Comparison of various algorithms for DTM interpolation from LIDAR data in dense mountain forests

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Abstract
The main aim of the work presented here has been to evaluate which combination of filtering and interpolation algorithms can offer the best DTM accuracy in conditions involving very dense forest in mountainous areas. The study area was in the Sudety Mountains of south-western Poland, close to the Czech border. For each filtration, almost 100 DTMs were generated, with final analysis confined to just 6 most-accurate models. The results show that slope and particularly undergrowth vegetation are the most important factors influencing DTM accuracy in dense mountain forests. However, all methods of interpolation are capable of reaching very similar levels of error after proper calibration.

Keywords: ALS, DTM, accuracy, mountain forest.

Introduction
Digital terrain model (DTM) is a numerical representation of the Earth’s surface without any additional objects on its plane. DTM represents one of the most important geospatial datasets used in various applications. It plays an important role in hydrological modelling [Beven and Kirkby, 1979], forest parameter modelling [Hyppä et al., 2012; Miścicki and Stereńczak, 2013] and risk analysis [Wilson and Gallant, 2000; Chen et al., 2014]. Nowadays, airborne laser scanners (ALS) are among the most important tools used in acquiring measurements for DTM interpolation. One of the major challenges in ALS data processing is the huge size of the files created from the data registered. Two main steps in ASL data processing are required to handle the processing of data from a cloud of points to a digital terrain model. These are filtration/classification of the ground points and interpolation of the DTM surface on the basis of these filtered points. In the past, selected studies presented evaluations of wide ranges of algorithms for DTM filtration/classification and interpolation from ALS data [Sithole and Vosselman, 2004; Aguilar et
al., 2005; Bater and Coops, 2009; Heritage et al., 2009]. Sithole and Vosselman [2004] evaluated a wide range of filtering algorithms. The eight filters developed by various individuals or groups assessed in relation to 15 different sample areas were active contours [Elmquist, 2001; Elmquist et al., 2001], the regularisation method [Sohn and Dowman, 2002], the modified slope-based filter [Roggero, 2001], spline interpolation [Brovelli et al., 2002], hierarchical modified block minimum [Wack and Wimmer, 2002], progressive TIN densification [Axelsson, 1999, 2000], the modified slope-based filter [Sithole, 2001] and hierarchical robust interpolation [Kraus and Pfeifer, 1998, 2001; Briese and Pfeifer, 2001; Pfeifer et al., 2008]. Sithole and Vosselman [2004] concluded that the best filtering algorithm may vary from landscape to landscape, meaning that optimal filter performance depends on landscape type. Where vegetation is concerned, all the algorithms work well on tall vegetation. Three out of eight of the analysed algorithms offered effective filtering of both the vegetation on slopes and low vegetation. Performance of the active contours and hierarchical robust interpolation for all three vegetation classes was good (“fair” and “poor” being the other options). The regularisation method and hierarchical modified block minimum were assessed as “good” in two of the three cases.

A study by Bater and Coops [2009] focused on interpolation methods and their influence on DTM accuracy. The routines used to generated DTM were linear, quantic, natural neighbour, regularised spline, spline with tension, a finite difference approach (ANUDEM) and inverse distance weighted (IDW) interpolation, at spatial resolutions of 0.5, 1.0 and 1.5m. The DTM spatial resolution of 0.5 proved to be the most accurate. Linear and natural neighbour interpolators were revealed as the most conservative algorithms, while tending to manifest the smallest overall ranges of errors. IDW routines were influenced greatly by their parameterizations, with outliers often exceeding ±6m. Mean absolute errors for young forests ranged from 0.18-0.23m, in contrast to mean absolute interpolation errors in the old-forest category equalling 0.10-0.13m. Su and Bork [2006] evaluated kriging, splining and inverse distance weighting. They found that, in comparison with kriging, IDW created an interpolation surface with fewer overall errors.

Many important technical aspects of data acquisition influencing DTM accuracy were evaluated by Hyyppä et al. [2005], Stereńczak and Kozak [2011] and Sue and Bork [2006]. With last echo (LE) points, the acquisition conducted during the leaf-off period resulted in the smallest random error, i.e. 7-17cm in most of the plots. The use of a non-optimal season increased the random error by 3, to 9cm [Hyyppä et al., 2005]. This is why seasonal effects, when herbaceous plants start growing after snow meltdown and before trees turn green, are seen so clearly in deciduous stands [Stereńczak and Kozak, 2011]. The density of the point cloud particularly influences DTM accuracy at fine (0.5 and 1m) DTM resolution [Guo et al., 2010]. Using last echo ensures greater accuracy of interpolated models as compared with a model based on first echo (FE) data [Hyyppä et al., 2005]. The use of a nadir angle was found to result in larger errors in the point cloud, with this influencing the accuracy of the resulting DTM. Off nadir angles should thus be kept to less than 15° [Su and Bork, 2006].

The influence of vegetation has been evaluated in many papers [Reutebuch et al., 2003; Hopkinson et al., 2004; Su and Bork, 2006; Bater and Coops, 2009; Stereńczak and Kozak, 2011; Stereńczak et al., 2013]. Thinning influences DTM accuracy. The errors for clear-cuts were smaller than for a thinned or uncut stand (from 0.16 up to 0.31m respectively).
[Reutebuch et al., 2003]. A seasonal influence on DTM accuracy was more evident in single-layer than multilayer stands. Tree species also play an important role, as Stereńczak and Kozak [2011] reported. These authors also found it more marked in larch or alder stands than in those formed by pine or oak. In open areas, the presence of lower vegetation gives rise to DTM error values and levels of error values that correlate positively with vegetation height [Hopkinson et al., 2004]. Particularly difficult environments for DTM interpolation are areas of dense vegetation, such as young forests [Bater and Coops, 2009; Stereńczak et al., 2013] and scrub [Hopkinson et al., 2004], which can generate height errors of up to a few metres. Such errors arise because no LIDAR pulses can penetrate this complex structure for a ground echo. Stand and site factors have been found to influence the ratio of ground returns to outgoing pulses significantly [Watt et al., 2013]. When combined into a multiple regression model, these factors were shown to account for 48% of the variance in the national New Zealand dataset extending across a wide range of stand conditions and broad topographic gradients [Watt et al., 2013].

Among a wide range of applications for the filtration and interpolation of airborne laser scanner data that are available for various digital models, some are open-source, while the remainder are commercial. The variety can confuses the end-user, because the number of variants can extend to hundreds of options. Additionally, implementation of an algorithm similar to those described in the literature can cause problems with different implementations, with different results ensuing [Pietrzak, 2013]. Moreover, many companies acquiring ALS data also offer DTM and digital surface models as possible products. It is not sure if this ensures any better quality of DTMs, in forested areas in particular. It is thus clear how large the number of available tools, methods and strategies for DTM interpolation is. Some tests on DTM interpolation on the basis of ALS data were also carried out, though none of these concerned densely-forested mountainous area.

The aims of the work described here were thus: i) to evaluate which combination of filtering and interpolation algorithms can ensure best DTM accuracy in conditions of very dense forest in mountainous areas; ii) to determine whether DTM acquired by an ALS data provider achieves greater accuracy than those interpolated by automatic procedures in available software; and iii) to decide which factor(s) (among forest structure, slope, off-nadir angle, understory vegetation and filtration and interpolation algorithm) most influenced DTM accuracy. To answer these questions, large amounts of field data referenced measurements characterised by geodetic accuracy were acquired, processed and used.

**Methods and materials**

**Study area**

The study area is situated in south-west Poland, on the border between the gamines (local-authority areas) of Platerówka and Lubań. It covers about 2 km² (Fig. 1) and is entirely occupied by a complex forest growing on very rich mesic upland forest habitats. Forest tree species embraced by the work are thus Norway spruce (*Picea abies* L.), Scots pine (*Pinus silvestris* L.), European beech (*Fagus sylvatica* L.), Sycamore maple (*Acer pseudoplatanus* L.), Common oak (*Quercus robur* L.), European ash (*Fraxinus excelsior* L.) and Silver birch (*Betula pendula* Roth) (Tab. 1).
The ages of forest stands studied ranged from 29 to 114 years. Most stands were of multi-layered structure, consisting of up to 3-4 stand-forming species (Fig. 2), along with understorey vegetation of various heights (Tab. 2). Altitudes ranged between 232 and 375m. a.s.l., with slopes larger than 25°. Because of the location and relief we called the area as mountainous, but as Figure 2 shows, there are not rocky or very steep hills.
Figure 2 - Selected pictures of stands of different structure, undergrowth, slope and species composition.

Table 2 (Continued on the next page) - Characteristics of forest stands.

| no | area [ha] | dominant tree species     | age [years] | dbh [cm] | height [m] | crown closure class\(^a\) | growing stock [m\(^3\)×ha\(^{-1}\)] |
|----|-----------|---------------------------|-------------|----------|------------|---------------------------|-------------------------------------|
| 1  | 3.74      | Common oak                | 35          | 15       | 13         | 2                         | 147                                 |
| 2  | 3.06      | European ash              | 80          | 37       | 29         | 2                         | 338                                 |
| 3  | 1.77      | European beech            | 84          | 37       | 29         | 2                         | 437                                 |
| 4  | 6.71      | European beech            | 80          | 32       | 28         | 2                         | 348                                 |
| 5  | 2.52      | European beech            | 30          | 12       | 11         | 3                         | 32                                  |
| 6  | 6.91      | Norway spruce             | 110         | 36       | 31         | 3                         | 520                                 |
| 7  | 0.84      | Norway spruce             | 90          | 34       | 29         | 2                         | 514                                 |
| 8  | 3.25      | Norway spruce             | 110         | 39       | 32         | 3                         | 419                                 |
| 9  | 2.77      | Norway spruce             | 115         | 38       | 32         | 3                         | 416                                 |
| 10 | 0.89      | Norway spruce             | 55          | 26       | 26         | 2                         | 334                                 |
| 11 | 4.22      | Norway spruce             | 90          | 36       | 30         | 2                         | 300                                 |
| 12 | 5.11      | Norway spruce             | 110         | 36       | 32         | 3                         | 278                                 |
| 13 | 0.45      | Norway spruce             | 50          | 21       | 20         | 2                         | 277                                 |
| 14 | 1.06      | Norway spruce             | 125         | 41       | 31         | 4                         | 197                                 |

\(^a\) Crown closure classes: dense=1, moderate=2, released=3, opened=4
Table 2 (Continued from preceding page) - Characteristics of forest stands.

| no | area [ha] | dominant tree species   | age [years] | dbh [cm] | height [m] | crown closure class \(a\) | growing stock \([m^3\times ha^{-1}]\) |
|----|-----------|-------------------------|-------------|----------|------------|---------------------------|----------------------------------|
| 15 | 6.25      | Scots pine              | 55          | 28       | 25         | 2                         | 317                              |
| 16 | 1.67      | Scots pine              | 75          | 32       | 26         | 3                         | 311                              |
| 17 | 5.64      | Scots pine              | 50          | 28       | 24         | 2                         | 277                              |
| 18 | 1.77      | Scots pine              | 30          | 17       | 14         | 3                         | 128                              |
| 19 | 5.65      | Silver birch            | 28          | 11       | 16         | 2                         | 109                              |
| 20 | 0.09      | Sycamore Maple          | 39          | 19       | 18         | 2                         | 157                              |
| 21 | 2.99      | Sycamore Maple          | 39          | 19       | 18         | 2                         | 148                              |
| 22 | 3.15      | Sycamore Maple          | 40          | 16       | 18         | 2                         | 147                              |
| 23 | 0.72      | Sycamore Maple          | 25          | 4        | 8          | 2                         | 31                               |

* Crown closure classes: dense=1, moderate=2, released=3, opened=4

LIDAR Data

Surveys were conducted using the RIEGL Airborne Laser Scanner (ALS) LMS-Q680i system, in August 2012 (Tab. 3). The strip adjustment made using TerraSolid software resulted in 2cm std. Georeferencing was based on Real Time Kinematic measurements of six planes oriented in various directions.

Table 3 - Specifications for point cloud (source: data provider).

| Parameters                   | Value                          |
|------------------------------|--------------------------------|
| File format saving           | LAS, POINT DATA RECORD FORMAT 3|
| Average point density        | 6 pts./m2                      |
| Average altitude error       | ≤0.15m                         |
| Average error grid coordinates| ≤0.20m                         |
| Cross-track overlap          | Min. 50%                       |
| Registration                 | Full-Waveform                  |
| Laser wavelength             | 1550nm                         |
| Beam width                   | 0.5m                           |
| AGL Height                   | 1025m                          |

Ground reference data

Field reference data were acquired in the period from 10-14 June 2013. Measurements were based on 6 GPS points determined to sub-centimetre accuracy (Fig. 3). RTK GPS measurements were placed in open areas or out on fields to receive “fix” mode. On the basis of these 6 points, geodetic measurements were carried out using an electronic total station. The points were then used for picket measurements. The final positioning and height errors for 1640 reference points (the geodetic control network) in the X, Y and Z planes were Mx=0.051m, My=0.051m and Mz=0.030m respectively.
All pickets were characterised by information concerning the number of forest layers above the measurement point, the height of undergrowth in measurements and the type of tree species close to the mirror. The development of a database in the course of measurements allowed relationships between variables to be indicated for the purpose of further work.

**Data processing**

**Ground point filtering**

The presented research made use of four different filtrations, of which two were carried out using TerraScan software (Terrasolid company) using an algorithm based on an active TIN model. Results for that filtration depend on three main output parameters, i.e. max building size, iteration angle and iteration distance [Axelsson, 2000]. The first filtration was carried out by the data provider, with manual data correction, whilst the second was done fully automatically by ourselves.

The second tool used in the filtration process was LASGround (part of LAStools software - rapidlasso GmbH). This tool is also inspired by Peter Axelsson and his active TIN model. TerraScan and LAStools both use the same model of filtration, though implementation differs [Pietrzak, 2013]. In the research conducted, two default filtration methods dedicated to natural environments with few anthropogenic objects were used in LAStools. The first type is called “Wilderness”, and was applied with settings of step 3m (raster size), spike 1±10m (the threshold in metres at which spikes get removed) and offset 0.05m (maximal offset in metres up to which points above the current ground estimate are included).
other adopted filtration is “Nature”, with settings of step -5m, spike 1+10m and offset 0.05m.

**Interpolation**
The results of previous filtrations became input data with which to generate DTMs using different interpolation methods implemented via four different software packages (ArcMap 10.2 (ESRI), TerraScan (Terrasolid), TreesVis (FELIS Freiburg) and Opals (TU Vienna)). In the case of each filtration, a large number of parameters implemented in the software used (Tab. 4), almost 100 DTMs were generated. Further analysis then centred on the best six selected models (at least one for each software used and each filtration variant). Our intention in using the software names and algorithms implemented was to make this analysis easier for end-users to understand and repeat. This is all the more relevant given that algorithm implementation does not always generate exactly the same results [Pietrzak, 2013].

| Software | Interpolation methods             | Parameterization                                                                 |
|----------|----------------------------------|---------------------------------------------------------------------------------|
| ArcMap   | Inverse distance weighted (IDW)  | Powers of 0.5, 1.0, 2.0, 3.0 were tested                                         |
|          |                                  | Search radius: fixed and variable                                               |
|          |                                  | Number of points: 4, 6, 8, 12, 16, 20                                            |
|          |                                  | Maximum distance: 1.0, 2.0, 2.5, 3.0                                            |
|          | Natural Neighbour                | Grid spacing: 0.1m, 0.2m, 0.3m, 0.4m, 0.5m, 0.6m, 0.7m, 0.8m, 0.9m, 1.0m, 1.5m, 2.0m, 3.0m. |
|          | TIN                              | The TIN will use constrained Delaunay triangulation, which will add each segment as a single edge. |
|          | Trend                            | Polynomial order: 1 - 9                                                           |
|          |                                  | Type of regression: linear                                                        |
| TerraScan| Triangulated                     | Grid spacing: 0.5m                                                               |
|          | Highest Z                        | Model buffer: 100m                                                               |
|          | Lowest Z                         | Max triangle: 10m                                                                |
|          | Average Z                        | For each point the appropriate grid cell is determined and the height of the point is mapped to this cell |
|          | snap grid                        |                                                                                   |
| Opals    | nearest neighbour                | Number of points: 8, 12                                                           |
|          | Moving average                   | Search radius: 1.0m, 2.0m, 3.0m                                                   |
|          | Moving planes                    |                                                                                   |
|          | Moving paraboloid                |                                                                                   |
| TreesVis | Rauh                             | In 4th iteration differences are in magnetic force set on 100000 (Rauh) and 10000000 (Ganzrau). |
|          | Ganzrau                          |                                                                                   |
Given the different interpolation methods being implemented in each different software package, the authors decided to discuss those allowing the most accurate DTMs to be generated, i.e. Inverse Distance Weighted [Burrough and McDonnell, 1998], Natural Neighbour [Guo et al., 2010], TIN, Triangulated (http://geo.tuwien.ac.at/opals/html/ModuleGrid.html) and Moving Planes [Weinacker et al., 2004].

DEM validation
Forest layers
A number of forest-canopy layers was attributed locally to each of the geodetic pickets established in each study area. This feature indicates the number of forest stories observed above and in the immediate vicinity (a 2-3m radius) of the picket (Fig. 4). Given the separate assessment for each picket, a single stand may have had all kinds of cases present within it. To consider different incidence angles, we ensured in the field that the described structure extends over an area influenced by this factor. A larger area was needed where trees were higher, and vice versa.

![Figure 4 - A schematic representation of the meaning of forest layer labels.](image)

A value of 0 means that there were no leaves or branches in the zenith above the picket, which is typical for pickets situated on roads or in forest gaps. A value of 1 means that the picket was covered by leaves and branches of one tree storey. An analogous situation characterises values 2 and 3, but classification was always based on stories distinguished
clearly. Different solutions were implemented for the attribution of value 4, as it was used to
distinguish between pickets situated in all-aged parts of the stand structure. Given the lack
of a larger number of cases 3 and 4, and given the similarity when it came to representing
forest structure, it was decided to merge data for the purposes of statistical analysis (Tab. 5).

| Forest structure                              | Code | No. of pickets measured in the field |
|-----------------------------------------------|------|-------------------------------------|
| No forest layer                               | 0    | 191                                 |
| One forest layer                              | 1    | 1006                                |
| Two forest layer                              | 2    | 320                                 |
| Tree forest layers or all-aged stand          | 3 and 4 | 106                       |

**Slope**

Differences in relief are among factors influencing the accuracy of DTM. A derivative layer
slope was generated for each DTM. Slope values divided into the 6 groups 0-5°, 5-10°,
10-15°, 15-20°, 20-25° and > 25° were attributed to all pickets. The average slope of the
research area calculated on the basis of surveys is 9.6%. The defined number of pickets for
the different slope classes were: 0-5°-355 pickets, 5-10°-641 pickets, 10-15°-382 pickets,
15-20°-141 pickets, 20-25°-58 pickets, > 25°-46 pickets.

**Off-nadir angle**

Surveys were planned to identify differences in accuracy in relation to flight axis (line/
path). With a view to correct results being obtained, a single strip of flight was divided into
100m zones corresponding with the 5-degree zones characteristic for scanners of off-nadir
angle. The maximum value for that angle was 20°, as corresponding to a distance of 400m
from the flight axis. For each off-nadir angle class, the defined numbers of pickets were as
follows: 0-5 (5)°-370 pickets, 5-10 (10)°-617 pickets, 10-15 (15)°-322 pickets and 15-20
(20)°-304 pickets.

**Undergrowth height**

One of the factors influencing the accuracy of DTM values generated from ALS is the
height of the undergrowth. This is of key importance when photogrammetric flights take
place in the summer months, when most vegetation is in full growth or fully covered with
leaves. A height of undergrowth group was assigned to each picket in the database prepared.
Seven groups were in fact distinguished: 0mm - no undergrowth, 100mm, 200mm, 300mm,
400mm, 500mm, ≥ 600mm - high grass. For these different undergrowth height classes,
the number of pickets were as follows: 0mm- 952 pickets, max 150mm - 110 pickets, 150-
250mm - 128 pickets, 250-350mm -145 pickets, 350-450mm - 159 pickets, 450-550mm
- 66 pickets and more than 550mm - 63 pickets.

**Picket type**

Each of the pickets was classified into one of five groups of picket type, i.e. 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd}
stand story, ground and forest road. The ground group includes pickets above which there were no leaves or branches in the zenith. The duct (dirt road) group consists of pickets
situated on roads. For each picket type class defined, the statistics were as follows: 1\textsuperscript{st} stand story - 410 pickets, 2\textsuperscript{nd} stand story - 121 pickets, 3\textsuperscript{rd} stand story - 29 pickets, ground - 888 pickets and duct - 175 pickets.

**Selection of optimal terrain models**
The most accurate terrain models were chosen using reference data represented by the geodetic pickets. Pixel values from digital terrain models were compared with the heights of the corresponding pickets prior to RMSE and BIAS being calculated for each model. Additionally, a number was determined for pickets in the case of which algorithms did not interpolate the surface. Root mean square error was used to quantify random errors [Stereńczak et al., 2013] by reference to the Equation [1]:

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Z_{\text{Raster}} - Z_{\text{Field}})^2}{n}} \]  \[1\]

where:
\( Z_{\text{Field}} \) is the “z” reference coordinate,
\( Z_{\text{Raster}} \) is the DTM pixel value,
\( n \) is the number of observations.

BIAS allowed for the calculation of the load - as the difference between expected and reference values.

\[ BIAS = Z_{\text{Raster}} - Z_{\text{Field}} \]  \[2\]

where:
\( Z_{\text{Field}} \) is the “z” reference coordinate (elevation),
\( Z_{\text{Raster}} \) is the DTM pixel value.

As specific parameters are set, certain interpolation methods like IDW produce DTM with ‘no-data’ cells. It is thus important that DTM evaluation take account of the number of pickets for which no information about height is available.
The three components described above are criteria used to assess the accuracy of digital terrain models. Each is given a specific weighting, showing the parameter considered most important in our opinion, i.e. RMSE -50%, BIAS -30% and number of pickets without height value -20%.
Differences were assessed for significance using a paired t-test with Statistica software, with a 95% confidential level applied in Statistica software.

**Most important variables**
We used a GLM (General Linear Model) to detect the most important factor affecting DTM accuracy. Many continuous and qualitative variables were evaluated in terms of their explaining the greatest part of variability.
Results

Density

Results for filtration differed from one method used to another. Means and standard deviations (in parentheses) concerning ground point density for pixels overlapping with ground measurements were 3.16 pts./m$^2$ (2.22), 2.96 (2.05), 2.70 pts./m$^2$ (1.72) and 2.70 pts./m$^2$ (1.72) for LAStools Wilderness, LAStools Nature, TerraScan and Data Provider respectively. When mean ground points density with automatic filtration was compared with that generated by Data Provider, differences were found to be statistically significant for both LAStools filtrations (Tab. 6). TerraScan filtration results did not differ significantly. We know from data supplier, that he carried out mainly automatic filtration in TerraScan, with very little manual corrections, which is confirmed in our results.

Table 6 - Mean density differences between the four filtrations.

|                  | LAStools Nature | TerraScan | Data Provider |
|------------------|-----------------|-----------|--------------|
| LAStools Wilderness | 0.20*          | 0.46*     | 0.46*       |
| LAStools Nature   | -               | 0.26*     | 0.26*       |
| TerraScan         | -               | -         | 0.00        |

* - difference significant at the 95% confidence level

Interpolation

For every filtration we generated about 100 DTMs, using different methods of interpolation with the four programs. To present the best of these, the authors opted for 6 terrain models for each of the 4 filtrations run. In comparison we also presented an accuracy analysis of digital terrain model delivered by the Data Provider.

- ArcMap (1) - interpolation using the IDW Method. Settings: power -1, search radius fixed; search radius settings: distance -2.5 m; minimum number of points -8
- ArcMap (2) - interpolation using the TIN Method; default settings, with the Nearest Neighbour Method used to transform into GRID;
- ArcMap (3) - interpolation using the IDW Method. Settings: power -1, Search radius: fixed; search radius settings: distance -2.5m; minimum number of points -4;
- ArcMap (4) - interpolation using the Nearest Neighbour Method. Settings: n/a;
- TerraScan (1) - interpolation using the TIN Method. Setting: n/a;
- Opals (1) - interpolation using the Moving Planes Method. Settings: distance - 5.0m; minimum number of points -12;
- Opals (2) - interpolation using the Nearest Neighbour Method. Settings: distance - 5.0m; minimum number of points -12;
- TreesVis (1) - interpolation using “Ganzrau”;
- Supplied DTM - interpolation in TerraScan using the TIN method.

The accuracy of DTMs generated by the four different filtrations is very similar in each case (Fig. 5). Root mean square error (RMSE) ranges from 0.19 to 0.23m (differences up to 4cm). The smallest RMSE (0.191m) was achieved using the Nearest Neighbour Method in ArcMap (“Nature” filtration), while the lowest (0.226m) was observed in the model generated using the Natural Neighbours Method in Opals (“Wilderness” filtration setup).
BIAS values for all DTMs ranged from 0.133m to 0.155m. The lowest value was noted for the model generated using the Ganzrau method in TreesVis (with Nature filtration), while the highest came with the model generated by the Moving Planes Method in Opals software (using Wilderness filtration). Additionally, the DTM generated on the basis of filtration prepared by the data distributor using TerraScan characterises smaller vertical (height) errors (expressed by the BIAS indicator) than the DTM from LAStools filtration.

There are statistically significant differences in the cases of the pairs of DTM pixel values (results for specified interpolation methods) at the 95% confidence level (t-test for dependent samples):

- Opals 2 - Nearest Neighbour Method, differences between filtration based on the data provider or carried out using the LAStools Wilderness algorithm (p=0.00);
- ArcMap 1 - IDW method, differences between filtration based on the data provider or carried out using the LAStools Wilderness algorithm (p=0.03);
- TreesVis - all compared filtration gives different results of interpolation (p=0.00).

DTMs obtained from the data provider and investigated algorithms differ significantly for TreesVis interpolation (LAStools Wilderness and provider filtration), TerraScan (both LAStools filtrations), Opals (both LAStools filtrations) and ArcMap 4 (LAStools Wilderness filtration).

**Forest layers**

Forest layers influenced the accuracy of the generated models created on the basis of Data Provider filtration and filtration carried out in TerraScan software in similar way (Fig. 6). The only differences occurred in some filtrations used in ArcMap, but these do not
exceed 1cm. The highest BIAS values were observed in models generated on the basis of LAStools filtration (Wilderness) while the largest RMSE was noted for LAStools filtration (Wilderness) and TerraScan filtration. In points that were under forest of two stories, the largest errors characterised models generated on the basis of distributor filtration carried out using TerraScan software. In the forest stand with three stories and in the selection forest stand the smallest errors occurred in DTMs generated using LAStools Nature filtration. In LAStools Wilderness filtration DTMs generated in TreesVis differed significantly from others, with errors being several times greater. The most accurate DTMs were made on the basis of ArcMap and TerraScan interpolations. Models generated in Opals and TreesVis emerged as least accurate. Differences in accuracy with corresponding models (e.g. ArcMap 2) generated on the basis of data from different filtrations do not exceed 1-2cm.

Figure 6 - RMSE and BIAS for the DTM under a number of canopy stories above the picket (LAStools using Wilderness: BIAS: 0.12-1.2m, RMSE: 0.24-3.87m).

**Slope**

Generated models characterize similar RMSE and BIAS errors range for analyzed slope values (Fig. 7). In our study method of filtration is not found to influence the results of interpolation. Differences in the DTM were not significant. With 4 out of 7 methods of interpolation (Supplied DTM, ArcMap (2), TerraScan, TreesVis) RMSE and BIAS deteriorate gradually with increasing slope, but for slopes equal to 20° and 25° errors decreased. Supplied DTM, ArcMap (2) and TerraScan DTMs were generated using the TIN interpolation method. These models are characterised by the smallest range for RMSE in all observed classes - between 0.16 (0-5°) and 0.275 (20-25°).

The broadest range for RMSE error was noted for Opals 2 interpolation - from 0.16 (0-5°) to 0.425 (20-25°), and in Wilderness filtration in TerraScan (error range at the level of 3.6m).
Off-nadir angle while scanning

BIAS and RMSE were observed for interpolations generated using the TIN method (Supplied DTM, ArcMap (2), TerraScan and TreesVis), in order to off-nadir angle, characterize similar variability. With off-nadir angles of 0-5° and 5-10°, errors are at a similar level (differences up to 1 cm); while in the 10-15° class they are greater by 5-7cm and in the 15-20° class lower by 2-3 cm (Fig. 8).

With the ArcMap (2), Opals (2) and TreesVis (1) methods, the difference between RMSE and BIAS errors (with an off-nadir angle at the 0-5° and 5-10° level) is equal to about 12cm. Other methods generate an error of a range that does not exceed 7cm.

The methods of filtration used in this research do not influence DTM interpolation.
Undergrowth height

A majority of the pickets were situated in areas of low vegetation below 10cm in height, or else in ducts or roads (952 out of 1640). The RMSE for the DTM in that group is of about 10cm. In wetter places the undergrowth was dominated by various grass species, so a large number of pickets (120) were measured near undergrowth of height greater than 50cm. The error for this group was twice as great as in the group with no undergrowth, reaching more than 30cm.

The DTM generated using TIN methods (Supplied DTM, ArcMap(2)) was characterised by a smaller range of RMSE and BIAS errors between points that were measured without the influence of undergrowth and points measured in the area with the tallest undergrowth (600m and more). The range of BIAS reached 15cm, while that for RMSE reached 12.5cm. In comparison with TerraScan (1), the range of BIAS for the Opals (1) and Opals (2) methods reached 16.5cm, while that for RMSE was of 18cm (Fig. 9).

The error in the first 5 classes does not differ, as various methods of interpolation are taken into consideration. In contrast, in TerraScan (1), Opals (1), Opals (2) and TreesVis (1), errors are about 5cm different from those in other interpolations.

Filtration has no influence on the results. Differences in errors reach 3cm. In general BIAS is equal to almost half of the undergrowth height, while RMSE is equal to half of the undergrowth height “+” 5cm on average.

![Figure 9 - RMSE and BIAS distribution for the DTM in relation to undergrowth height (LAStools using Wilderness: BIAS: 0.24-0.75m RMSE: 0.32-2.93m).](image)

Picket type

It is obvious that the highest DTM accuracy characterises places with no undergrowth, for example on a duct (Fig. 10). BIAS error is smaller than 8cm and RMSE less than 10cm. The greatest influence on errors in ground class are those exerted by the two parameters of undergrowth height and slope. With the ground class the BIAS and RMSE errors are twice as large as those in the duct class.
Figure 10 - RMSE and BIAS for the DTM with regard to picket location (LAStools using Wilderness: BIAS: 0.53-1.5 m RMSE: 0.73-2.21m).

**Most important variables**
Understorey vegetation height has a more major influence on DTM accuracy (p=0.000) than slope (p=0.038). Analysis concerned the 15 measurement points with observed and expected values out of the expected range. Depending on the point, factors influencing error the most included:
- the height of forest undergrowth (for points located on a flat area);
- slope value (for points located in an area of insignificant undergrowth height);
- density of the points cloud, as a base for height interpolation in those points (density was 1 point higher than the mean for the whole area), the possibility in this area being the classification of ground as an object from a low vegetation class;
- the difference between measurement point height and height in the closest ALS point in 3D space (at the level of 60cm).

4 measurement points located on stumps in the research area were marked out in the field. In all analysed classes these were filtered from DTMs. Mean values for BIAS and RMSE were calculated for all interpolation methods, which were generated from data-provider filtration, TerraScan filtration, LAStools Wilderness and Nature filtration; and equalled: 0.143m/0.208m, 0.143m/0.208m, 0.159m/0.3215m and 0.145m/0.207m. Finally, the model interpolated in TreesVis displays the greatest differences with BIAS=0.62m and RMSE=2.79m. The method implemented using TreesVis is shown to be very sensitive to filtration results, with DTM generation needing to be carried out under strict control.
Discussion

Different filtration strategies resulted in different ground-point densities. In general, the point cloud was dense and offered a very effective reflection of topography in the study area. The highest density of points marked as ground and later used in DTM interpolation was noted for LAStools Wildness filtration (3.16 pts./m²), but this did not result in the most accurate DTMs. Differences were nevertheless very small (about 1-2cm) - a contrast with the overall findings from previous studies [Aguilar et al., 2005; Guo et al., 2010]. BIAS and RMSE for all DTMs, interpolated from denser data, assume the highest values, leading to the conclusion that too many off-ground points were preserved in the ground-point cloud and used in DTM interpolation. The density of ground points in the other studies was between one-sixth and half as great as in the presented work.

Our results showed that filtration done by supplier was nothing more than automatic filtration in TerraSolid software. Even if some additional editing was carried out, it was not detectable from statistical analysis. It can thus be concluded that work in a forest area does not necessitate the use of additional filtration, as there is a limited number of possibilities to check whether filtration is carried out properly or not. For example, a possible method can entail checks on the quality of filtered points to determine if all those in the vicinity of the derived DTM are classified as ground points. The accuracy of the generated models on the basis of distributor filtration and that created in TerraScan software is at the same level as studied in the manuscript. The only differences characterised certain interpolations used in ArcMap, though these do not exceed 1cm. The most accurate DTMs were made on the basis of ArcMap and TerraScan interpolations. Models generated using interpolation methods in Opals and TreesVis were the least accurate. Our findings are similar to those presented by other researchers [Su and Bork, 2006; Bater and Coops, 2009]. Algorithms such as the Nearest Neighbour and TIN interpolations achieve the greatest accuracy. Slightly poorer were Moving Planes and IDW, with the latter needing a number of different settings if best ones are to be found. The active contours algorithm implemented in TreesVis was very sensitive to point cloud density. The authors used map algebra to compare the two DTM models generated in TreesVis. The first model was generated from all cloud point data, the second only from ground class. Differences between these models ranged from -4m to +3m, attesting to the fact that the creation of a good model in any software requires that ground class first be extracted from the points cloud data.

It seems that the most automatic method was implemented in TreesVis and LAStools, and proved to be slightly less accurate. Most advanced settings are available in TerraScan and Opals, and this offers more flexibility in DTM improvements and site-specific settings. With ArcMap, users can create a DTM using a few algorithms. Each algorithm provides for the choice of advanced settings as well, with this capable of influencing the accuracy of DTMs. A look at difference trends between reference and DTM values (Fig. 6) reveals that the best accuracy was achieved in the cases of stands with one layer and multilayer objects. The slightly more limited accuracy for areas without trees reflects the presence of grass and herbaceous plants [Hopkinson et al., 2004; Gorte et al., 2005; Jan, 2005; Abraham and Adolt, 2006]. In one-layer spruce stands especially, there is no grass or herbaceous plants, so these do not influence DTM accuracy at all. In two-layer stands it is usual for the second layer to include deciduous shrubs that can prove difficult for LIDAR pulses to penetrate. Multi-layer stands are a mixture of many tree species, with a very non-homogeneous
structure and many gaps. This can explain why models are as good as in one-layer stands. There is usually no ground vegetation in such stands, because there is almost no light inside. We did not evaluate the influence of forest thinning on DTM accuracy, as was presented in a previous study [Reutebuch et al., 2003].

The influence of slope on DTM accuracy presented in this study is very similar to that found by previous studies [Pfeifer et al., 2004; Aguilar et al., 2005; Hodgson et al., 2005; Hyppä et al., 2005; Chaplot et al., 2006], and even the very difficult environment did not change generally-known trends. RMSE and BIAS values are generally greater with increased slope. Differences between filtrations are of up to 7cm, though 2-3cm on average. Generated models are characterised by similar RMSE and BIAS error ranges. In general, an RMSE value was about 1.5 times the slope angle value.

Findings from the current study show that the most accurate parts of the model are related to central parts of the strip. Overlap between strips improves accuracy, and this trend is easily detectable (Fig. 8). Differences between strip parts can be up to two-fold. Results of this kind were partly attested to by previous research. For example, Su and Bork [2006] observed the smallest RMSE in the off-nadir class of 3 - 6. They also emphasised that lower values of RMSE in these points correspond with flat terrain. This could suggest that slope has greater influence on DTM accuracy than the off-nadir angle.

Undergrowth height is the most important factor influencing DTM. Figure 9 presents very clear trends regarding RMSE and BIAS, whatever the filtration and interpolation analysed. This was already proved by previous research [Hopkinson et al., 2004; Gorte et al., 2005; Jan, 2005; Abraham and Adolf, 2006]. As this paper makes clear, previous findings are still valid in a very dense forest structure located in a mountainous area.

In the work presented here, most common software was analyzed and evaluated on the basis of a very large number of reference measurements. Results for the best DTMs show that in general all software and all methods evaluated offer reasonable results of interpolation after the setup of best parameters, in specific forest site conditions. The final comparison was confined to the most accurate models. It is clear that differences between reference measurements and pixel values from these selected models are very similar. Above all, no large differences were noted between DTMs from data supplier and other DTMs interpolated using automatic methods. It can be concluded that, in our case, there was no need to order a DTM from supplier, because such solutions does not offer any marked improvement in DTM accuracy. This is valid only for stand areas, not for infrastructure or other land-cover classes. In general, differences of accuracy in corresponding models (e.g. ArcMap 2), generated on the basis of data from different filtrations, do not exceed 1-2cm. There is no clear correlation between BIAS and RMSE. Higher values in BIAS error do not always raise values of RMSE and vice versa, with lower values in BIAS error not having to cause lower RMSE.

The digital terrain model represents one of the most important items of spatial data used in forest. Our results showed overall that all algorithms give reasonable results in a forested area. The compared methods of filtration and interpolation show that best cases do not differ much between one and another, with a maximum of 5cm for RMSE and BIAS values (Fig. 5). The environment and topography play the most important role, and explain most of the variability in DTM accuracy, in our case forest layers much less influence on the DTMs accuracy.
Conclusions
The final conclusions from the research are as follows:

1. Slope, and especially undergrowth vegetation, are the most important factors influencing DTM accuracy in the conditions of dense forest in mountainous areas;
2. All methods of interpolation are capable of achieving very similar errors following the selection of best settings;
3. In terms of ground class, BIAS and RMSE errors are twice as large as in the duct/road land cover class;
4. In general, BIAS is equal to almost half of undergrowth height, while RMSE is equal to half of undergrowth height “+” 5cm on average;
5. Our study shows that in our case there was no added value of ordering the filtered point cloud, as well as interpolated DTM, if any software or interpolation algorithm dedicated to ALS point cloud analysis, is already implemented or freely available, and filed reference data were acquired.

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References
Abraham J., Adolt R. (2006) - Stand height estimation using aerial images and laser datasets. Proceedings of the International Workshop: 3D Remote Sensing in Forestry, pp. 24-31, Schneider K. (Ed.), Vienna, 14-15 February 2006.
Aguilar F.J., Agüera F., Aguilar M.A., Carvajal F. (2005) - Effects of terrain morphology, sampling density, and interpolation methods on grid DEM accuracy. Photogrammetric Engineering and Remote Sensing, 71: 805-816. doi: http://dx.doi.org/10.14358/PERS.71.7.805.
Axelsson P. (1999) - Processing of laser scanner data-algorithms and applications. ISPRS Journal of Photogrammetry and Remote Sensing, 54 (2-3): 138-147. doi: http://dx.doi.org/10.1016/S0924-2716(99)00008-8.
Axelsson P. (2000) - DEM generation from laser scanner data using adaptive TIN models. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIII (Pt. B4/1): 110-117.
Bater Ch.W., Coops N.C. (2009) - Evaluating error associated with lidar-derived DEM interpolation. Computers Geosciences, 35: 289-300. doi: http://dx.doi.org/10.1016/j.cageo.2008.09.001.
Beven K.J., Kirkby M.J. (1979) - A physically based variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24: 43-69. doi: http://dx.doi.org/10.1080/0262667909491834.
Burrough P.A., McDonnell R.A. (1998) - Principles of Geographical Information Systems.
Chaplot V., Darboux F., Bourennane H., Leguédois S., Silvera N., Phachomphon K. (2006) - *Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density.* Geomorphology, 77: 126-141. doi: http://dx.doi.org/10.1016/j.geomorph.2005.12.010.

Chen Z., Zhang B., Yongshun H., Zuo Z., Zhang X. (2014) - *Modeling Accumulated Volume of Landslides Using Remote Sensing and DTM Data.* Remote Sensing, 6: 1514-1537. doi: http://dx.doi.org/10.3390/rs6021514.

Elmqvist M. (2000) - *Automatic Ground Modelling using Laser Radar Data.* Master thesis, Linköping University, Linköping, Sweden, 30 p.

Elmqvist M. (2001) - *Ground estimation of laser radar data using active shape models.* Proceedings OEEPE workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Elevation Models, 1-3 March, OEEPE Publication, 40, 8 pp.

Elmqvist M., Jungert E., Lantz F., Persson A., Soderman U. (2001) - *Terrain modelling and analysis using laser scanner data.* International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (Pt. 3/W4): 219-227.

Gorte B., Pfeifer N. Elberink S.O. (2005) - *Height texture of low vegetation in airborne laser scanner data and its potential for DTM correction.* Proceedings of the ISPRS Workshop Laser scanning, XXXVI (3/W19): 150-155.

Guo Q., Li W., Yu H. Alvarez O. (2010) - *Effects of Topographic Variability and Lidar Sampling Density on Several DEM Interpolation Methods.* Photogrammetric Engineering Remote Sensing, 76 (6): 1-12. doi: http://dx.doi.org/10.14358/PERS.76.6.701.

Heritage G.L., Milan D.J., Large A.R.G., Fuller I.C. (2009) - *Influence of survey strategy and interpolation model on DEM quality.* Geomorphology, 112 (3-4): 334-344. doi: http://dx.doi.org/10.1016/j.geomorph.2009.06.024.

Hopkinson C., Chasmer L.E., Zsigovics G., Creed I.F., Sitard M., Treitz P. Maher R.V. (2004) - *Errors in LIDAR ground elevation and wetland vegetation height estimates.* Proceedings of the ISPRS Working Group on Laser-Scanners for Forest and Landscape Assessment, Freiburg, Germany, Institute for Forest Growth, Institute for Remote Sensing and Landscape Information Systems, Albert Ludwigs University Tennenbacherstr, XXXVI (8/W2): 108-113.

Hyyppä H., Yu X., Hyyppä H., Kaartinen H., Kaasalainen S., Honkavaara E., Rönnholm P. (2005) - *Factors affecting the quality of DTM generation in forested areas.* International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVI (3/W19): 85-90.

Hyyppä J., Yu X., Hyyppä H., Vastaranta M., Holopainen M., Kukko A., Kaartinen H., Jaakkola A., Vaaja M., Koskinen J., Alho P. (2012) - *Advances in Forest Inventory Using Airborne Laser Scanning.* Remote Sensing, 4 (5): 1190-1207. doi: http://dx.doi.org/10.3390/rs4051190.

Jan J.F. (2005) - *Comparison of Forest Height Derived Using LIDAR Data and Aerial Photos.* Taiwan Journal of Forest Science, 20: 13-27.
Kraus K., Pfeifer N. (1998) - *Determination of terrain models in wooded areas with airborne laser scanner data*. ISPRS Journal of Photogrammetry and Remote Sensing, 53 (4): 193-203. doi: http://dx.doi.org/10.1016/S0924-2716(98)00009-4.

Kraus K., Pfeifer N. (2001) - *Advanced DTM generation from LiDAR data*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (3/W4): 23-30.

Miścicki S., Stereńczak K. (2013) - *A two-phase inventory method for calculating standing volume and tree-density of forest stands in central Poland based on airborne laser-scanning data*. Forest Research Papers, 74 (2): 127-136. doi: http://dx.doi.org/10.2478/FRP-2013-0013.

Pfeifer N., Kostli A., Kraus K. (1998) - *Interpolation and filtering of laser scanner data-implementation and first results*. International Archives of Photogrammetry and Remote Sensing, XXXII (3/1): 153-159.

Pfeifer N., Gorte B. Elberink S.O. (2004) - *Influences of vegetation on laser altimetry - analysis and correction approaches*. Proceedings of the ISPRS working group on Laser-Scanners for Forest and Landscape Assessment, XXXVI (8/W2): 283-287.

Pietrzak J. (2013) - *Fast and efficient processing of clouds (Szybkie i efektowne przetwarzanie chmury)*. Geodeta Magazyn Geoinformacyjny, 10 (221): 29-32, (in Polish).

Reutebuch S.E., McGaughey R.J., Andersen H.E., Carson W.W. (2003) - *Accuracy of a high-resolution lidar terrain model under a conifer forest canopy*. Canadian Journal of Remote Sensing, 29 (5): 527-535. doi: http://dx.doi.org/10.5589/m03-022.

Roggero M. (2001) - *Airborne laser scanning: clustering in raw data*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (3/W4): 227-232.

Sithole G. (2001) - *Filtering of laser altimetry data using a slope adaptive filter*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (3/W4): 203-210.

Sithole G., Vosselman G. (2004) - *Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds*. ISPRS Journal of Photogrammetry and Remote Sensing, 59 (1-2): 85-101. doi: http://dx.doi.org/10.1016/j.isprsjprs.2004.05.004.

Sohn G., Dowman, I. (2002) - *Terrain surface reconstruction by the use of tetrahedron model with the MDL Criterion*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (3A): 336-344.

Stereńczak K., Kozak J. (2011) - *Evaluation of digital terrain models generated from airborne laser scanning data under forest conditions*. Scandinavian Journal of Forest Research, 26: 374-384. doi: http://dx.doi.org/10.1080/02827581.2011.570781.

Stereńczak K., Zasada M., Brach M. (2013) - *Influence of terrain slope, model pixel size and stand structure on accuracy of DTM generated under pine stands from LIDAR data*. Baltic Forestry, 19 (2): 252-262.

Su J., Bork E. (2006) - *Influence of Vegetation, Slope, and Lidar Sampling Angle on DEM Accuracy*. Photogrammetric Engineering Remote Sensing, 72 (11): 1265-1274. doi: http://dx.doi.org/10.14358/PERS.72.11.1265.

Wilson J.P., Gallant J.C. (2000) - *Terrain Analysis. Principles and Applications*. Wiley, New York, 479 pp.
Wack R., Wimmer A. (2002) - *Digital terrain models from airborne laser scanner data - a grid based approach*. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIV (3B): 293-296.

Watt M.S., Adams T., Watt P., Marshall H. (2013) - *Influence of stand and site conditions on the quality of digital elevation models underlying New Zealand forests*. New Zealand Journal of Forestry Science, 43: 5. doi: http://dx.doi.org/10.1186/1179-5395-43-5.

Weinacker H., Koch B., Heyder U., Weinacker R. (2004) - *Development of filtering, segmentation and modelling modules for LIDAR and multispectral data as a fundamental of an automatic forest inventory system*. Proceedings of ISPRS working group VIII/2 “Laser-Scanners for Forest and Landscape Assessment”, Thies M., Koch B., Spiecker H., Weinacker H. (Eds.), Freiburg, University of Freiburg, pp. 90-95.

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