# Assessment of forestry parameters at single-tree level by using methods of LIDAR data analysis and processing

## Avaliação de parâmetros florestais de árvores individuais utilizando métodos de análise e processamento de dados LIDAR

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## Abstract

In this paper a chain of laser scanning data processing in order to automatically detect the principal forestry parameters deriving from a single-tree extraction approach is presented. The overall method was based on mathematical morphology operations to assess the cartographical position of them, as well as the height of the trees. Starting from single-extracted trees, a segmentation algorithm made it possible to classify the laser point data as a subset of crown points. For each tree, some morphometric and biometric parameters were estimated. A method to distinguish between some of principal tree species of alpine latitudes is afterwards presented. The species classification was based on the study of the single crown Gaussian curvature, from estimated differential parameters of the Taylor's formula extended to second order terms. The experiments, carried out in the Alpine context of the North-East Italy (Friuli Venezia Giulia Region), highlighted that the percentage of tree extraction ranged between 70% and 95% in juvenile and mature forests respectively while 80% - 90% of corrected classified tree species (coniferous and broad-leaved) was obtained. Concerning the stand volume, the estimation accuracy varied between 80% and 95% in broad-leaved and coniferous stands respectively.

**Key words**: LIDAR; tree extraction; morphology; curvature; forestry assessment.

## Resumo

Neste trabalho, é apresentado uma cadeia de processamento de dados de rastreamento a laser, a fim de detectar automaticamente os parâmetros florestais

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principais decorrentes de uma abordagem de extração de árvores individuais. O método global foi baseado em operações de morfologia matemática para avaliar a posição cartográfica, bem como a altura das árvores. A partir da extração de árvores individuais, um algoritmo de segmentação permitiu classificar os dados a laser como um subconjunto de pontos de copas. Para cada árvore, alguns parâmetros morfométricos e biométricos foram estimados. Um método para distinguir algumas das principais espécies de árvores de altitudes alpinas é apresentado depois. A classificação de espécie foi baseada em estudos da curvatura de Gaussian de árvores de copa única, de parâmetros diferencias estimados pela fórmula de Taylor estendidos aos termos de segunda ordem. Os experimentos, realizados no nordeste da Itália (região de Friul-Veneza Júlia), destacou que o percentual de extração de árvore variou entre 70% e 95% em florestas juvenil e adulta respectivamente, enquanto 80% - 90% das espécies de árvores classificadas (coníferas e folhosas) foram obtidas. Quanto ao volume de povoamento, a precisão da estimativa variou entre 80% e 95% em povoamento de folhosas e coníferas, respectivamente.

**Palavras-chave:** LIDAR; extração de árvores; morfologia; curvatura; avaliação florestal.

## Introduction

Monitoring of the forestry ecosystem is a current topic in the wooded resources sustainability debate. To characterize the vegetation from an ecological state and biomass content point of view, a detailed knowledge of the single tree population is needed. The assessment of such parameters is critical in terms of field operations and time needed. In this context, aerial laser scanning (also well known with the acronym LIDAR, Light Detection And Ranging) is a promising survey technique for forestry inventories because of its capacity to directly assess the three dimensional structure of the forest due to the high point number of sampling per surface.

Airborne laser scanning is a Remote Sensing technology which started to be used from the beginning of the '90's. In 1995, only three sensors were operating in the world. This figure multiplied in the following years, with a peak in sales in 2000. Today there are many companies and operators in the Airborne Laser Scanning sector, testimony to the success of the technology. The strength of the LIDAR technique lies in its capacity to survey the elements present on the Earth's surface in a three-dimensional way by detecting and measuring the geometric or cartographic position of millions of 3D point coordinates. The productivity of the instrument and its accuracy means that laser scanning can be considered as an alternative technique of topographic survey in many applications.

The obtained three-dimensional point cloud constitutes the so-called raw data. What is innovative in the forestry sector is the creation of algorithms and appropriate interconnected procedures with which to process the raw data and provide a series of outputs which is normally obtained following a costly ground survey campaign (population density, single tree height, evaluation of dendrometric volume, as well as the creation of thematic maps of the physiognomic structure of the wood, fire risk, and hydrogeology, and study of the habitat among others).

The trend in international research in the area of development of methods useful for survey and classification of the elements which form the forestry can be concisely resumed as follows:

–implementation of techniques and algorithms for the filtering and the classification of points corresponding to the ground (AXELSSON, 2000);

–extraction of single trees (HYYPPÄ and INKINEN, 1999, ANDERSEN et al., 2001).

The availability of methods to automatically identify single trees has permitted the development of ulterior lines of research regarding:

– morphometric analysis and characterization of single tree crowns (TIEDE et al., 2005);

– species classification (BRANDTBERG et al., 2007);

– growth estimates using multi-temporal scans (YU et al., 2004);

– estimation of Leaf Area Index (BARILOTTI et al., 2006; SASAKI et al., 2008), canopy gaps and fraction cover survey;

– characterization of vertical structure (ZIMBLE et al., 2003);

– estimation of dendrometric stand volume (ABRAMO et al., 2007).

In our research, the principal objective was to develop and implement a specific tool of algorithms to extract some of the principal parameters needed in the forestry management plans. It has to be considered that this aspect is of particular interest in an Italian context (let say in a global context as well), especially in Friuli Venezia Giulia, an alpine region (N-E Italy) with 43% of its area covered in forest, of which 60% is managed.

In this paper, a single-tree based procedure is presented in order to obtain the estimation of the following morphometric and biometric parameters: population tree density, stand height, canopy base height, dendrometric stand volume, single-tree species.

## Implemented methods

A complete processing chain has been developed, starting with raw laser points as input data and ending with derived tree parameters for each single tree. The procedure is composed of a series of elaborations and transformations that can be schematically related to the following methodological aspects:

– pre-processing of the raw laser data;

– application of mathematical morphology algorithms to extract the canopy apexes;

– identification of the laser points belonging to the single crowns by means of a cluster analysis algorithm;

– low vegetation sub-clustering using a local filtering method;

– species and volume estimation at single tree-level.

## Tree extraction by morphological analysis

The method proposed for the tree extraction is based on the morphologic analysis of the laser point cloud. Accordingly, the Top Hat algorithm, whose formulation is relative to the image elaboration theory (SERRA, 1982), was implemented. This mathematical function allows the extraction of the highest elements in the scale of the represented values (independently from the image typology (ANDERSEN et al., 2001). If we consider f(x) as the grey value of a generic pixel x of a point localized in u; f(X) as the corresponding value of the transformation of the matrix X; λ as the structural geometric element to determine (or as the dimension of the explorative kernel centered in x), the Top Hat function is based on the Opening transformation [1] defined as follows:

$$O_\lambda f(X) = D_\lambda [E_\lambda f(X)] \qquad [1]$$

Therefore, the following transformations of Erosion (2) and Dilatation (3) are applied:

$$E_\lambda f(X) = inf\{f(u) : u \in \lambda x\} \; [2]$$

$$D_\lambda f(X) = sup\{f(u) : u \in \lambda x\} [3]$$

The extraction of the local maximums in the scale of the image values is carried out by using the function Top [4] that subtracts the primitive image (function) from the Opening-transformed function:

$$TOP = \{x: f(x) - O_\lambda f(X)\} \quad [4]$$

Extending the Top Hat concept directly to the pre-filtered point cloud (classified vegetation points), a step forward in the method allows the detection of the set of points belonging to the top of the crown (apexes), avoiding the interpolation on raster surfaces (in Figure 1).

## Delineation of crown morphological values

In order to identify the single crowns a region growing algorithm was implemented. Starting from the previously extracted

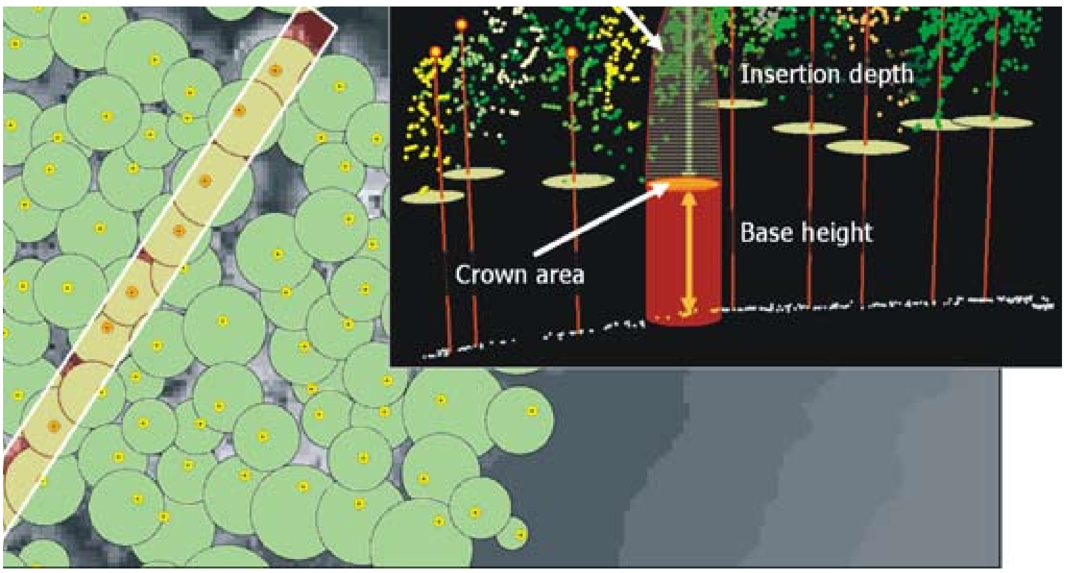


**Figure 1**. Example of crown delineation parameters. In the left: vectorial single crown database. In the section (on the right): single clustered crown points, ground points, tree height, crown base height and insertion depth, crown area and volume

apexes, the algorithm classifies iteratively the vegetation points with respect to the nearest apex according to the planar distance and the height difference criteria.

The crowns are then delineated using polygon circles whose parameters (centre and radius) are calculated analyzing the planimetric coordinates of the points belonging to the clusters. The barycentre of the point distribution is assumed as being the centre of the crown. Each circle is drawn using a radius equal to the following equation [5]:

$$r = [(X_{Max} - X_{min}) + (Y_{Max} - Y_{min})] / 4 \quad [5]$$

The equation 5 allows the calculation of the average radius of the cluster distribution. The crown depth is calculated as the difference between the maximum height and the minimal height of the points belonging to the cluster. Moreover, the height of crown base height is calculated. An example of delineated crown parameters is given in figure 1.

## Specie determination

As a topographic instrument, the main advantage in using laser scanning data is the opportunity to obtain morphological and structural parameters at single tree level. Relatively less known is the possibility of investigating the forestry species, which is usually detected at area level through more traditional field work or passive Remote Sensing images.

The principal Airborne Laser Scanning (ALS)-based methods developed for tree species classification are basically related on two different main LIDAR characteristics: penetration rate differences and intensity return. The best accuracies were generally reached in leaf-off datasets. Reliability of former methods seems to be affected by ecological condition of the dataset as well as the LIDAR instrument used (first & last vs multipulse vs fullwaveform) while latter methods need efficient models of intensity data calibration. Moreover, relatively few examples of satisfactory results had been reached in species discrimination in leaf-on surveyed data. For these reasons, our issue was to develop a reliable and robust method based on the single tree top morphology (namely, the curvature) for assessing the outcome of coniferous, broad-leaved and mixed standing species in Alpine latitudes.

Our proposal to compute the local Gaussian curvature for each tree is based on the application of a non parametric local polynomial regression extended to the second order differential terms. Dealing with parameters estimation by regression models, the main advantage of a non parametric approach consists in its full generality (CROSILLA et al., 2008). In our case, to locally estimate the surface passing through the clustered crown laser points, neither a priori knowledge of the point geometry nor the fitting analytical function is required.

For the local analysis of a surface obtained from a laser point cloud, some fundamental quantities, defined in differential geometry, were considered. In particular, local Gaussian, mean and principal curvature values were taken into account. All these can be obtained from the so-called "Weingarten map" matrix A of the surface (DO CARMO, 1976), that is given by:

$$\mathbf{A} = -\begin{bmatrix} e & f \\ f & g \end{bmatrix} \begin{bmatrix} E & F \\ F & G \end{bmatrix}^{-1} \quad [6]$$

where E, F, and G = coefficients of the so-called "first fundamental form" and e, f, and g = coefficients of the “second fundamental form”.

The Gaussian curvature K corresponds to the determinant of A:

$$K = \frac{eg - f^2}{EG - F^2} \quad [7]$$

The mean curvature H can be instead obtained from:

$$H = \frac{eG - 2fF = gE}{2\left(EG - F^2\right)} \quad [8]$$

The curvature values are then used to perform classification of the single trees species. Some examples of clustered crowns and respective parabolic surfaces approximating the point distributions are given in figure 2, that shows different tree species within different forestry compositions. An example of species classification into two of the investigated forestry plots is given in figure 3.

## Estimation of dendrometric stand volume

In dendrometry, the volume of a single standing trunk is classically calculated by multiplying the basimetric area, which corresponds to the diameter surveyed at

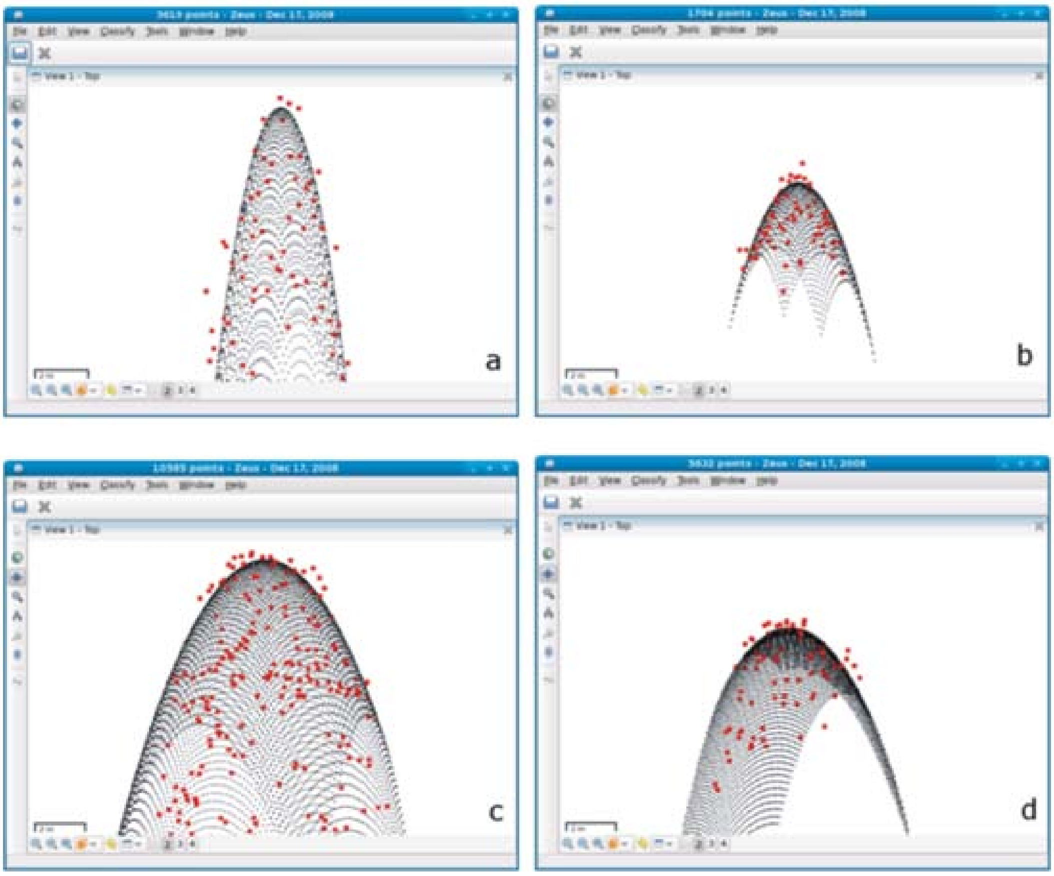


**Figure 2.** Examples of clustered crowns points and respective surfaces approximating the point distribution for: a) mature spruce; b) mature larch; c) mature beech; d) juvenile beech

**Figure 3**. Examples of single tree extraction and species classification results in two leaf-off plots (PH_F and PH_E, from the left to the right). Spruces, larches and birches are colored in yellow, red and blue, respectively

1.30m from the ground, by the height of the tree and a co-efficient of reduction. Usually the unitary volume values are pre-calculated and can be read in the appropriate list, the stereometric tables, in which volume is expressed as a function of diameter (single entry stereometric tables) and height (double entry stereometric tables).

Moving on from single tree trunk volume to the volume of the tree trunks present in top soil/growth, the classic procedure foresees an integrated survey of the diameter, at 1.30m from the ground, and height, above a certain threshold, of all the trees. This survey can be carried out on the whole surface covered by the top-soil (total stand measure) or on a sample area (sampling method for test area). The existing correlation between diameter at breast height and height per sample is subsequently set. This correlation, called ipsometric curve, can be used in different ways according to the stereometric tables available.

In the case where a single entry table is set out, theoretically, the ipsometric curve does not directly enter into the procedure of the volume calculation, but may be useful at the same time, for example to verify the conformity of the table to the top soil typology to be estimated. If instead, a tariff system is available, that is to say more than one single entry table, the ipsometric curve (or part of it) is useful to establish the best fitting tariff for the specific forestry soil.

Finally, if a double entry table is set out, the ipsometric curve allows the choice of the volume which corresponds to the "correct" diameter-height combination of the top soil. Already from this short illustration of the procedure adapted in dendrometry for the volume estimation of the trees within each topsoil typology, it seems evident that the surveys foreseen concentrate for the most part on a diameter of 1.30m from the ground, while the height survey is extra and always a sample of the whole population.

Simplifying the concepts, we can therefore talk about a dendrometric diameter or rather a procedure which is based essentially on survey of the diameter. The reason for this choice of procedure is obvious to say the least, as using ground survey is much simpler and immediate measuring the diameter of the tree rather than its height. Through laser scanning data processing the whole survey on the population height is available, a fact which allows the passage from dendrometric diameter to dendrometric ipsometry.

Using specific algorithms which use LIDAR data as input data it was possible to obtain the ipsometric seriations of entire forestry populations, a fact which allowed us to use the height, and not the diameter as an entry parameter to the cubic system.

This implemented methodological approach permits us to express the tariffs used in the Friuli Venezia Giulia Region (where the experiment was carried out) as a function of height. To obtain this result, the ipso-diametric relations present in the traditional tariffs were used. This means that the volume calculated with the new tariffs can be compared to that calculated with the traditional tariffs.

## Results

All the experiments were performed in different mountainous parts of Friuli Venezia Giulia characterized by coniferous, mixed and broad-leaved forests with different population densities, structure, age and ecological conditions. Different LIDAR surveys were used as raw data having different characteristics in terms of scanning point density (up to about 10 pts/m$^2$), period of survey campaign (leaf on and leaf-off seasons) and sensor used (first and last pulses or multipulses laser scanners).

Several field survey campaign were performed ad hoc in 20 peculiar mountainous forestry plots, geo-referenced by differential GPS (DGPS) technique. The position of each tree within all the plots was taken by a topographic total station survey campaign. Subsequently, each tree was georeferenced by integrating the GPS and the topographic surveys. Finally, the diameter at breast height, the crown base height and the species were surveyed for a total of about 800 reference trees.

The percentage of correctly extracted trees varied meaningfully depending on the structure of the different forestry plots examined. Juvenile forests, with a high population density and a high percentage of small diameters, highlighted the difficulty of using laser technology to characterize the population well. In these cases, underestimation was evident in terms of "dominated" trees (BARILOTTI et al., 2007). On the contrary, the results seemed to improve significantly when the forestry plot was mature and mono-storey structured (even-aged). In this case, the percentage of extracted trees reached high values in coniferous forests (80-92%) as well in broad-leaved forests (83%).

The overall accuracy obtained for the three investigated species classification (spruce, beech and larch) ranged from 74% up to 90% in leaf-on condition and from 85% up to 95% in leaf-off. Laser point densities lower than 3-4 pts/m$^2$ tends to reduce this level of accuracy (BARILOTTI et al., 2009).

The volume estimation results showed standard deviation values comprised between 6 and 11%, respectively in the cases of spruces stands and beech stands (ABRAMO et al., 2007).

The extracted single-tree parameters, integrated in a GIS environment in order to create a database for the forestry sector, integrate the information on both the vertical and horizontal structure, the species composition and volume available for the study of forestry ecosystems and can be used to reconstruct accurate photo-realistic renderings of the investigated territory (in figure 4). at single-tree level, from the point cloud. The results highlighted that this new way to detect the forestry parameters from remote, can provide detailed information for the assessment of vast forested areas, reducing the time needed and possibly the costs compared to the traditional field work. This information can be used at every level of territorial governance for the sustainable management of forestry resources, which is very important for biodiversity maintenance, stem volume and biomass estimation, habitat mapping and conservation.

**Figure 4.** Photorealistic rendering in a forestry study area (Pramosio, Udine) obtained by the integration of LIDAR DTM (Digital Terrain Model) and LIDAR-extracted forestry parameters and digital orthophotos (image elaborated by means of VNS software).

## Conclusions

The derivation of quantitative forest parameters from ALS data over complex mountainous environments was reported in this paper, with the main objective of presenting a full chain of laser scanning data processing in order to automatically extract the principal forestry parameters,

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