been assessed using *t*-tests for dependent samples (paired *t*-test).

The use of simple tests for means is limited to cases that analyze only two factors for consideration. The multiple uses of such tests in cases of more than two factor levels inflate the statistics and may lead to incorrect test results. Another approach, therefore, assumes the use of the analysis of variance (ANOVA). The ANOVA approach has been widely used as a tool for comparison between various terrain models and the performance of DTMs under varying conditions. For example, Zhang et al. (2009) have checked the effects of the model source and the pixel size on the hydrologic and erosion simulation. The problems in the ANOVA use for comparison of DTMs have been widely discussed by Aguilar et al. (2005). The researchers used factorial ANOVA in their studies, but they also noticed that interpolation error in the model may be spatially autocorrelated. This can lead to the variability of the RMSE being lower than expected and may cause inflation of the ANOVA test statistics. The authors used geostatistical methods to assess autocorrelation of residuals and designed the sampling density in such a way, that it eliminated or minimized the influence of autocorrelation on the ANOVA results.

The use of ANOVA is limited to situations, where all factors (independent variables) are expressed as categorical variables. When continuous variables are involved, more accurate results can be obtained with the use of the analysis of covariance (ANCOVA). There are also papers concerning the application of other, more advanced approaches, such as the General Linear Model (GLM) and Mixed Models (MM). The above-mentioned methods, however, do not take into account the fact that analyses of various models and various conditions are done for the same points. In such cases, one of the assumptions of ANOVA/ANCOVA, the independence of residuals for measured groups, is violated. Measurements of the same point are expected to be highly correlated and the use of analysis of variance increases the risk of obtaining inaccurate test results. For instance, where each subject is measured regularly (over time) or observed under different treatment conditions, the repeated measures analysis of variance or covariance (RM ANOVA/ANCOVA) approach should be applied. In such cases, time or repeated measures are referred to as within-subject factors. Investigated factors that can influence measurements of the subject are referred to as between-subject factors. Analysis of variance for repeated measures has been applied in studies from various fields (e.g. Duck et al. 2004).

The main aim of the presented study was to assess the impact of selected pine stands factors on the DTM accuracy and the influence of grid spacing on the quality of the resultant terrain model. Models with resolutions of 0.5 m, 1 m, 2 m, 3 m, 5 m and 10 m have been tested for Scots pine (*Pinus sylvestris* L.) stands at its different developmental stages. Test areas have been placed on slopes and on flat terrains. We have used two test methods of data processing. In the first one, we used height values from single model pixels, and in the second one – smoothed (filtered) values from 3 by 3 pixel windows that replaced the "Z" coordinate of the center pixel, which were used for DTM generation.

Materials and Methods

Study Area

The study was carried out in the Milicz Forest District in western Poland. The total area is 26,250 ha, of which 96% (25,362 ha) is covered by forests. The dominant tree species in the region include Scots pine (*Pinus sylvestris* L.) – 76%; Oak (*Quercus* sp.) – 9%; and Beech (*Fagus sylvatica* L.) – 4.7%. The sample terrain was selected based on the following criteria:

- availability of Scots pine stands of different ages (distinct developmental stage),
- access to an open horizon, which determines stable GNSS observations.

Based on the field inventory and review of the available data, it became apparent that the area consisting of four Pine compartments (marked as 220d, 220b, 220a and 219d) meets the above-mentioned criteria. The total study area exceeds 5 hectares (Figure 1). The dominant species is Scots pine. The age of stands varies significantly due to the research requirements. The detailed description of the stand is presented in Table 1.

Table 1. Basic characteristics of the stands located in the measured area

Area code	Age, yr	Average height, m	Habitat	Site class	Stocking
220 b	2	0	Bśw	II	1.0
220 a	9	2	Bśw	I	1.0
219 d	28	11	Bśw	I	1,1
220 d	109	22	Bśw	III	0.4

where: *Bśw* – oligotrophic site (fresh coniferous forest site), *Site class* – site quality according to Schwappach yield tables for Scots pine (Schwappach 1908), *Stocking* – as compared to Schwappach yield tables for Scots pine for a particular site class (Schwappach 1908).

The southern part of the research plot, which takes approximately 70% of the total area, was almost flat. The remaining 30% was a sand dune with a height of about 10 meters and a constant slope of 10° (Figure 1). The whole research area has been divided into eight research sub-plots, differentiated by the stand characteristics and terrain type (Figure 2). The terrain configuration allowed us to locate an additional reference point at the top of the dune, which meant that there was a significant expansion of the surveying coverage.

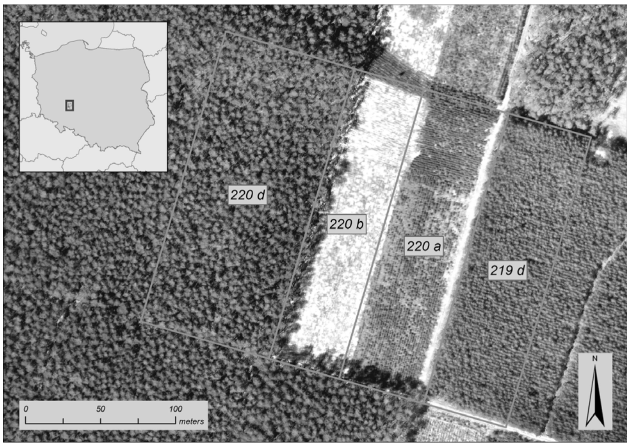

Figure 1. Location of research plots and Milicz forest with reference to borders of Poland

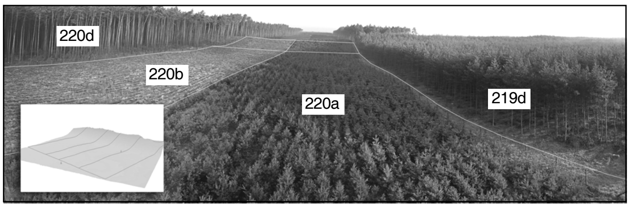

Figure 2. DTM visualization and the image of research plot borders in relation to the real terrain

Field data

The presence of open areas around the research plot allowed the measurement of reference points by dual-frequency geodetic quality GNSS receiver. More than 2 hours of data capture was taken for each reference point with the use of a Topcon HiperPro receiver in the static mode (Figure 3)

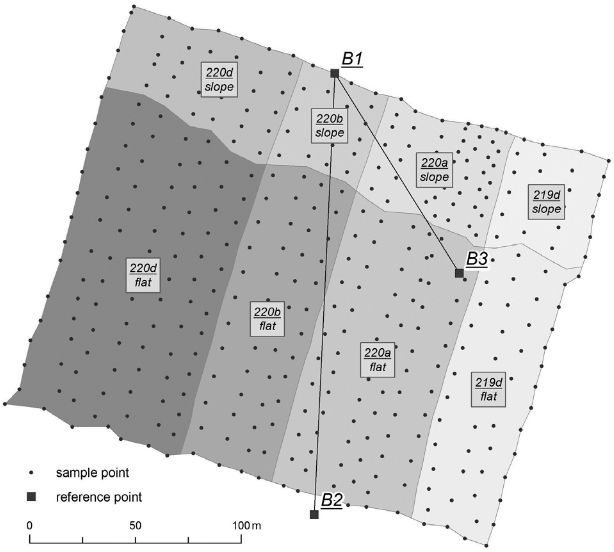

Figure 3. Map of research plots, reference points and sample points

All data were post-processed using the ASG-EUPOS (Polish network of reference stations) on-line application and finally presented in the Polish local coordinate system "1992". Positioning and height errors for reference points (B1, B2) in the X, Y and Z plane were Mx=0.003 m, My=0.005 m, Mz=0.02 m, respectively.

Using a reference line (B1-B2), 362 sample points have been measured by the total station using trigonometric (for the Z value – elevation) and polar method (for the X, Y values). Because of the limited visibility, an additional point B3 was created, which allowed us to capture 106 additional sample points. The total number of sample points was 468. The accuracy for single points depends on a distance between reference points (B1, B2, B3), and distance and angles to sample points. In this research the mean accuracy is below 0.05 m (Doskocz 2005).

LIDAR data

LIDAR data was collected and pre-processed by the TopoSys Company using the Falcon II System on 2-3 May 2007. The detailed characteristics of the system used are shown in Table 2. The first (FE) and last echo (LE) of each beam were recorded. The point density for the last echo (LE) was 7-8 point/m^2.

Table 2. LIDAR system characteristics

Scanner	TopoSys (Falcon II System)
Wavelength	1540 nm
Scanning angle	14.3° (+/-7°)
Flight height	700 m
Laser footprint size	0.7 m
Number of reflections (echoes)	2

Digital Terrain Model

Based on the LE point cloud LIDAR data, Digital Terrain Models with various grid spacing were generated by TreesVis Software (FELIS, Freiburg, Germany). This software uses an active contour algorithm (Elmqvist 2000) to filter data points. In this study, the software has generated DTMs based on the properties of a flat terrain because no steep slopes were present, similar to a flat area. DTM models with 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m and 10 m grid spacing were generated. For more details about the software and implemented active contour algorithm for DTM calculation, see the paper by Weinacker et al. (2004).

Methods

An original point's data set for LE and FE clouds was clipped by the polygons which represent the border for every research plot. Based on the spatial relation, it was possible to select one point from the LIDAR cloud, which was the nearest to the sample point measured by total station. In this way, a comparison of the "Z" value between LIDAR points and real ground level could be carried out.

According to the DTM raster dataset analysis, it was necessary to extract the height value from each pixel and assign them to geodetic sample points. Additionally, for all DTMs, the mean value of 3×3 pixel window replacing each pixel was also used (Table 3). The investigation should prove if slope cause distortions in single pixel values compared to the mean value of 9 pixel windows with the central pixel placed in position of a single pixel. Filtration was done in postprocessing on DTM pixel values. Checks were made to determine the influence of both values on the results for the selected DTM raster spacing. Afterwards, all geodetic sample points received values extracted from the DTM.

Because the same points have been investigated for various DTM resolutions, the differences between results have been evaluated by means of the General Linear Model (GLM) for repeated measures (RM GLM), with DTM resolution treated as a within-subject factor. The between-subject factors were terrain slope and stand age.

The systematic error was calculated as a mean error (ME) between LIDAR-based (raster) DTM and reference geodetic field measurements:

$$ME = \frac{\sum_{i=1}^{n}\left(Z_{Raster} - Z_{Field}\right)}{n} \qquad (1)$$

Root mean square error (RMSE) was calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{Raster} - Z_{Field}\right)^2}{n}} \qquad (2)$$

where: Z_{Raster} – „z" coordinate of the terrain point taken from a given LIDAR-based DTM, Z_{Field} – „z" coordinate of the terrain point measured in the field – reference data, n – number of observations.

Following the robust approach (Höhle and Höhle 2009), the median of errors was also tested as a potential substitute for mean error in cases where the error distribution does not follow the normal distribution. Additionally, the calculation of 68th and 95th error percentiles was carried out for comparison with ME, median and RMSE values. This analysis has been carried out following the approach described in ASPRS Guideline: "Vertical Accuracy Reporting for Lidar Data", and assigned to vegetation covered areas and not bare ground.

The detailed evaluation of differences for "Z" (elevation) values obtained for each point from single pixels and from 3×3 pixel window for all DTMs was done using the analysis of variance for repeated measurements (RM ANOVA), which is a special case of RM GLM, and the Friedman test (non-parametric equivalent of RM ANOVA). The normality of distributions was analyzed using the Shapiro-Wilk test. All analyses were performed with the use of SPSS and R software.

Results

For all the analyzed DTM grid resolutions, the overall distributions of errors differ significantly from the normal distribution ($p = 0.0000$) and they have all been shown to be negatively skewed (Figure 4). This supports the relevance of using alternative, non-parametric methods for data analysis.

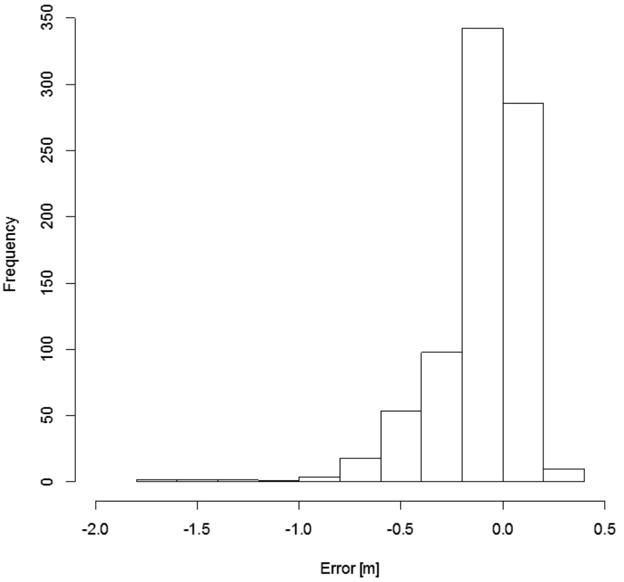

Figure 4. Distribution of DTM errors for the 2m raster resolution

The accuracy of the DTM generally increases with the increase in its resolution ($p = 0.0000$, Table 3), regardless of the DTM values used for comparison (i.e. heights obtained directly from the pixels and calculated as 3×3 pixel window means). Because of this, we used only the direct DTM values in all further analyses. The median values of errors are up to 50% smaller than mean errors. Such differences derive from the non-normal distribution of errors, where they have been shown to be skewed positively.

The overall relation between the location of the point on the slope or flat terrain and the model accuracy has also been evaluated (Table 1, Figure 5). The mean error of DTM for points located on the slopes is on average 5 times higher than for points located on flat areas ($p = 0.0000$). The same rule was observed for a median of errors. For flat terrain, RMSE, ME, median and 68th percentile have very similar values and trends. If the type of terrain is taken into account, then for the majority of DTMs the distribution of errors does not follow the normal distribution and usually reveals a slight negative skewness.

Results show that DTM errors are not significantly different in various stands (Figure 6); however, the p-value was relatively low ($p = 0.069$). For a flat area, in all cases, apart from RMSE, consistent trends in differences between DTM and reference negative errors were observed for large pixel size DTMs and positive errors for small ones ($p = 0.0000$, Figure 5). For slopes, this situation is different and almost in each case a

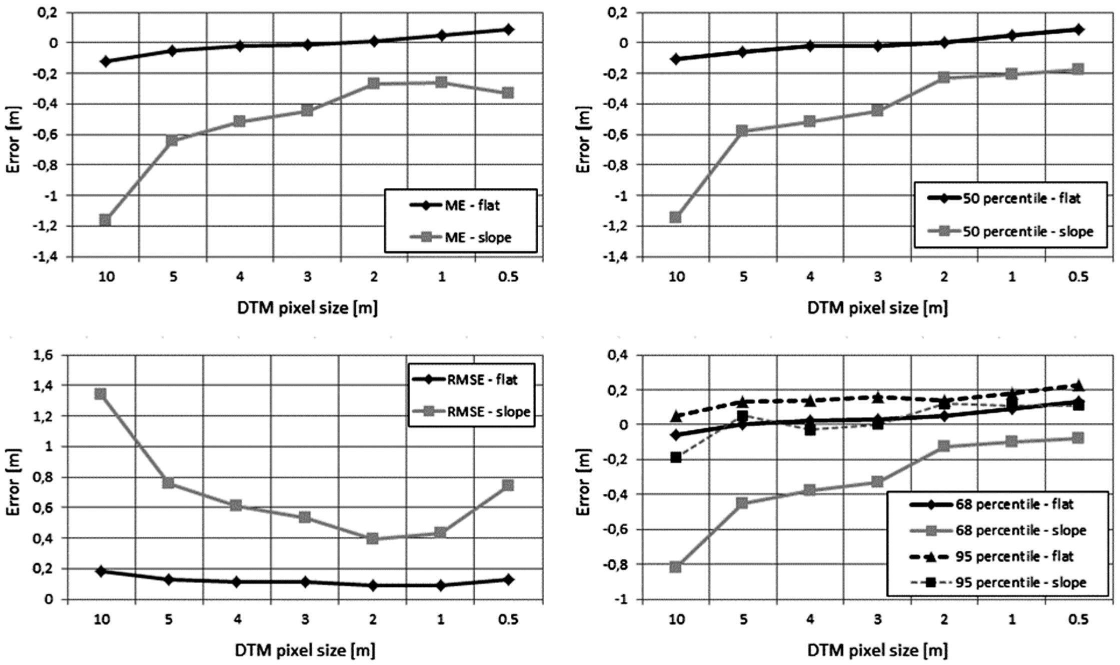

Figure 5. The relationship between mean errors (ME), RMS errors (RMSE), median (M), percentiles (68 and 95) and DTM grid resolution for flat and slope test terrain

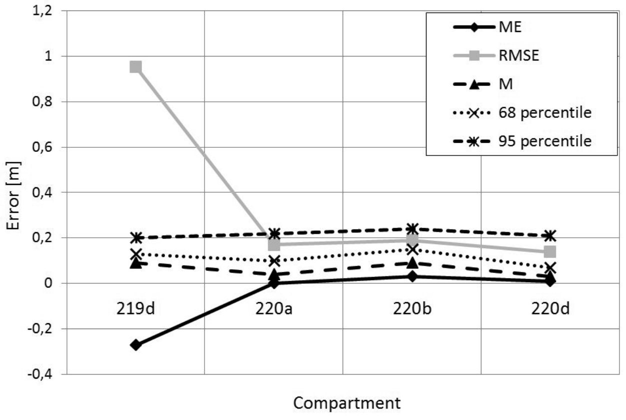

Figure 6. Errors in different stands for all DTM resolutions

different trend is noticed. In all analyzed cases, the average value of errors for slopes was -0.52 m, whilst on flat terrain it was -0.01 m. Slope greatly influenced the DTM value generally underestimating its value from as much as 1.15 m per M (50th percentile).

When different stands were taken into account, all percentile error values have similar trends and almost similar values (Figure 6) for all stands. ME (negative value) and RMSE (large positive value) for compartment 219d show a different trend compared to percentile error values. For flat terrain, the ME value for all stand has a similar trend and move from positive values in smaller DTM pixels to negative values in larger pixels value (Figure 7). RMSE error varied between 0.07 m up to 0.22 m for flat areas. There are some small trend differences for compartment 219d which in larger DTM pixel size RMSE become the smallest values compared to other pixel sizes (Figure 8). Slopes generally cause larger ME and RMSE values (Figures 7 and 8), and large variations were noted in the compartment 219d, whose trend for different raster size differed from other ones.

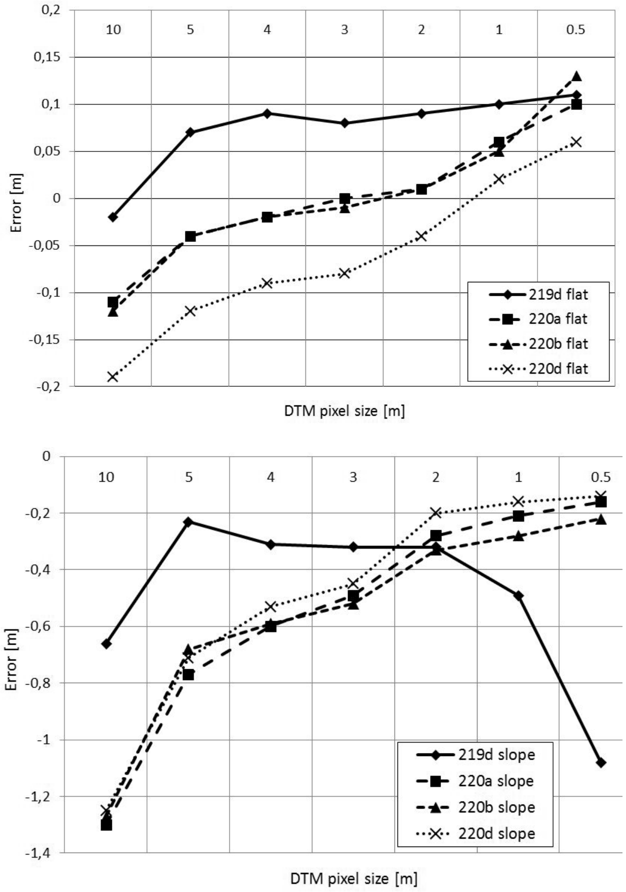

Figure 7. The relationship between ME and DTM resolution for different terrains and stands (left – flat terrain, right - slope)

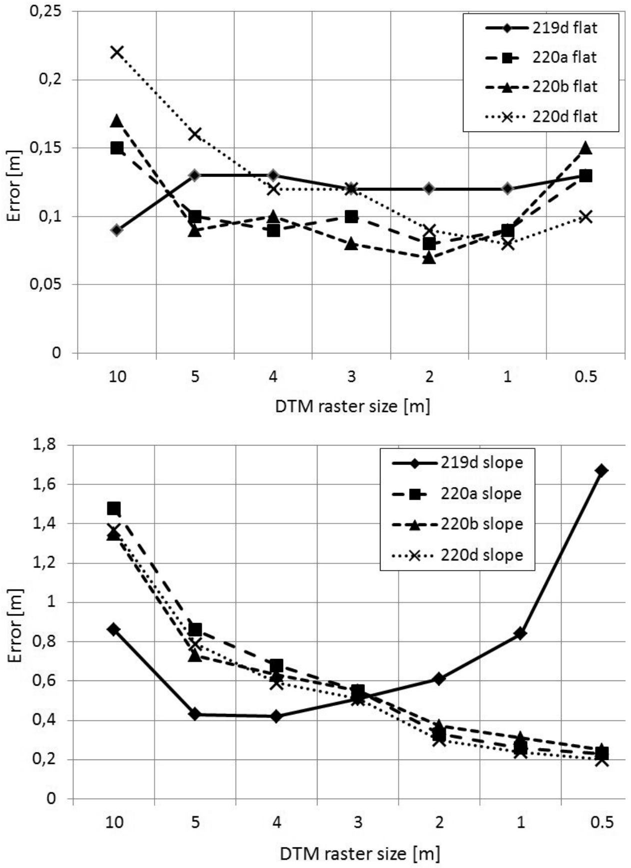

Figure 8. The relationship between RMSE and DTM resolution for different terrains and stands (left – flat terrain, right – slope)

Discussion

Different approaches assume the use of classical ANOVA, GLM or MM for the DTM accuracy assessment. In this study, we have applied the special case of the General Linear Model for repeated measures – repeated measures analysis of variance (RM ANOVA) as the most suitable for such analyses. However, it is also worth mentioning that the use of ANOVA and RM ANOVA is allowed only if the error distribution follows the normal distribution. In our case, the distribution of errors is far from normal and is positively skewed. As such, there is a risk of obtaining incorrect results, i.e. the test will show significant differences more frequently than they actually occur. Even if the ANOVA F statistic is relatively resistant to the violation of the normality assumption, the non-parametric equivalent of the RM ANOVA, Friedman test, which replaces analyzed dependent variables by their ranks, seems to be a good alternative for investigations. It has been used in this study to check, if the answers obtained by RM AVOVA for differences between DTM generated directly from pixel "Z" values and DTM generated from 3x3-pixel window can be considered as correct. The disadvantage of the Friedman test is that it can't be used for more than one factor with repeated measurements.

We found no differences in the accuracy assessment for flat areas using a single pixel value or a mean from 9 neighboring pixels (smoothed model). The differences between direct values and the averaged ones were very similar. This is not true for slopes; however, a fact also noticed by Aguilar et al. (2005) in mountainous area. Another discovery was that DTM generated under forest conditions in pine stands was generally accurate for the flat areas. The mean errors varied within a range of -0.12 to 0.09 m for flat and -0.26 to -1.16 m for slope terrain. RMS errors varied within a range of 0.09 to 0.18 cm for the flat and 0.39 to 1.34 m for the sloped terrain. The most accurate DTM (with the smallest bias) was generated in a 2- and 9-year-old pine stands (in both cases ME=0.00 m) and the least accurate in a 28-year-old stand (ME=0.07 m) on the flat terrain. In sloped terrains, the situation was the opposite and the 109-year-old Pine stand was as good as the 28-year-old stand (ME= -0.49 m in both compartments). In both terrains, differences between compartments were no larger than 0.07 m. In the case of flat terrains, where young trees had not created, the forest cover as yet ALS pulses had an easy path to reach the ground. For older Pine stand, not as many pulses were able to penetrate the tree layers, which were very dense in the 28-years old Pine stand, therefore, smaller numbers of laser points were used for DTM interpolation.

The obtained errors were much larger for slopes and varied between -0.26 to -1.16 m for ME and 0.39-1.34 m for RMSE for all raster grid spacing. Consistently increasing negative differences between DTM and references for models with increasing pixel size have been noticed for compartments 220a, 220b and 220d. On slopes, it was also noted that the area of overstocked young stands (compartment 219d) revealed a different relationship pattern between DTM accuracy and raster spacing. Large errors were noted, especially for high resolution DTMs. It seems that an insufficient number of points on the ground, due to stand structure and slope, could cause these large errors and, in addition, multiple reflection. The lack of points and interpolation algorithms, which generally prefer the lowest points inside specified pixel sizes, caused received differences.

The performed analyses allowed us to verify various rules and measures for DTM accuracy assessment. By comparing ME, RMSE, M, 68th and 95th percentile it became apparent, that ME, M and 68th percentile values are almost the same and follow the same trends. All can therefore be used as values for error determination, as well as a part of confidence interval calculations. The percentile approach can also be safely used for not normally distributed and skewed data. It was also observed, that the 95th percentile is not sensitive to large errors connected (in the investigated case) with terrain and stand characteristics. It is difficult to draw any conclusions if the 95th percentile is subject to a positive bias or the remaining error estimates (ME, M, 68th percentile) reveal a negative bias. Nevertheless, this fact gives the possibility to assess the character of the analyzed area (terrain or stand type) by comparing the values of the 95th percentile with the ME/RMSE/M/68th error percentile. If the 95th percentile >> 1.96 x RMSE, the structure of the stand or the terrain is complex and can generate high DTM errors.

Many published studies conclude that in the forest areas, due to dense low vegetation, LIDAR-derived terrain models tend to overestimate the reference ground height coordinates, which is attributed to the presence of a non-corrected filtering error (e.g. Hodgson et al. 2005, Goodwin et al. 2006, Su and Bork 2006). In our case, overestimation is present for general ME value and for the smallest DTM pixels size. With an increase in the size of the pixel, the reference model is increasingly underestimated, mainly because of the filtering strategy for DTM interpolation and slope influence (Elmqvist 2000).

Nevertheless, we proved that pixel values and values from 3×3 pixel windows for different raster resolutions are not statistically different. They are similar especially for flat terrain, and in the case of slopes with 10 m DTM resolution, larger errors were noticed. Conversely, we proved that slope causes much larger errors in the same forest conditions. Four analysed compartments were partly on a flat terrain and partly on a slope. Where the slope was not steep, it caused an increment of the ME from -0.01 m for flat area to

-0.52 m for sloped terrains and an increase of the RMSE from 0.12 m for flat area to 0.69 m for sloped terrains. Slope and sparse vegetation are the most frequent reasons for errors mainly because filtering algorithms are not able to distinguish between real and false ground points (Pfeifer et al. 2004, Wagner at al. 2004). Use of larger DTM pixels resulted in larger error values (Wu et al. 2008) and in our case especially because of the filtering strategy, in all of the analyzed terrains (Figure 5).

Conclusions

The main findings drawn from the presented study are as follows:

The main factors influencing DTM accuracy come from different sources: the applied measurement technology (model grid spacing and ability of terrain identification) and the natural conditions (terrain characteristics - slope and vegetation – stand developmental stage).

The differences between direct DTM pixel values and mean (smoothed) values from 3x3 windows for flat area were practically the same (difference from 0.00 to 0.01 m). On the slope (<= 10°), the differences varied from 0.02 cm for 0.5m pixel size to 0.23 cm for 10m pixel size but they were not significantly different from each other.

The analysis of the influence of various factors on the DTM accuracy should be performed using a "repeated measures" approach, such as RM GLM (RM ANOVA/ANCOVA) or the Friedman test.

For the assessment of DTM accuracy, different measures can be used, such as ME, RMSE and percentiles. For the presented study, ME and the 68th percentile values are almost the same and follow the same trends. This is caused by the skewed error distribution. At the same time, the 95th percentile is sensitive to large errors originating from the terrain and stand characteristics.

The use of percentiles is much more appropriate than mean-based measures, as the data distribution is not normally distributed and skewed.

Using a combination of various error estimates (95th percentile vs. remaining ones) may provide information about the character of the analyzed terrain.

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Received 07 January 2013
Accepted 28 November 2013

ОЦЕНКА ТОЧНОСТИ ЦИФРОВЫХ МОДЕЛИ РЕЛЬЕФА СОЗДАННЫХ ОТ ДАННЫХ ИЗ АВИАЦИОННОГО ЛАЗЕРНОГО СКАНИРОВАНИЯ ДЛЯ ЛЕСНЫХ УСЛОВИЙ

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Резюме

В статье представлен анализ влияния разных факторов на точность Цифровых Модели Рельефа (ЦМР), созданных для лесных условии в сосновых древостоях. Модели имеющие размер пикселя 0.5, 1, 2, 3, 4, 5 и 10 метров были оценены. Точность оценки была проведена для 4 возрастных классов (стадии развития) в плоской местности и на склоне. Кроме того, был выполнен анализ различия для результатов полученных из отдельных пикселей и из движущегося окна размером 3x3 пикселей для разных разрешении ЦМР. Общая Линейная Модель для повторяемых измерений была использована для выполнения анализа.

Только переполнены молодые древостои представляют другую схему взаимоотношения между точностью и разрешением ЦМР. Ошибка модели на склонах была, в среднем, в 3 раза больше, чем для плоской местности. Координаты высот деревьев, получены из ЦМР созданного с помощью прямой величины пикселей по высоте являются немного точными, чем те, которые получены с помощью движущегося окна размером 3x3 пикселя, однако эта разница не является статистически значимой. Использование квартили для определения точности модели является значительно более соответствующим, чем показателей созданных на основе арифметической средней, особенно для данных, которые являются не нормально распределенними и ассиметрическими.

Ключевые слова: цифровая модель рельефа, авиационное лазерное сканирование, дисперсионный анализ для повторяемых измерений, анализ ошибок, квартиль, поверхность земли, сосна обыкновенная, склон