Retrieval of Canopy Height Profiles from Lidar Measurements
over Coniferous Forests

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To be submitted to TGARG in August 2004
Abstract - The current algorithm for retrieval of canopy height profiles (CHPs) from lidar waveforms is based on the simplifying assumptions of insignificance of the effects of multiple scattering and a uniform horizontal distribution of vegetated elements. These assumptions make it hardly applicable in the case of coniferous forests, characterized by a high degree of clumping and significant multiple scattering of radiation in the near-infrared spectrum. In this study, we modify the current algorithm to account for clumping of needles into shoots, multiple scattering of radiation between the needles of a shoot, shoots inclination and multiple scattering of radiation between shoots. The performance of the modified algorithm is evaluated with SLICER waveforms collected over the BOREAS old black spruce site in summer 1994.

Index terms – Lidar remote sensing, canopy height profile, coniferous canopies.
I. INTRODUCTION

Large-footprint waveform-recording lidar altimeters have been considered to be the best remote sensing tool for gathering information on vertical forest structure [Lefsky et al., 2002]. The group of airborne vegetation lidars consists of two instruments: the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) [Harding et al., 2000], extensively used in 1994-1997, and the currently used Laser Vegetation Imaging Sensor (LVIS) [Blair et al., 1999]. The main product includes tree heights and canopy height profiles (CHPs), or the distributions of canopy material with height, that can be retrieved from lidar waveforms.

The current algorithm for retrieval of CHPs was developed following the main principles of MarArthur & Horn’s technique [MarArthur & Horn, 1969] for estimation of foliage height profiles (FHPs) in broadleaf forests. The algorithm is based on the simplifying assumptions that (1) the horizontal distribution of leaves is uniform and (2) only single scattered photons contribute to the return signal. Besides, what is retrieved is the vertical distribution of nadir-intercepted surfaces, not the actual CHP.

Retrieved CHPs, normalized by the total canopy area index (CAI), have been shown to provide a good approximation of relative vertical canopy distributions in closed-canopy, temperate deciduous forests [Harding et al., 2001]. The algorithm was also utilized in the biomass estimation [Lefsky et al., 1999] and the light transmission studies [Parker et al., 2001], again for deciduous forest sites. In general, due to the underlying assumptions, the algorithm is considered hardly applicable to the case of coniferous canopies.

First, the representation of a coniferous tree structure as a number of parallel layers with uniformly distributed needles totally ignores the fact of needles clumping. However, the clumping of needles into the shoots changes the way trees interact with incident laser radiation. More radiation is allowed to penetrate deeper into the canopy without being intercepted. Second, there are two sources of multiple scattering in the coniferous canopies: the scattering of radiation between the needles of a shoot and the scattering of radiation between shoots themselves. The first type of scattering makes a shoot scattering coefficient change from that of a needle [Smolander and Stenberg, 2003]. The ignorance of the second type of scattering may lead to an inaccurate retrieval of the amounts of foliage in the lower parts of the canopy. In the case of relatively dense canopies, one of the effects of multiple scattering is related to a significant enhancement of the lower part of the signal [Kotchenova et al., 2003]. Ignoring this effect will result in an erroneous assignment of a larger amount of foliage to the lower part of the canopy, which may be critical for photosynthesis and light transmission studies.
The main objective of this study is to modify the current algorithm for retrieval of CHPs to make it applicable for coniferous forests. We will propose a way to account for needles clumping, shoots inclination and two types of multiple scattering. The performance of the modified algorithm will be tested over a coniferous forest site measured by SLICER.

II. STUDY SITE

SLICER data used in this study were collected over the southern old black spruce site (SOBS, 53°59' N, 105°07' W) located in the BOREAS southern study area in Saskatchewan, Canada. This site was a subject of intensive field campaigns carried out in summer 1994 as part of BOREAS field activities. Black spruce (*Picea mariana*) is one of the major boreal tree species. The ground-collected data sets included stem density, forest age, tree heights, leaf area index (LAI) [Chen et al., 1997], and optical properties of needles and soils [Middleton et al., 1997]. SLICER measurements were taken on July 29th, 1996. We ignored the small dynamic growth of trees during the two-year period.

The collected SLICER waveforms were processed following the procedure described in [Harding et al., 2001]. One of the SLICER signals, smoothed and normalized by the maximum return, with the detected noise threshold, is shown in Fig. 1a. The vertical resolution is 0.33 m.

III. THE ALGORITHM FOR RETRIEVAL OF CHPs

A. Current version

In the current version of the algorithm, the cumulative canopy area index, $CHP_c(z)$, above height $z$ inside the canopy is calculated as

$$CHP_c(z) = -\ln \left( 1 - \frac{R_v(z)}{R_v(0) + \rho_v \frac{R_{gr}}{\rho_{gr}}} \right),$$

where $R_v(z)$ is the vegetation return above height $z$, $R_v(0)$ is the total vegetation return, $R_{gr}$ is the ground return (Fig. 1a), $\rho_v$ is the hemispherical reflectance of a vegetated element, and $\rho_{gr}$ is the hemispherical reflectance of the ground. The second part of the logarithmic expression is usually referred to as cover($z$), the fraction of sky covered by vegetation above height $z$ [Lefsky et al., 1999]. $CHP_c(z)$ is analogous to the conception of cumulative leaf area index above height $z$, $\text{LAI}_c(z)$, with only difference of accounting for all (foliage and woody) canopy surfaces. The theory behind Eq. (1)
can be found in [Ni-Meister et al., 2001]. CHP(z) is calculated through the differentiation of CHP_c(z) at each height interval, starting from the top of the canopy. Hereafter, we will refer to the current version as the M-H algorithm.

B. Modified version

The modification of the algorithm will consist of three following steps: (1) the account for the scattering of radiation between the needles of a shoot, (2) the account for the shoot inclination, (3) the empirical correction of the retrieved CHPs to eliminate the effects of multiple scattering of radiation between the shoots. The contribution of each modification will be evaluated separately for a large number of different CHPs.

Step 1. Smolander & Stenberg have developed a relatively simple method to relate needle and shoot reflectance coefficients [Smolander & Stenberg, 2003]. The replacement of the scattering properties of needles with those of shoots allowed them to use a shoot as a basic structural element and describe the canopy structure in terms of spatial and angular distribution of shoots.

The method is based on the assumption that the probability \( p_{sh} \) for a scattered photon to hit the same shoot again remains constant in successive interactions. Then, the shoot scattering coefficient, \( \rho_{sh} \), is related to the needle scattering coefficient, \( \rho_n \), as

\[
\rho_{sh}(\lambda) = \frac{\rho_n(\lambda) - p_{sh}\rho_n(\lambda)}{1-p_{sh}\rho_n(\lambda)},
\]

where \( \lambda \) is the radiation wavelength. Using this relationship, Smolander & Stenberg showed that a “shoot-like leaves” structure simulates well the reflectance behavior of a real coniferous canopy. In their simulations, \( p_{sh} \) was assumed to be dependent only on the shoot structural characteristics and calculated as

\[
p_{sh} = 1 - 4 \cdot \text{STAR},
\]

where \( \text{STAR} \) is a spherically averaged shoot silhouette to total needle area ratio. Eq. (3) was first obtained empirically and then proved using ray tracing simulations for shoots of different length and structure.

Within the CHP retrieval algorithm, if the vegetation structure is described in terms of spatial distribution of shoots, \( \rho_{sh} \) needs be substituted into Eq. (1) as \( \rho_n \). CHPs calculated from the same
SLICER waveform from Fig. 1a with $\rho_v = \rho_n$ and $\rho_v = \rho_{sh}$ are shown in Fig. 1b. The calculations were made for $\rho_n = 0.41$ and $\text{STAR} = 0.133$. The value of $\rho_n$ was taken from field measurements [Middleton et al., 1997], the calculation of $\text{STAR}$ will be discussed in the following sections. The application of Smolander & Stenberg’s method led to the enhancement of the total retrieved CAI by 18%, from 0.52 to 0.61.

**Step 2.** The orientation of a shoot inside the canopy is described with the STAR-function, defined as

$$\text{STAR}(\Omega) = \frac{\text{SSA}(\Omega)}{\text{TNA}}, \quad (4)$$

where $\text{SSA}(\Omega)$ is the shoot silhouette area in direction $\Omega$, and $\text{TNA}$ is the total needle area of a shoot.

The conception of STAR is analogous to the G-function, or the mean projection of foliage unit area in the direction of propagation, originally developed for flat leaves [Ross, 1981]. When shoots are used as the basic structural elements, the G-function is

$$G_{sh}(\Omega) = \frac{\text{SSA}(\Omega)}{\text{TNA}}, \quad (5)$$

where $\text{SSA}(\Omega)$ is the mean shoot silhouette area of the considered shoots, and $\text{TNA}$ is the mean needle surface area of these shoots. Thus, $G_{sh}$ is the mean STAR of the shoots weighted by their needle surface area [Oker-Blom et al., 1991]. For a spherical shoot orientation, when there is no preferred direction for a shoot axis, $G_{sh}$ is defined as [Oker-Blom & Smolander, 1988]

$$G_{sh} = 2 \cdot \text{STAR}. \quad (6)$$

The spherically averaged STAR is mathematically defined as

$$\overline{\text{STAR}} = \frac{1}{\text{TNA}} \int_{4\pi} \frac{1}{4\pi} \text{SSA}(\Omega) d\Omega, \quad (7)$$

where $4\pi$ designates the integration over all possible directions.

To account for shoot orientation with the CHP retrieval algorithm, the restored profiles need to be weighted with the $G_{sh}$-function, i.e., $\text{CHP}(z)/G_{sh}(z)$. A CHP retrieved from the waveform in Fig. 1a with respect to step 1 and 2 is shown in Fig. 1b. For this retrieval, we assumed the spherical shoot orientation and used $G_{sh} = 0.266$. The total CAI value has changed to 2.29.
Step 3. Empirical correction of the retrieved CHPs for the multiple scattering of radiation between shoots will be performed using the time-dependent stochastic radiative-transfer (RT) model developed in [Kotchenova et al., 2003]. The model simulates the propagation of lidar signals through vegetation canopies based on the time-dependent stochastic RT equation, which is solved numerically using the successive orders of scattering approximations. Such an approach allows for description of multiple scattering effects and realistic representation of forest structure including foliage clumping and gaps. The model is parameterized with field measurements of tree structural and optical properties.

The percentage of an averaged SLICER signal generated by multiply scattered photons is estimated through the comparison of model simulations with and without multiple scattering. A change in the retrieved CHP due to the accounting for the effects of multiple scattering is illustrated in Fig. 1b. The total CAI of the CHP retrieved following steps 1 and 2 from the SLICER waveform in Fig. 1a is now diminished by 14%.

IV. CONIFER CANOPY MODELS

Calculation of STAR is the most complicated part of the proposed method. STAR depends on a number of parameters characterizing the structure of a shoot, its orientation and position in the crown. Shoots originating from different whorls of the tree may represent a wide range of STAR values. Moreover, for rotationally asymmetrical (flat) shoots, typical for the shade shoots of *Picea* species, a rotational angle is added to the list of parameters required for the STAR calculation. Most of *Pinus* species are characterized by rotationally symmetrical shoots [Stenberg, 1996].

However, the value of STAR is required only for the G-function calculation. The shoot scattering coefficient $\rho_{sh}$ depends only on the spherically integrated STAR. To make the algorithm dependent only on $\overline{\text{STAR}}$, one needs to use the canopy models with specific shoot orientations, e.g., spherically, vertically or horizontally oriented shoots, where $G$ is defined by $\overline{\text{STAR}}$ [Oker-Blom & Smolander, 1988]. $\overline{\text{STAR}}$ can be calculated directly from the field measurements of shoot parameters or modeled empirically. The value of $\overline{\text{STAR}}$ for a shoot with no mutual shading between needles is 0.25 [Lang, 1991]. The departure of $\overline{\text{STAR}}$ from 0.25 is caused by the overlapping of needles.

In this study, we will utilize three conifer canopy models, which are frequently used in the light interception studies [Stenberg, 1996]. The models differ by the way of $\overline{\text{STAR}}$ modeling:
1. Shoots are uniformly distributed and spherically oriented. All canopy layers are characterized, on average, by the same $\overline{\text{STAR}}$ value. This model is usually called the standard simulation. Hereafter, we will refer to this simulation as mod 1.

2. Shoots are uniformly distributed and spherically oriented, but the mean $\overline{\text{STAR}}$ increases from 0.1 to 0.25 with the degree of shading (DS). The increase is modeled in two ways:
   a) as a linear function of the degree of shading, i.e.,
   $$\overline{\text{STAR}} = 0.1 + 0.15 \cdot DS(z);$$
   (8)
   b) as a quadratic function of the degree of shading exceeding 50%, i.e.,
   $$\overline{\text{STAR}} = 0.1 \text{ for } DS(z) \leq 0.5,$$
   $$\overline{\text{STAR}} = 0.1 + 0.15 \cdot ((DS(z) - 0.5)/0.5)^2 \text{ for } DS(z) > 0.5.$$
   (9)
   (10)

DS(z) is defined as the ratio of photosynthetically active radiation (PAR) absorbed by the canopy above height $z$ to the total radiation incident on a horizontal surface above the canopy. Hereafter, we will refer to the simulation with the linear $\overline{\text{STAR}}$ function as mod 2a, and to the simulation with the quadratic $\overline{\text{STAR}}$ function as mod 2b. The both models incorporate the vertical changes of the shoot inclination angle. Shoots are usually more horizontally oriented in the lower part of the canopy.

V. ANALYSIS

We estimated the performance of the modified algorithm over 50 SLICER waveforms collected over the SOBS site. The modified algorithm was operating in three different modes, designated as mod 1, mod 2a and mod 2b, according to the types of conifer models. Each mode consisted of three separate steps described in Section III.B.

The degree of shading was calculated from the PAR transmittance data collected in the SOBS site during the 1994 summer field campaign [Ni et al., 1997]. The measurements were taken at 2, 4, 6, 8 and 10 m inside the canopy with the help of optical sensors at 10-min time step for almost every day of the campaign. Then, the average PAR transmission on clear days was calculated for each height.

In this study, the PAR transmission data were linearly extrapolated to produce a vertical distribution with the resolution of 0.33 m. The maximum tree height was defined individually for each SLICER waveform as the difference between the maximum of the ground return and the start of the vegetation return [Harding et al., 2001]. The transmittance at the maximum height was set to 1. Thus, the vertical
distribution of DS slightly varies between the waveforms. It was calculated as \( DS(z) = 1 - T(z) \), where \( T(z) \) is the canopy transmittance.

Five example SLICER waveforms are represented in Fig. 2a. Total vegetation returns, transferred later into CHPs, are designated as \( R_v(0) \). CHPs retrieved from these signals by the M-H and the modified algorithms are shown in Fig. 2b. The retrievals show the dependence on the type of \( \text{STAR} \) modeling. The profiles retrieved by mod 1 are stronger than those retrieved by mod 2a but less stronger than those retrieved by mod 2b.

The results of the analysis are also represented in Table 1. We compared the average CAI values obtained after the application of the M-H and the modified algorithms. The indices were calculated separately for each profile and then summed to produce the average values. Within the modified algorithm, the contribution of each improvement was evaluated separately for each mode.

The retrieved average CAIs were compared with the field measurements of the effective leaf area index (LAI), \( L_e \) [Chen et al., 1997]. \( L_e \) is measured near the ground surface with the help of optical instruments. All aboveground materials, such as needles, branches and tree trunks, are included in \( L_e \). Thus, the conception of \( L_e \) is analogous to the conception of CAI measured on the ground. For the SOBS site, \( L_e \) measured between July 19 and August 8 was 1.87.

The results represented in Table 1 show that the average CAI retrieved by the M-H algorithm is extremely low. The account for the multiple scattering between the needles of shoots (Step 1) led to an increase of CAI. The increase is significant for mod 1 and mod 2b, 23.0% and 24.9%, respectively, and less significant for mod 2a, only 11.0%. Clumping of needles into shoots decreases the total area of intercepted surfaces. If we consider two surfaces located at height \( z \), one with uniformly distributed needles and the other with the same needles clumped into shoots, the lidar return will be stronger for the first surface. Also, the scattering coefficient of shoots is less than that of needles. To get the return of the same strength from the second surface, one needs to add more shoots, i.e., increase the canopy CAI.

The account for the shoot inclination (Step 2) led to a significant increase of the CAI values. After Step 2, the range of the calculated CAIs partially overlaps with the range of the field-measured CAIs of BOREAS species [Chen et al., 1997]. The less increase is again observed for mod 2a. The empirical correction for multiple scattering of radiation between shoots (Step 3) led to a slight decrease in the calculated CAI values, no more than 15% on average for all three modes. It was mentioned above that
the ignorance of the multiple scattering effects led to larger amounts of foliage erroneously assigned to the lower part of the canopy. As a result, the calculated CAI is larger than in reality. Step 3 is required to correct this.

The performance of the modified algorithm is sensitive to the type of canopy structure. Mod 1 and mod 2b demonstrate better agreement with the field-measured $L_c$ than mod 2a. However, compared to mod 1, mod 2a and 2b have an advantage of capturing the response of shoots to shading. The shoots become more horizontally inclined the lower they are in the canopy, in order to increase their PAR interception efficiency. Changes in shoots inclination angles, or in $\overline{\text{STAR}}$, cause a more rapid decrease of the penetrated light. As a result, there comes a point where this strategy can no longer increase the PAR interception ability. Moreover, the shoots in the upper part of the canopy are usually characterized by the same $\overline{\text{STAR}}$ values. The shoots start changing their inclination angle when they start obscuring each other. Mod 2a fails to account for these effects. Stenberg [1996], who studied the effects of shoot structure on light interception, also noted that the simulation of $\overline{\text{STAR}}$ as the quadratic function of DS was more close to reality than the linear function.

VI. CONCLUSIONS

Conifer canopies are characterized by several levels of clumping: needles are clumped into shoots, shoots into branches, branches into whorls, and whorls into crowns. In our study, we have considered only the first level of clumping, by relating shoots and needles scattering properties. The effects of additional grouping, other than the clumping of needles into shoots, can be included by multiplying the G-function by a clumping index [Chen et al., 1997]. However, in the case of the M-H algorithm, the use of the clumping index will contradict with the underlying assumption of a uniform distribution of vegetated elements.

Clumping of needles into a shoot, shoots inclination and multiple scattering of radiation between the shoots are the effects that can be taken into account without contradicting the basis of the M-H algorithm. The main advantage of the developed algorithm is in the utilization of the mathematically corrected approach for transferring from the distribution of needles to the distribution of shoots. This approach includes the effects of multiple scattering of the needles of a shoot, which are significant in the case of the lidar (near-infrared) spectrum. Also, the proposed algorithm allows for realistic modeling of conifer canopy structure, with accounting for changes in shoot inclination with height.
REFERENCES


Table 1. Average canopy area indices (CAIs) of 50 SOBS CHPs retrieved by the M-H algorithm and by the modified algorithm operating in three different modes.

<table>
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<tr>
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<th>Average CAIs retrieved by the M-H algorithm</th>
<th>the modified algorithm</th>
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<tbody>
<tr>
<td></td>
<td>Step 1</td>
<td>Step 2</td>
</tr>
<tr>
<td>mod 1</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.56 (23.0% ↑)</td>
<td>2.09 (14.1% ↓)</td>
</tr>
<tr>
<td>mod 2a</td>
<td>0.50 (11.0% ↑)</td>
<td>1.56 (12.9% ↓)</td>
</tr>
<tr>
<td>mod 2b</td>
<td>0.56 (24.9% ↑)</td>
<td>2.61 (14.8% ↓)</td>
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Fig. 1. (a) The processed SLICER waveform. The noise level is shown with the dashed line. $R_v(z)$ is the vegetation return above height $z$, $R_v(0)$ is the total vegetation return, and $R_{gr}$ is the ground return. (b) Retrieval of CHP: (0) – the current algorithm, (1) – accounting for radiation scattering between the needles of a shoot, (2) – accounting for shoot inclination, (3) – accounting for multiple scattering between shoots. Step (2) includes step (1). Step (3) includes steps (1) and (2).
Fig. 2. (a) Example SLICER waveforms. The vegetation returns converted later into CHPs are designated as $R_v(0)$. (b) CHPs retrieved by the M-H algorithm and by the modified algorithm operating in three different modes: mod 1, mod 2a and mod 2b.