



## Article

# Identification of the Forest Cover Growth on Landscape Level from Aerial Laser Scanning Data

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**Abstract:** Aerial laser scanning technology has excellent potential in landscape management and forestry. Due to its specific characteristics, the application of this type of data is the subject of intensive research, with the search for new areas of application. This work aims to identify the boundaries of forest stands, and forest patches on non-forest land. The research objectives cover the diversity of conditions in the forest landscapes of Slovakia, with its high variability of tree species composition (coniferous, mixed, deciduous stands), age, height, and stand density. A semi-automatic procedure was designed and verified (consisting of the creation of a digital terrain model, a digital surface model, and the identification of peaks and contours of tree crowns), which allows after identification of homogeneous areas of forest stands and/or forest patches (areas covered with trees species canopy) with selected parameters (height, crown size, gap size), with high accuracy. The applicability of the proposed procedure increases the use of freely available ALS data (provided by the Office of Geodesy, Cartography, and Cadastre of the Slovak Republic) and freely distributable software tools (QGIS, CloudCompare).

**Keywords:** airborne laser scanning; digital terrain model; digital surface model; forest stand delineation; forest patch identification



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## 1. Introduction

Airborne laser scanning is an active measurement/surveying technology [1]. For practical applications (the level of which the technology has reached chiefly), the scanner is mounted on an airplane, helicopter, or unmanned aerial vehicle (UAV) [2]. The scanner sends short infrared pulses to the examined surface or objects, which are then reflected from them back to the scanner. Based on the precisely measured time of the received reflected pulse, the known position of the sensor and the parameters of the pulse, the distance between the scanner and the object, and the position of the reflection point are calculated [3]. In forestry applications, the first return usually comes from the tops of the trees (the surface of the forest canopy), the next from the various parts of the trees and the stand within it, and the last from the ground surface. Multiple reflections represent helpful information about forest stands' vertical and horizontal structures [4]. An airborne laser scanning (ALS) equipment system consists of multiple components. It includes a laser measurement unit; an optomechanical scanner, control, monitoring, and recording units; a kinematic global positioning system receiver; and an inertial measurement unit (IMU) [5]. IMUs consist of gyroscopes and accelerometers [6].

Mapping the boundaries of the forest and forest stands is one of the main tasks of forestry mapping. It is also the starting point for conscientious and objective planning of all forestry activities. Forest management refers to and differs from forest units that are

spatially defined, based on the mapping of their boundaries with respect to environmental conditions, forest stand characteristics, and the overall landscape context. In addition to its importance within forestry, this issue also affects several other sectors to which forests and forestry are related (mainly environmental protection, land management, agriculture, water management; and the real estate market, economic and social areas). Data on the size and nature of forests are the basis for overview and summary information on the country's forest cover, the health of forests, wood sources, carbon stocks, etc. [7].

LiDAR technology represents an effective way of obtaining relevant information about forest ecosystems [8]. The particular importance of ALS applications in forestry results from its ability to significantly contribute to the accurateness and correctness description of the three-dimensional structure of the forest stand [9]. Concerning forest inventories, two groups of basic approaches were presented—the area-based approach and the individual tree detection approach. Several detailed reviews, e.g., refs. [10–15] were published. Using ALS data to create a digital surface model (DSM) and the subsequent generation of automatic model segmentation was studied by Ref. [16]. In this case, the ALS data were combined with aerial photogrammetry. Also others Refs. [17,18] investigated this combination of approaches. Tree crown identification provided information on the number of trees and calculation of the canopy closure. Using this information can help to identify the spatial units of the forest. Similar approach was used by [19] but did not implement the canopy closure criterion. Normalized DSM expression generated from ALS data used Ref. [20].

Two digital models—the digital terrain model (DTM) and the digital surface model (DSM)—play a critical role in identifying the boundaries of forest stands and patches. The precision of out-coming digital models generated from ALS data depends on many factors Ref. [21], especially the density of points per spatial unit and distribution of points through space. The crucial factor is also the strategy of classification of point cloud and interpolation methods used for generating digital models. Effects of every single factor were studied by [22–24]. Digital terrain and surface models can serve a wide range of purposes. The normalized DSM (height of forest canopy) is an example of the use of digital models, where it follows from the difference between the two models [25,26]. The vertical accuracy of digital models (DTM, DSM) is an essential qualitative factor, as it directly or indirectly affects all outputs created from, or based on, them [7].

Forest concepts and definitions are mentioned mainly concerning forest degradation and loss, and/or potential wood sources and other forest products and ecosystem services. A compilation of forestry terms and definitions, including the FAO and IUFRO definitions of forest, was presented by [27]. Historical overview of purposeful concepts and definitions of the forest depending on the purpose of its use, various aspects of the condition and dynamics, and the broader landscape context was presented by [28]. Ref. A detailed overview of definitions and their specifications and clarifications according to the purpose of the use is published on the website of The Convention on Biological Diversity (more details at <https://www.cbd.int/forest/definitions.shtml> (accessed on 14 April 2023)). The specific definition of the forest category was also created as part of the CLC service (formerly known as the “CORINE Land Cover Programme”), coordinated by the European Environment Agency (EEA). It provides consistent and thematically detailed information on land cover and land cover changes across Europe (more details at <https://sdi.eea.europa.eu/catalogue/geoss/eng/catalog.search#/home> (accessed on 14 April 2023)).

For our work, we used the widely accepted definition of forest according to FAO [29]. It is also called the general definition of a forest and contains the following criteria: it is an area covered by a canopy of forest tree species, it has a minimum area of 0.5 ha, the minimum width of its area is 20 m, the forest cover is at least 10%, and the potential height of the trees is greater than 5 m (except mountain pine, where it is 2 m). With only minor deviations regarding forest coverage/stocking and avoiding local non-forested areas (holes over 300 m<sup>2</sup>), this definition was implemented into the national Slovak legislation.

After the social, economic, and political changes in 1989, the already existing phenomenon—the problem of cultivated agricultural land abandonment—became even

more prominent and intensified in the land use in Slovakia. It consist the spontaneous overgrowth of meadows and pastures with trees and shrub vegetation, and its various stages of succession. Estimates of the extent of the changes vary, Ref. [30] presented an acreage of approximately 450,000 ha, representing about 18% of the area of agricultural land according to the records of the real estate cadastre. It can be assumed that the included successional stands did not necessarily have the nature of a forest according to all the above criteria. During the National Forest Inventory and Monitoring in 2015–2016, the area of the so called “white areas” was estimated to be approximately  $288,000 \pm 39,000$  ha [31]. In this case, the areas met all the criteria for defining a forest. Thus, in practice, we encounter problems related to the up-to-datedness of the cadastre and the resulting inconsistencies between its evidence and the reality concerning the type of land. Another factor is that the forest is a dynamic ecosystem that tends to expand continuously, so it is necessary to find a suitable approach to dynamically update the forest boundaries, for practical issues and for the cadastre, with an objective workflow that could be applied nationally.

The main goal of this work was to propose and practically verify a semi-automated methodology for identifying the boundaries of forest stands and the identification (delineation) of forest patches on non-forest land. Application on a broad national level was envisaged using freely available ALS data and software tools. The next phase of the research was to evaluate the correctness of the results of the automatic classification of ALS data by comparison with reference data and cadastral records.

## 2. Materials and Methods

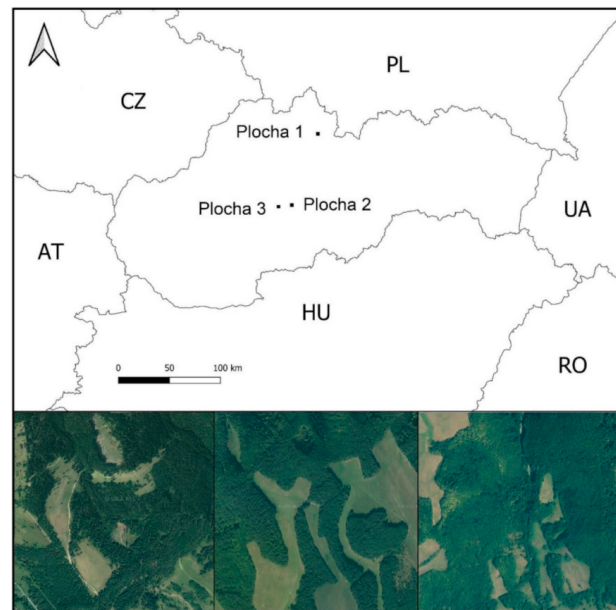
### 2.1. Research Areas

The research areas were selected by purposeful selection, so that their characteristics covered the variability of the investigated criteria. We mainly considered the composition of the tree species (coniferous, mixed, deciduous stands), age, height, and density of the stand. Regarding stands on non-forest land (white areas), the type of land according to cadastre records, stand-alone trees, or cadastral parcels were registered as forest parcels. Each experimental area was represented by a square with dimensions of  $1000 \times 1000$  m with a total area of 100 ha.

The localization in the territory of Slovakia and the essential spatial connections of the research areas follow from the content of Figure 1. The first research area (Area 1) was in the Western Tatras, in the district of Liptovský Mikuláš near the village of Malé Borové. It represented stands of coniferous tree species. Smaller areas were deforested by sanitary logging after damage caused by the spruce beetle. There were eight forest stands between 15 and 115 years old. The second research area (Area 2), representing the conditions of mixed stands, was on the territory of the Zvolen basin, in the district of Zvolen near the village of Tŕnie. There were 13 forest stands between 20 and 105 years old. The third research area (Area 3), with stands of deciduous trees, was on the territory of the Zvolen basin in the district of Zvolen near the village of Sampor. There were 13 forest stands between 15 and 150 years old. Other characteristics of the research areas are presented in Table 1.

**Table 1.** Characteristics of research areas.

	Area 1	Area 2	Area 3
Acreage (ha)	100	100	100
Average slope (%)	16.69	14.69	9.78
Orientation	East	East	Southwest
Tree composition	70% coniferous, 30% deciduous	70% deciduous, 30% coniferous	50% deciduous, 50% coniferous
Main tree species	Norway spruce	European beech, European hornbeam	Scotch pine, European beech
Altitude (m)	812–1003	402–484	356–539
Management system	Shelterwood system	Shelterwood system	Shelterwood system



**Figure 1.** Map and orthophotos of research areas with coordinates of center WGS84 ( $\varphi$ ,  $\lambda$ ): **left**—Area 1 ( $49.227368^\circ$ ,  $19.551719^\circ$ ); **middle**—Area 2 ( $48.611927^\circ$ ,  $19.044885^\circ$ ); **right**—Area 3 ( $48.624450^\circ$ ,  $19.210638^\circ$ ).

## 2.2. ALS Data

ALS data were obtained from the Digital Relief Model (DMR) 5.0 project implemented by the Office of Geodesy, Cartography and Cadastre of the Slovak Republic (more details at [https://www.geoportal.sk/en/zbgis/als\\_dmr/](https://www.geoportal.sk/en/zbgis/als_dmr/) (accessed on 14 April 2023)). The data are freely available for the entire territory of Slovakia on the source portal, in the .las format. According to the metadata, the Ground class contains a maximum of 0.5% of incorrectly classified points per 1 km<sup>2</sup> area. Within the other classes (low vegetation, buildings, and high vegetation, except for the unclassified class), a maximum of 10% occurrence of incorrectly classified points per 1 km<sup>2</sup> is permissible.

We used data from areas in Banská Bystrica for experimental plots 2 and 3, and Tatras for experimental plot 1. For each project area, the results of the purposeful verification of the absolute positional and height accuracy of the point cloud, as well as the verification of the absolute height accuracy of the output DSM on geodetically, precisely measured height and position control points (located in open space at several randomly selected locations), are also published [32]. The point density was 30/m<sup>2</sup> in experimental area 1, and 22/m<sup>2</sup> in experimental areas 2 and 3. The horizontal accuracy of the point cloud for area 1 is 0.04 m, and 0.05 m for areas 2 and 3. The scanning period was November 2018–May 2019 for areas in Banská Bystrica, and June 2018–September 2018 for areas in Tatras.

## 2.3. Software Tools

Several software tools of different types and purposes were used in the research process. The most important were the environments for processing aerial laser scanning data (CloudCompare), the QGIS environment for working with geographic information, the Kokeš system for processing cadastre data, and the Summit Evolution environment for creating vector layers of reference data as focal points. To a lesser extent, other means were also used for partial tasks in the processing and statistical data analysis, creating and editing visualizations, and preparing documents for publication in electronic and analog forms.

The open-source tool CloudCompare (more details in [33] at <http://www.cloudcompare.org/> (accessed on 14 April 2023)) was created in 2009 in the C++ language. It was produced under the GNU GPL version 2 license (GNU General Public License). The QGIS system



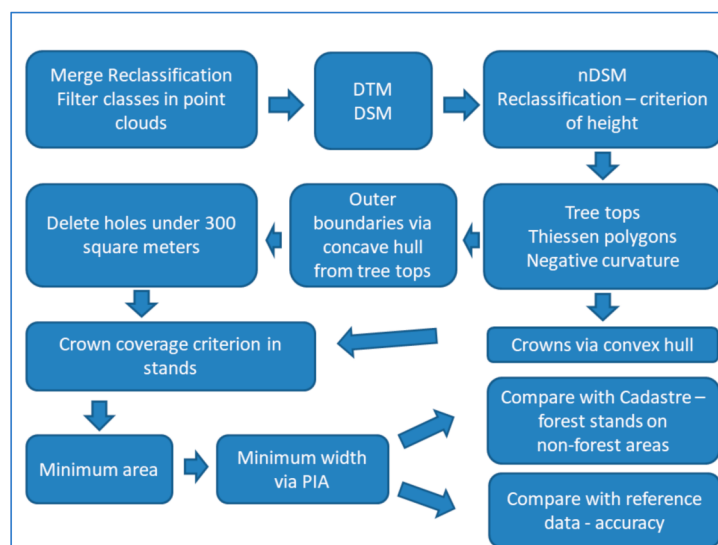
(more details at <https://www.qgis.org/en/site/> (accessed on 14 April 2023)) is one of the freely available GIS environments. It implements a wide range of functions for processing geodata—from input through to the initial processing, to analysis and visualization. QGIS, as software, has relatively modest functionalities. However, it is designed to directly implement other GIS applications, which complement it appropriately and thus expands its usability. It is the principle of the so-called toolboxes, with an integrated graphical user interface.

Kokeš (more details in [34] at <http://www.cgs.sk/Produkty/Kokes.aspx> (accessed on 14 April 2023)) is specialized interactive software for creating, processing, and visualizing geodetic information and cadastre data of Slovak provenance.

Summit Evolution (more details at <https://www.datem.com/summit-uas/> (accessed on 14 April 2023)) provides a set of powerful tools for displaying and recording 3D data from stereophotogrammetry. The software includes CAD and GIS interfaces, the creation of vector representations of objects from stereo models in a 3D environment, automatic adjustment of functions, generation of contour lines, and many other tools. It offers tools for converting orthophotos with DMT files to stereo image pairs, and .las files to stereo image pairs.

#### 2.4. Methodology

The sequence of processing ALS data from a publicly available source using free software tools to identify the boundaries of forest stands and forest patches can be considered the main result of the experiment. This process is structured and non-trivial, with more specific details. For general orientation, we have presented a diagram in Figure 2.

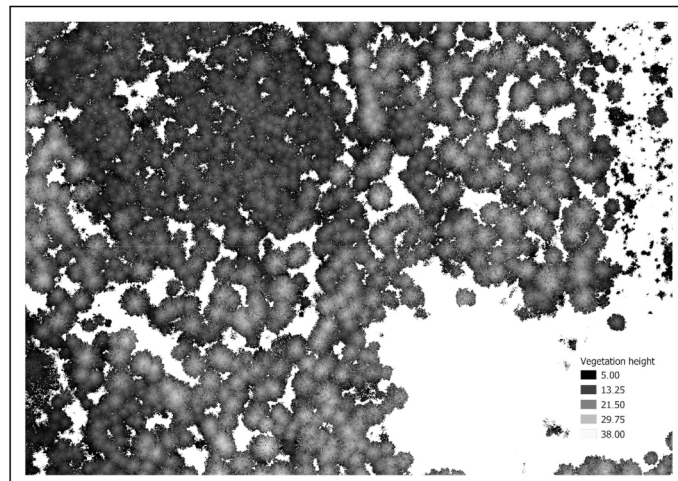


**Figure 2.** Diagram of the methodology workflow.

As we have already mentioned in the description of the source data, the input point clouds in .las format have been pre-classified by their supplier. The data blocks were processed in the CloudCompare environment. Possible merging of scans was made possible by using its Merge module. Subsequently, the operator checked the correctness of classification in the 3D interface of CloudCompare software. Potential reclassification of incorrectly classified points (buildings on forest areas, extremes, etc.) was provided on point clouds by manual check and reclassification. The result of this step was the correct categorization into the classes used in the next steps of our research. These were the classes of ground (terrain surface) and low, medium, and high vegetation. Extraction of each individual class was carried out using module Filter points by value.

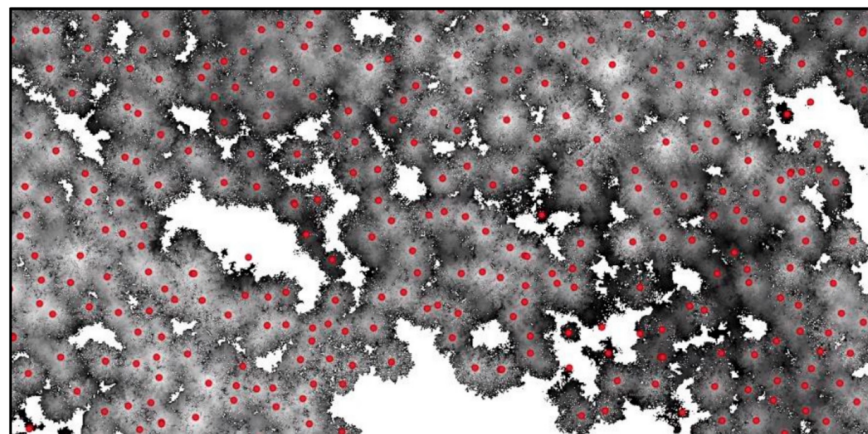
The next step was the rasterization of the cloud of points on a grid with a resolution of  $0.25 \times 0.25$  m. The class ground (terrain surface) was used to create the DTM, and the

layers “low vegetation”, “medium vegetation”, and “high vegetation” were used to create the DSM. The CloudCompare software includes a Cloud to 2D Raster Conversion module. The normalized DSM (nDSM) was created by subtracting the DTM values from the DSM values, using the raster calculator in the QGIS software. The values of the created nDSM represented the height of the vegetation canopy (in our case, stands of forest tree species) above the terrain surface. Using the Sort by Table module, we could exclude stands below the selected height value as needed. We could check the fulfillment of the selected minimum height criterion for classifying the patch into the forest category (example see in Figure 3).



**Figure 3.** Visualization of an example of a normalized digital surface model (nDSM) after reclassification according to the height criterion.

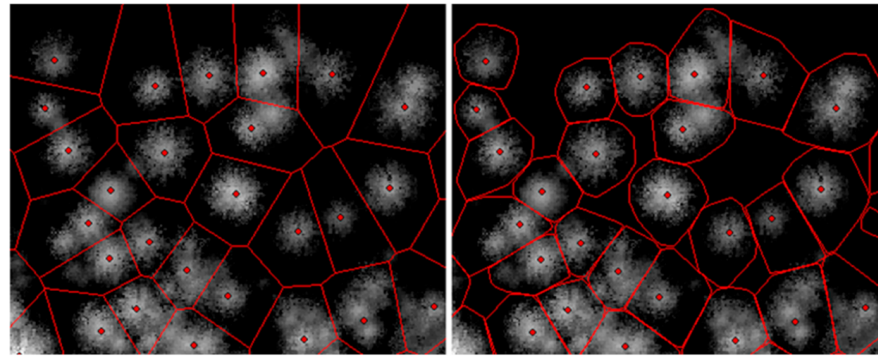
To locate the outer boundaries of continuous areas of forest stands, or edges of forest patches (leading along the outer perimeters of crowns at the edges of stands or forest patches), it was first necessary to identify individual tree crowns. This non-trivial procedure also conditioned the assessment of the degree of density of the tree canopy, or the coverage of the growth area with their crowns. The methodology published by [35] was used to identify tree crowns. Based on this methodology, the first step was finding the treetops. Surface local maximum searches and tree crown identification are implemented in QGIS software, using the Tree Density plug-in via the Tree Density Calculator. The input for this module was nDSM; the output was an information layer of points representing the tops of tree crowns with an assigned height (example see in Figure 4).



**Figure 4.** Visualization of an example of identifying the treetops based on nDSM values.

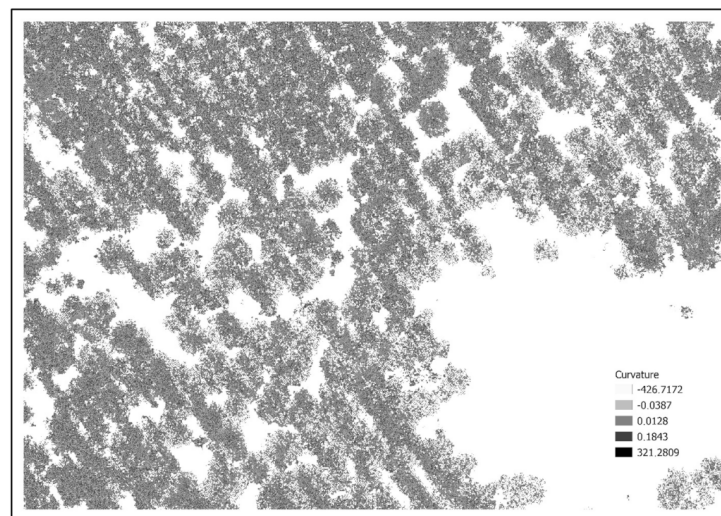
Continuing according to the adopted methodology, it is subsequently possible to identify tree crowns (their outlines) based on the combination of convex polygons around each

treetop with the evaluation of the curvature parameters of the nDSM. Such an approach also contributes to higher accuracy of identification/delineation of the gaps between tree crowns. The convex polygons around the tops of the trees represent, from a geometric point of view, the so-called Voronoi or Thiessen polygons, which can be created in the QGIS environment using the Voronoi polygons module. The resulting polygons are always continuous and convex, as seen in Figure 5-left, but do not correctly represent the circumference of the crowns.



**Figure 5.** Comparison of (left) Thiessen polygons; and (right) polygons adjusted for negative curvature, both based on nDSM.

This deficiency can be eliminated based on assessing the nDSM surface curvature parameters (Figure 5-right). We can calculate surface curvature values in the QGIS environment using the `r.slope.aspect` module (result of calculation see at Figure 6).



**Figure 6.** Visualization of an example of the curvature values for the digital surface model (nDSM).

Negative curvature values represent concave shapes, and positive values represent convex shapes. Zero curvature values are inherent to flat surfaces. Concave shapes, i.e., negative curvature values, are typical for tree crown canopies. By selecting (reclassifying) areas with negative curvature values and the subsequent automated vectorization of their perimeter, vector layers were created, delimiting areas of crown canopies. By combining vector geometries delimiting Thiessen polygons and areas with negative curvature values, we obtain the required identification of tree crown perimeters and the gaps between them. We present a visualization of an example of the application of the procedure in the left part of Figure 5.

The outer perimeter of continuous and convex areas of forest stands or forest patches could be achieved by rasterizing the layer of tree crowns, and the subsequent reversal of vectorization with smoothing of the edges to exclude small discontinuities between the

individual crowns. In cases where there is a need to define the boundary of the forest stand or forest patch through the position of tree trunks on its perimeter, it is possible to use the information layer of treetops for this purpose. The QGIS environment has a plug-in module called Concave hull, which presents possibilities to identify so-called alpha shapes and allows you to connect points representing the tops of trees (and thus also their trunks) to the perimeter line of an object filled with points (forest stand or forest patch area filled by treetops) even with gaps or unfilled areas (holes) with the specified size.

To be able to evaluate canopy closure parameter, in addition to the definition of continuous and convex areas (according to the previous step), it is also necessary to identify areas not covered by crowns (not overgrown) more prominent than 300 m<sup>2</sup> in terms of the requirements for defining a forest. On the other hand, not considering such areas would lead to gross distortions in determining the canopy closure. For this purpose, we can use the Erase Holes module in the QGIS environment to fill the holes below the set area. For canopy calculation itself, it was necessary to create a tree crown mask raster from which the area covered by vegetation (tree crowns) could be calculated. Using the tools of the Zonal Statistics module, the proportion of this area covered by vegetation against the continuous area of forest cover or forest patch without gaps larger than 300 m<sup>2</sup> was then calculated.

It was relatively easy to perform the final checks on whether the forest patches identified by the procedure described so far meet the requirements of the forest definition. The area of the created continuous and convex areas of stands or forest patches was determined automatically and stored in the attribute table of objects of the relevant information layer. Subsequent filtering made it possible to exclude objects with an area smaller than the specified threshold value—in this case, 0.3 ha. The minimum stand width criterion was applied based on the assumption that a circular shape with a diameter of 20 m can be inscribed in the polygon, which represents a stand or forest patch, according to the criterion. The request was made possible by the application of the PIA (Poles of Inaccessibility) analysis implemented in the QGIS environment, in the Select function within the plug-in module, with subsequent processing of the attribute table of the selected points. The condition was that they could describe a circle with a radius of 10 m.

The data and information layers of the cadastre were first processed in Kokeš software. In addition to an elementary visualization of maps, and access to databases, forest stands were identified by filtering, and a vector information layer was created with their location. After exporting to the .shp format, processing the cadastre documents in the QGIS environment was possible. It was possible to either confirm the agreement or the inconsistency of the content between our process of the created layer of forest stands or forest patch, with the cadastre evidence, up to the identification and quantification of the acreage of white areas and their other characteristics.

### 2.5. Reference Data

To evaluate the correctness and accuracy of the ALS data classification according to the procedure mentioned above, it was necessary to create relevant reference data. The essential requirement was that their positional accuracy was higher, or at least comparable to, the positional accuracy of the processed ALS data and the products derived from them. At the same time, they should be up-to-date and correspond to the reality in the given experimental territories. After considering the possibilities, we decided to create special-purpose materials by vectorization on a stereo model from very accurate aerial photographs.

Suitable areal images with sufficient overlap and a spatial resolution of 25 cm were obtained from the Institute of Forest Resources and Informatics, National Forest Centre Zvolen. The imaging took place at the end of summer in 2021. The processing of aerial images and the creation of stereo models, as well as the subsequent vectorization of the boundaries of forest stands and forest patches, was carried out in Summit Evolution software. These reference data were vectorized using Planar technology to display 3D pairs of orthophotos using polarized glasses and a unique joystick.



The Accuracy module within the Semi-Automatic Classification plug-in in the QGIS software was used to evaluate the accuracy of the classification. It was necessary to import reference data, and data from the automatic classification of forest stands obtained from ALS into the module. The result is a table showing the areas of individual classes of both rasters, the mean error, the overall classification accuracy, and the kappa index.

### 3. Results

The research results contribute to the versatile use of aerial laser scanning data in forestry and land management. A semi-automatic methodological procedure was designed and verified, which allows the identification of homogeneous forest stands and/or forest patches (areas covered with tree species canopy) with selected parameters (height, size of crowns, size of gaps) with high accuracy. When identifying forest stands and/or forest patches, it is explicitly checked whether the selected area meets all forest criteria according to the FAO definition. The applicability of the proposed procedure increases the use of freely available ALS data (provided by the Office of Geodesy, Cartography, and Cadastre of the Slovak Republic) and freely distributable software tools (QGIS, CloudCompare).

#### 3.1. Methodology as Such

The proposed methodology describes the procedures for processing ALS data from their acquisition in the state where they are referenced and classified. The research demonstrated that applying the procedure in the variable conditions of the experimental areas was successful. In addition to the factual correctness and the ability to implement the entire procedure in all cases, the time required for processing and the necessary intervention of the operator during data processing was also evaluated. The design and verification of the presented methodology naturally represented hours of research work. After it was debugged, the time requirement of the routine application to sample experimental territories was also tested. In addition to the size of the processed area, the total processing time was influenced by the performance of the hardware equipment and, above all, the experience and knowledge of the operator. Therefore, the absolute values of the processing processes' duration do not have a fundamental meaning. However, due to the nature of the application, the effort to create a batch, fully automated solution without operator input is not yet an option.

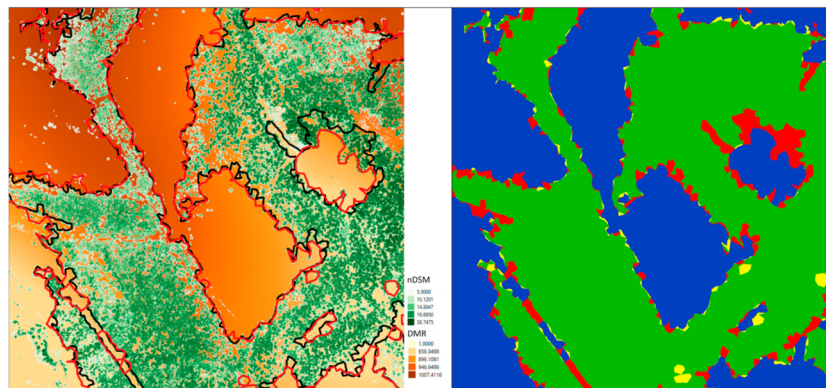
A semi-automatic approach, in which the operator's intervention during the routine application does not represent a high proportion of the processing time, is thus suitable. The recorded time data shows that the real average working time of the modules in the CloudCompare software was approximately 162 s, and the operator's work was 85 s—a total of 247 s (4.12 min). When creating the forest boundaries in QGIS software, the real average working time of the modules took 1537 s, and the operator's work was 341 s. This part of the processing took 1878 s (31.3 min) on average. Applying the criteria for inclusion in the forest category in QGIS took 27 s for the work of the modules, and 258 s for the work of the operator—a total of 285 s (4.75 min) on average. Identifying forest stands on an experimental area of 100 ha took 40 min and 10 s on average for all three research areas.

#### 3.2. Accuracy of Forest Stands and Forest Patches Boundaries Identification

As already stated in the methodology, we assessed the correctness and accuracy of the achieved results by comparing the boundaries of forest stands and forest patches derived by applying the above-mentioned semi-automatic procedure against reference data. These were the exact boundaries derived by manual vectorization on a high-fidelity stereo model in the Summit Evolution environment. An example of background data and their processing procedure for research area 1 follows from the content of Figure 7. In its left part, the drawing of the outer boundaries of forest stands and forest patches derived from the proposed semi-automated procedure is visualized in red. The black drawing represents the position of the reference (correctly located) boundaries. After the rasterization of both layers, it was possible to identify their mutual differences by cross-



classification, visualized in the right part of the image. By applying the Accuracy module in the Semi-automatic classification plug-in in the QGIS software, it was possible to generate a table with an evaluation of the accuracy of the automated classification compared to the reference data (Table 2).



**Figure 7.** Input data for accuracy assessment. **Left:** comparison of the stand (patch) boundaries by proposed methodology (red outline) and reference data (black outline). **Right:** Raster differences visualization from the comparison (green: correct forest area, blue: correct non-forest area, red: forest area overestimation, yellow: non-forest area underestimation).

**Table 2.** Evaluation of classification accuracy.

Accuracy Assessment	Area 1		Area 2		Area 3	
	Reference	Classified	Reference	Classified	Reference	Classified
Producer's accuracy [%]	100.00	96.87	88.02	95.77	95.80	98.00
User's accuracy [%]	96.04	100.00	91.00	94.27	97.36	96.80
Standard error	64.00	64.00	63.00	63.00	42.00	42.00
Kappa index	0.96		0.85		0.94	
Overall accuracy [%]	98.22		93.23		97.04	

The results of the assessment of the accuracy of the classification (thereby also the accuracy of the identification of the location of the boundaries of the stands and forest patches) are presented in Table 2. The table contains two approaches to assessing accuracy for all three research areas. The producer's accuracy is calculated by dividing the number of correct pixels in any class by the total number of pixels derived from reference data and includes the error of omission. The user's accuracy is the number of correctly identified pixels in any class divided by the total number of pixels recognized in that class. Inaccuracies are referred to as errors of commission.

The second option is the use of the overall correctness of the classification and its more detailed evaluation based on the Kappa (Khat) index of agreement. The overall correctness shows the correctness of categorizing individual elements of the image into the appropriate category: forest cover and non-forest land. The kappa index of agreement refines the overall correctness by errors from overestimating and underestimating the categories. The Kappa coefficient equals 0.96 in area 1, 0.85 in area 2, and 0.94 in area 3, which represents a relatively large agreement with the reference data. The time difference between the used data was essential in reducing the agreement and the resulting accuracy, which mainly affected research area 2. It is the only significant factor degrading the results of the classification accuracy assessment.

A specific group of results was represented by comparing the boundaries and the area of forest stands and patches derived from them, according to the above-mentioned proposed procedure with the record status of the cadastre. The results of the analysis are presented in Table 3. In the individual research areas, forest plots represent 23.39 to 53.95% of the total area, according to cadastre records. White areas represent 4.18 to 41.34% of the total area. Area 1 has up to 41.34 ha of potentially usable stands, which are legally

non-forest land. However, according to the FAO definition, they meet all the requirements for a forest and can be divided into several separate homogeneous stands (in terms of more detailed characteristics).

**Table 3.** Comparison of the area of forest stands, forest lands, and white areas.

Type of Land		Area 1 [ha]	Area 2 [ha]	Area 3 [ha]
Forest according to ALS data	Cadastral evidence	23.39	53.95	46.80
	White areas	41.34	4.18	23.79
Non-forest lands		35.27	41.87	29.41
Overall area		100.00	100.00	100.00

Overall, many white areas were identified in each study area, mostly with smaller acreage that were adjacent to larger contiguous forest plots. Several of these areas met all the criteria for classification as a forest (two in Area 1, five in Area 2, and three in Area 3), which can be divided into several separate stands or joined to already existing stands.

#### 4. Discussion

Our research has shown that the use of ALS technology has great potential in the identification of forest boundaries, in the creation of DTM and DSM, as well as in the identification of inconsistencies between the actual state and cadastre records (white areas). The results of the semi-automated classification of the ALS data compared to the reference data show 93.23 to 98.22% overall correctness with respect to area, or 0.85–0.96 according to the Kappa index of agreement. These values can be characterized as an almost perfect match between the reference and classified data representing the forest [36]. We present the results of studies with a similar focus in Table 4. The results we achieved were better than those in the study by [7] and comparable to the results according to [37] (overall accuracy of 93%), [38] (96%) and [20] (97%).

**Table 4.** Results of previous research on forest delineation.

Authors	Year	Data	Forest Definition	Accuracy	Kappa	Resolution
Straub et al. (2008) [20]	2008	ALS	CC, minimum height minimum area, minimum width	97.73%	-	1 m
Eysn et al. (2012) [37]	2012	ALS	CC, minimum height minimum area, minimum width	96%	0.92	1 m
Sačkov & Kardoš (2014) [7]	2014	ALS	CC, minimum height minimum area, minimum width	93%	0.85	2 m
Roces-Díaz et al. (2020) [38]	2020	ALS, Photogrammetry	minimum height	92.8%	0.87	2 m

In our study, the best results (overall accuracy of 98%) were achieved in area 1 (with a predominance of coniferous spruce stands). Such areas represent approximately 1/3 of Slovakia's forests. The classification results in mixed stands (about 2/3 of Slovakia's area) represented by area 2 and area 3 were somewhat worse (total accuracy 93–97%). However, the potential for their improvement by further optimization of the proposed procedure based on future research can be assumed.

Previous research results show a similar degree of overall accuracy and kappa indices but on less dense point clouds, and with lower spatial resolution. For example, ref. [7] used point clouds with a point density of 1.7–2.7 points per square meter. The authors worked with all criteria for forest definition but with different individual parameters and mostly on one research area. Our research consists of three separate research areas with variable and different natural conditions and tree species composition. The research was based on freely available data, and the methodology was developed in freely available software. Some parts of the methodology are in line with the common forest identification processes from ALS, but specific approaches have also been developed, especially regarding the software

used. New approaches are represented by the application of the width criterion and the determination of the boundaries of stands based on the tops of individual trees.

Forest patches identification based on classification and hierarchical merging of a LiDAR-derived Canopy Height Model in a tropical rainforest in Sumatra, Indonesia was published by Ref. [39]. Attributes of the identified patches were used as inputs for k-medoids clustering. The clusters were then analyzed by comparing them with identified forest types in the field. The topographic attributes of the clusters were analyzed to determine whether the structural classes, and potentially forest types, were related to topography. The work represents a mature approach in which elements of analysis based on the Area Based Approach are added to the use of DSM. Supplementing the calculations and use of point cloud metrics has great potential for supplementing and improving the methodology proposed by us in future.

Even though the proposed semi-automatic procedure was designed for a specific type of ALS data and the context of use for identifying the boundaries of forest stands and patches in the conditions of Slovakia, it can be considered universal. It uses universal point cloud data structures, formats, and standard processing procedures to generally known and accepted intermediate products or derivatives. Moreover, positive developments have been taking place recently regarding the free availability of ALS data. According to the portal Laser Scanning Forum (<https://www.laserscanningforum.com/forum/> (accessed on 14 April 2023)) such data are available not only in countries with a tradition in this area (USA, Canada, UK, Germany) but also in many European countries such as the Czech Republic, Poland, Estonia and Slovenia.

The importance of applying software environments with open-source code should also be emphasized. They are open to using, combining, and integrating even single-purpose and simple components from heterogeneous sources. However, applying common data structures and processing rules allows to build from them even quite complex and structured tools. Details of sub-process parameters in freely distributable software environments allow it to be adapted to specific application conditions. Some procedures and the application of specific tools are purposeful. However, in general, they point to a creative approach to their design and offer possibilities for adaptation and alternation.

A Tree Density Calculator representing an essential utility in our work can be introduced as an example here. Although several approaches are known, published, and implemented, which could be used to identify the tops and outlines of tree crowns in general, the essential advantage of TDC is its simplicity and complexity as the unified procedure. The only parameter that requires iterative verification in the conditions of a specific stand is the size of the floating window in the search for the local maximum, which depends on the size of the tree crowns.

## 5. Conclusions

Forests play an important role in landscape management. Their acreage in Slovakia has increased significantly in recent decades. Therefore, it is important to know their actual location and area. The stratification of the landscape into forest and non-forest has a direct impact on various subsequent geoinformatics workflows but is also necessary for cadastre and forestry (forest inventory). Aerial laser scanning technology is currently applied to the identification of forest stands and their boundaries with relatively high accuracy. Compared to optical imaging, where only the surface is scanned, this technology produces information-rich and potentially more usable data. The only disadvantage is the higher cost of producing ALS data, and the expensive processing software, which is currently changing for the better. This is also evidenced by our research, which used QGIS and CloudCompare software. Plug-ins for this software have huge potential.

We proposed a new methodology for forest identification. We used freely available software for the identification process, and it was possible to automate it with minimal operator intervention. The methodology was tested on publicly available data. Based on the achieved results, the presented methodology has the potential to be implemented

on a wide (even national) scale in Slovakia. Concerning the use of generally known data structures and procedures (sources of which are grown), it is also portable, and adaptable to similar and other conditions.

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