GEOMETRICAL AND STRUCTURAL PARAMETERIZATION OF FOREST CANOPY RADIATIVE TRANSFER BY LIDAR MEASUREMENTS

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ABSTRACT:

A forest canopy is a complex system with a highly structural multi-scale architecture. Physical based radiative transfer (RT) modelling has been shown to be an effective tool for retrieval of vegetation canopy biochemical/physical characteristics from optical remote sensing data. A high spatial resolution RT through a forest canopy requires several geometrical and structural parameters of trees and understory to be specified with an appropriate accuracy. Following attributes on forest canopy are required: i) basic tree allometric parameters (i.e., tree height, stem diameter and length, crown length and projection, simplified crown shape, etc.), ii) parameters describing distribution of green biomass (foliage) (e.g., leaf area index (LAI), leaf angle distribution (LAD) or average leaf angle (ALA), clumping of leaves and density of clumps, air gaps and defoliation, etc.), and iii) parameters describing distribution of woody biomass (branches and twigs) (e.g., number, position and angular orientation of the first order branches – branches growing directly from stem, twig area index (TAI), twig angle distribution (TAD)). At very high spatial resolution (airborne image data), an insufficiently characterized structure of the forest canopy can result in inaccurate RT simulations. Direct destructive methods of measuring canopy structure are unfeasible at large-scales, therefore, in this paper we review the non-invasive Light Detection and Ranging (LIDAR) approaches. We also present some results on tree structure parameters acquired by a commercially available ground-based LIDAR scanner employed in scanning the matured Norway spruce trees.

1. INTRODUCTION

1.1 Radiative Transfer through Heterogeneous Canopies

Canopy radiative transfer models (RT) have been approved as an effective tool for retrieval of vegetation canopy biochemical/ biophysical characteristics from remote sensing data, as for example Leaf Area Index (LAI)(Gascon, Gastellu-Etchegorry et al. 2007; Kobayashi, Suzuki et al. 2007; Houborg and Boegh 2008), chlorophyll content (Myneni, Yang et al. 2007; Malenovsky, Homolova et al. 2008), or canopy water content (Koetz, Schaepman et al. 2004; Li, Goodenough et al. 2005; Cheng, Zarco-Tejada et al. 2006; Trombetti, Riano et al. 2008). Large variety of canopy radiative transfer (RT) models, currently presented to a scientific community (Widlowski, Robustelli et al. 2008), brings also diverse level of complexity when describing structurally heterogeneous canopies (Pinty, Widlowski et al. 2004). Only some of them were designed to take into account geometrical, optical, and structural variations within individual crowns, and so allow simulating top-of-canopy reflectance at very high spatial resolution. Precise parameterization of these models requires reliable input data, especially when dealing with highly organized canopies such as boreal or mountain coniferous forest.

Norway spruce (Picea abies (L.) Karst) is a common coniferous species of the boreal and high altitude forests. Proper structural and geometrical description of its highly organized crown architecture is quite challenging, as field-based destructive methods are labour intensive, spatially limited, and inoperable in case of tall mature trees. Also, non-destructive passive optical techniques (e.g., hemispherical photography) are limited in their capacity to distinguish structural changes occurring below the top of the canopy (Coops, Hilker et al. 2007). However, active non-invasive techniques, such as Light Detection and Ranging (LiDAR), can bring an alternative solution. This paper reviews mainly LiDAR non-invasive techniques and presents some results on tree structure parameters of Norway spruces retrieved from ground-based LiDAR scans.

1.2 Parameterization of Radiative Transfer Models

Canopy and Crown Structural Characterization: Canopy structure refers to the horizontal and vertical distribution of the components of biomass within a plant community. Realistic characterization of forest canopies for radiative transfer requires description of biomass distribution in both directions, with a special emphasis on the biomass clumping. Examples of canopy (crown) structural parameters are: leaf area index (LAI), gap fraction (GF), leaf angle distribution (LAD), leaf clumping (Ω), and others. Besides these common parameters, some species specific parameters can be required as well. The species specific parameters are typically a description of crown habitus (including crown length, width, and shape), or branching architecture (number and growing angularity of main branches).

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Traditional passive methods: Canopy LAI, LAD, GF can be determined using ground optical devices such as Li-Cor Plant Canopy Analyzer (PCA) LAI-2000, TRAC, or hemispherical (fish-eye) photographs. Besides traditional inventory techniques, some advanced mapping tools such as laser rangefinder combined with electronic compass and GIS software (e.g., FieldMap system) can be employed to characterize crown dimensions. Nevertheless, the most difficult task is to derive in-situ characterization of the leaf/wood biomass distribution in a 3-dimensional (3-D) space. Direct destructive measurements are hardly feasible for small young trees and almost impossible in case of tall mature trees. The use of indirect optical measurements seems to be a reasonable alternative, but their main limitation is the obstruction and shadowing of neighbouring trees. These methods are performing well in case of stand-alone growing trees, so called solitaires, but these trees are not representative for socially interconnected closed canopies, which are of particular interest for most studies. Solitaires do not compete with surrounding trees for light and resources; hence, they are growing in an environment of different radiation conditions and stress factors than trees inside a canopy. Consequently, their habitus is too far different (non representative).

LiDAR methods: Active lasers systems called LiDAR (or Light/Laser Radar or Light/Laser Detection And Ranging) can penetrate through turbid media of leaves and thus can provide reasonable 3-D description of the leaf/wood biomass distribution. LiDAR instrument operates with a beam of laser energy of the visible or infrared wavelength, which is transmitted towards a target. The timing and amount of energy that is scattered back from the target is measured. The return signal timing provides measurement of the distance between the instrument and the scattering object. The size of the laser beam used varies from 1-3 cm of diameter (small footprint) to approximately 5 -25 m (large footprint).

LiDAR sensors can be categorized as *discrete* or *waveform recording* based on the method of data capture (Lefsky, Harding et al. 2005). Discrete-return LiDAR devices, record multiple returns (most commonly two) from a single laser pulse when different portions of the pulse interact with the target at multiple positions along the vertical profile (Reutebuch, Andersen et al. 2005). These systems have generally a small footprint and high repetition rates being preferred for mapping individual crown or non-crown characteristics (Roberts, Tesfamichael et al. 2007). Waveform recording devices digitise the entire return signal resulting in a finely distributed vertical measurement of vegetation structure (Blair, Rabine et al. 1999; Harding, Lefsky et al. 2001). In general, they operate with a large footprint, which is indicative of multiple forest elements instead of individual trees (Lim, Treitz et al. 2003; Riano, Chuvieco et al. 2004).

Ground-based discrete return LiDAR is a relatively well-established technology with an increasing market in recent years. There are several commercially available systems such as the devices by Riegl, Optech, Trimble or Leyca (Froehlich and Mettenleiter 2004). Conversely, there are still relatively few waveform systems, as for instance ECHIDNA, one of the most advanced ground-based LiDAR systems designed for forest sensing (Lovell, Jupp et al. 2003). It is a full waveform, hemispherical laser scanner that can record a variety of viewing angles, beam sizes and shapes. This scanner is a day/night alternative to the classical hemispherical canopy photography, and provides the potential to estimate foliage density, projected foliage area and the angular distribution at all visible points in a canopy.

LiDAR devices can as well be mounted on airborne or satellite platforms. Airborne Laser Scanning (ALS) have been proved to be capable of deriving canopy height for stands or single trees, and vegetation density information like fractional cover (fCover) and/or leaf area index (LAI) (Means, Acker et al. 2000; Harding, Lefsky et al. 2001; Næsset and Bjerknes 2001; Lovell, Jupp et al. 2003; Morsdorf, Meier et al. 2004; Maltamo, Packalén et al. 2005; Morsdorf, Kotz et al. 2006; Hyypp, auml et al. 2008; Morsdorf, Frey et al. 2008).

The only operational spaceborne laser ranger is GLAS (Geoscience Laser Altimeter System) on board of the NASA's ICESat (Ice Cloud and Land Elevation Satellite). This sensor was not designed especially for vegetation applications, although. it became an active area of its research in recent years (Lefsky, Harding et al. 2005; Pang, Li et al. 2007; Rosette, North et al. 2008; Sun, Ranson et al. 2008).

2. GROUND-BASED LIDAR SCANNING OF NORWAY SPRUCE TREES

This section will present a case study demonstrating potential of a commercial LiDAR system as a non-destructive method to describe 3D tree structure. The commonly employed ground-based LiDAR system Ilris-3D (Optech Inc., Canada) was used for scanning of mature Norway spruce (*Picea abies* (L.) Karst.) trees to retrieve structural and geometrical information about crown architecture. The data are intended to be used for precise parameterization of canopy radiative transfer model DART.

2.1 The DART canopy radiative transfer model

Discrete Anisotropic Radiative Transfer (DART) model (Gastellu-Etchegorry, Martin et al. 2004) simulates bi-directional reflectance distribution function of heterogeneous landscape scenes. A DART scene is a 3D matrix of cells containing the landscape components (e.g. leaves, water, soil, and atmosphere) and solid parallelepipeds representing for example branches and stems. Cells are characterized by their optical and structural properties. Currently, the DART model enables an advanced three-dimensional description of forest species which is reflecting the eco-physiological features of canopy structure (Malenovsky, Martin et al. 2003). Full geometrical, structural and optical definition of forest species is given in the DART manual (CESBIO 2005). (Homolova 2005) presented detailed parameterization of a young N. spruce canopy.

The following DART input parameters were derived from the ground-based LiDAR scanning of mature Norway spruce trees:

- Basic trees' dimensions (tree height, proportion between live and dead part of a crown, crown diameter).
- Number and prevailing zenith angle of the first order branches along a tree height.
- Definition of an inner zone of total defoliation.
- Estimation of weight coefficients adjusting leaf density in horizontal direction.

2.2 Campaign description

Due to the recent logging activities open edges of two different mature N. spruce forests could be selected close to the permanent ecological research station "Bily Kriz" (Moravian-Silesian Beskydy Mts., Czech Republic; 18.54°E, 49.50°N; altitude of 936 m a.s.l.). The basic characterization of the selected N. spruce canopies is given in table 1. The cloud point data of forest canopy was recorded with the ground-based terrestrial LiDAR system Ilris-3D, coupled with the digital camera Canon EOS 350D. The Ilris-3D device emits up to 2500 laser pulses per second at the wavelength of 1500 nm within a field of view of 40°x40°. The first pulse data of the front line of trees were acquired from two scanning posts located about 60 m from the first forest edge (Mature 1), and one spot located about 40 m from the edge of the second forest stand (Mature 2).

Stand	Age	DBH [cm]	Height [m]	Trees/ha
Mature 1	100-110	53	40	160
Mature 2	75	37	29	420

Table 1. Basic characterisation of mature Norway spruce canopies selected for the ground-based LiDAR scanning.

2.3 Data processing

The basic processing of the raw LiDAR data comprised conversion of the raw binary data into ASCII format, merging of all the acquired scans per stand, and transformation of the clouds of points into the geo-projection system Universal Transverse Mercator (UTM) Zone 34N (WGS-84). Individual spruce trees along the forest edge have been identified and separated from the cloud of recorded points. A threshold separating leaf and wood biomass was determined manually for each tree based on the intensity of the reflected signal.

The basic tree dimensions were measured for each of the selected N. spruce trees. The typical branch architecture of the selected trees was described by means of their prevailing zenith angle in respect to the tree stem, and number of the first order branches along the tree height. All these parameters were determined manually.

The laser points, classified as a leaf biomass, and only half of a tree facing towards the LiDAR scanning system, were taken into account for statistical analyses of leaf biomass distribution within a crown. The description of the leaf biomass distribution was analysed using the statistical assessment of the laser hits occurrence within a crown. A GIS-based model, adopting the concept of a tree species definition in the DART model, was build to spatially describe the occurrence of laser hits, representing leaf biomass. Each cloud of point data, representing one tree, was divided into regular segments, 1m high vertical levels, which were afterwards divided into regular concentric rings in horizontal direction. Total, mean number of laser hits and its standard deviation were calculated for each crown segment. The horizontal profiles of laser hits distribution were plotted per vertical crown layer. The ascending, flat and descending part of the distribution function was determined, as well as the curve breaking points representing the horizontal positioning parameters (α, β, γ, κ).

2.4 Preliminary results

Figure 1 shows the merged and transformed laser scans of the whole forest edge (a), and an example of separation of woody (c) and leaf (d) biomass for one selected tree (b). The achieved mean position accuracy of the merging and transformation into UTM geo-projection system was equal to 0.1m and 0.7m for the first and second test site, respectively. Worse positioning accuracy at the second test site was caused by less accurate GPS measurements of the matching points' positions.

In total 20 individual trees were selected at the first location and 9 trees at the second location. The representative tree allometric parameters and description of the branch architecture characteristic were obtained for each experimental N. spruce canopy. The results are summarized in table 2. Large variability can be observed in proportion of live and dead crown, which is mainly caused by different environmental factors (e.g. light availability) influencing individual trees.

The statistical assessment of the leaf biomass distribution is still in progress. So far only results obtained from the analyses of one selected tree can be presented. Horizontal profile of distribution of laser points is given in figure 2. The zone of total defoliation and horizontal parameters adjusting leaf density are shown in the same figure. The complete structural parameterization of whole sensed mature Norway spruce canopy is expected to be available soon.

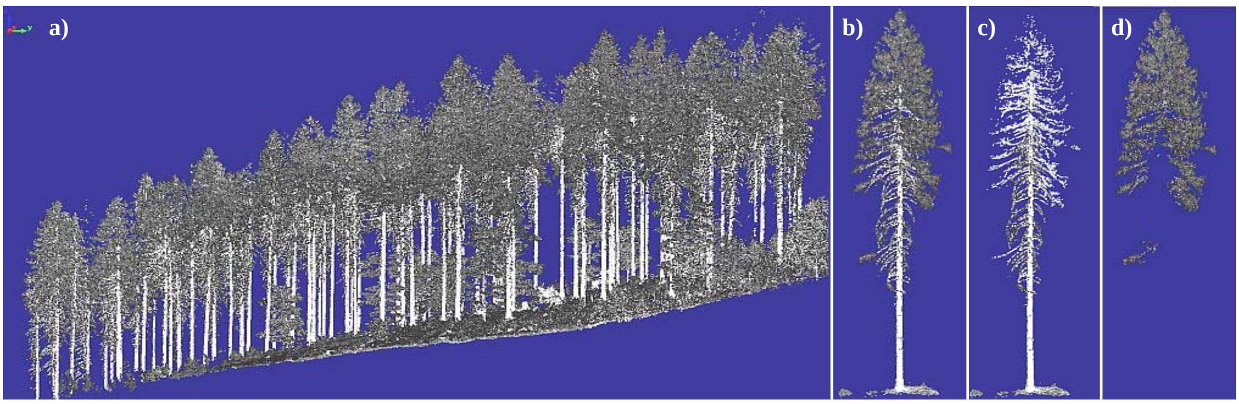

Figure 1. Example of the merged LiDAR scans of the open forest edge at the first scanning location (a). Example of one individual tree (b), separated wood (c) and leaf (d) biomass.

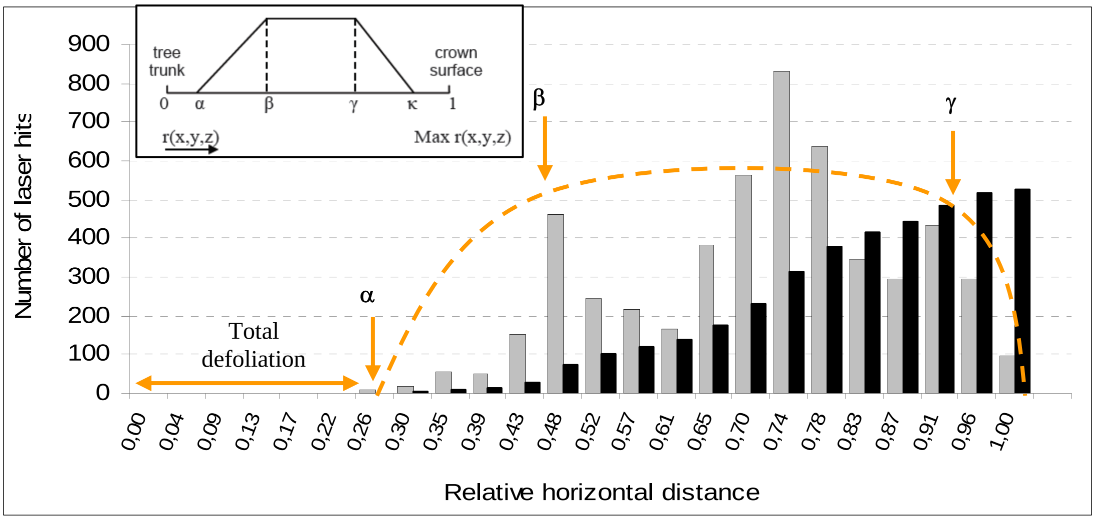

Figure 2. Example of typical the distribution of laser hits in the horizontal direction (from the stem toward the crown periphery) obtained from the statistical analyses of crown vertical layers at the lower part of a crown. The orange arrows point approximate position of the horizontal parameters defining horizontal density function adopted in the DART model and inner zone of total defoliation. The small graph in upper left corner represents the definition of positional parameters, which are used to calculate horizontal weights adjusting leaf density of a cell.

Parameter	Mature 1	Mature 2
Tree height [m]	40 (±3)	29 (±3)
Length of live crown [m]	16.4 (±4.3)	13.2 (±3.7)
Length of dead crown [m]	6 (±2.6)	3 (±2.1)
Crown radius [m]	3.4 (±1.1)	2.7 (±0.8)
Nb. of branches – top	10 (±3)	8 (±3)
Nb. of branches – bottom	6 (±2)	5 (±1)
Branch zenith – top [°]	87 (±10)	75 (±10)
Branch zenith – mid [°]	100 (±10)	90 (±90)
Branch zenith – bottom [°]	110(±10)	100(±9)
Branch zenith – dead [°]	120(±10)	105 (±10)

Table 2. Summary of selected parameters, describing the basic tree dimensions, and branch architecture. The values are presented as mean (±standard deviation). Top, mid, bottom and dead indicates different height part of a crown.

3. CONCLUSIONS

The ground based LiDAR scanning, possibly in combination with an airborne acquisition, seems to be a suitable way how to describe a 3-D structure of mature, tall forest canopies. However, the presented approach is still not ideal. There are some major limitation when using discrete ground-based LiDAR system: i) poor capturing of tree tops, which might be overcome employing an airborne LiDAR scanning, ii) multiple shadowing of the branches and poor quality of the cloud point data inside the canopy, which might be overcome by using full waveform LiDAR instruments, such as Echidna, and iii) operational wavelength range (around 1500 nm) of most of the commercial based LiDAR instruments which is not very convenient wavelength to capture green biomass because of the water absorption attenuating the return signal.

Due to the technical limitations of the discrete return LiDAR systems, they are not applicable in case of a larger-scale forest inventory. Nevertheless, it has been proved that they can be used for experimental purposes, preferably at the tree level or smaller spatial extent. Also, given the edge conditions of the scanned crowns in the specific case as presented here, the use of ground-based discrete LiDAR was reasonable.

The case study presented only preliminary results of crown structural characteristics obtained from the analyses of one sample tree. The representative description of the whole mature Norway spruce canopy will be derived and introduced into the DART model. Unfortunately, not all DART input parameters can be derived from the presented LiDAR data. Especially, information about the wood biomass distribution of small twigs can not be properly quantified.

The reliability of the proposed parameterization of N. spruce canopy radiative transfer has not been evaluated yet. It is planned to compare the DART simulated top-of-canopy reflectance against the real hyperspectral airborne reflectance imagery of very high spatial resolution. It is expected, that introduced geometrical and structural crown parameterization will increase the accuracy of the simulated canopy reflectance, and consequently the accuracy of physically-based retrievals of biochemical and/or biophysical vegetation properties from hyperspectral remote sensing data.

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