Inversion of a Lidar Waveform Model for Forest Biophysical Parameter Estimation

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***Abstract*—Due to its measurement principle, light detection and ranging (lidar) is particularly suited to estimate the horizontal as well as vertical distribution of forest structure. Quantification and characterization of forest structure is important for the understanding of the forest ecosystem functioning and, moreover, will help to assess carbon sequestration within forests. The relationship between the signal recorded by a lidar system and the canopy structure of a forest can be accurately characterized by physically based radiative transfer models (RTMs). A three-dimensional RTM is capable of representing the complex forest canopy structure as well as the involved physical processes of the lidar pulse interactions with the vegetation. Consequently, the inversion of such an RTM presents a novel concept to retrieve biophysical forest parameters that exploits the full lidar signal and underlying physical processes. A synthetic dataset and data acquired in the Swiss National Park (SNP) successfully demonstrated the feasibility and the potential of RTM inversion to retrieve forest structure from large-footprint lidar waveform data. The SNP lidar data consist of waveforms generated from the aggregation of small-footprint lidar returns. Derived forest biophysical parameters, such as fractional cover, leaf area index, maximum tree height, and the vertical crown extension, were able to describe the horizontal and vertical forest canopy structure.**

***Index Terms*—Biophysical parameters, fcover, inversion, leaf area index (LAI), light detection and ranging (lidar) waveform, three-dimensional (3-D) model, tree height.**

I. Introduction

CANOPY structure, both in horizontal and vertical dimension, is a key factor for the functioning of forest ecosystems. The dispersion and number of canopy elements within the three-dimensional (3-D) space directly controls the exchange and fluxes of energy and mass between vegetation and atmosphere [1]–[3]. The major physiological processes of vegetation including photosynthesis (over the scattering and absorption of incoming radiation) and evapotranspiration are influenced by the biophysical forest parameters that describe the canopy structure. Moreover, the quantification of canopy structure allows for the assessment of the above-ground biomass, which in turn indicates the above-ground carbon stock of the observed forest.

Remote sensing can provide spatially continuous observations of biophysical vegetation parameters for regional to global ecosystem studies in order to define realistic initial and boundary conditions of ecological models. The remote sensing technique light detection and ranging (lidar) is particularly suited to derive information about biophysical parameters such as tree height, fractional vegetation cover, canopy geometry, and above-ground biomass. A number of studies have shown the sensitivity of small- and large-footprint lidar systems relative to forest canopy structure with unprecedented accuracy [4]–[8]. The measurement principle of lidar relies on laser pulses propagating vertically through the canopy, while scattering events with the vegetation are recorded as function of time. The response obtained by lidar is consequently dependent on the vertical distribution of canopy elements such as the foliage, branches, and trunks, as well as the underlying terrain [9].

However, for the retrieval of forest parameters based on lidar data, the interaction of the laser with the complex 3-D canopy structure has to be adequately understood and interpreted. For this purpose, several radiative transfer models (RTMs) have been developed, incorporating a realistic forest stand representation, lidar sensor specifications, and the involved physical processes [10]–[12]. The inversion of such a physically based model provides a novel concept of retrieving biophysical parameters from lidar data in a robust and quantitative manner.

In this study, we propose to invert a 3-D lidar waveform model [12] to estimate tree height, fractional cover, and overstory leaf area index (LAI) of a coniferous forest. The invertibility and general potential for parameter retrieval of the model are first tested on a synthetic dataset. The performance of the proposed approach is further validated on an actual dataset of field measurements and lidar waveforms generated from small-footprint lidar returns.

II. Lidar Waveform Model

A 3-D waveform model was used to simulate lidar waveforms as a function of forest stand structure and sensor specifications [12]. The model constructs a 3-D representation of the observed forest stand taking into account the number and position of trees, crown geometry and shape, tree height, and underlying ground topography (Fig. 1). The crown itself is described as a turbid scattering medium parameterized by its foliage area volume density, the Ross–Nilson G-factor [13], and the foliage reflectance. Finally, the ground reflectance needs to be defined for an accurate waveform simulation.

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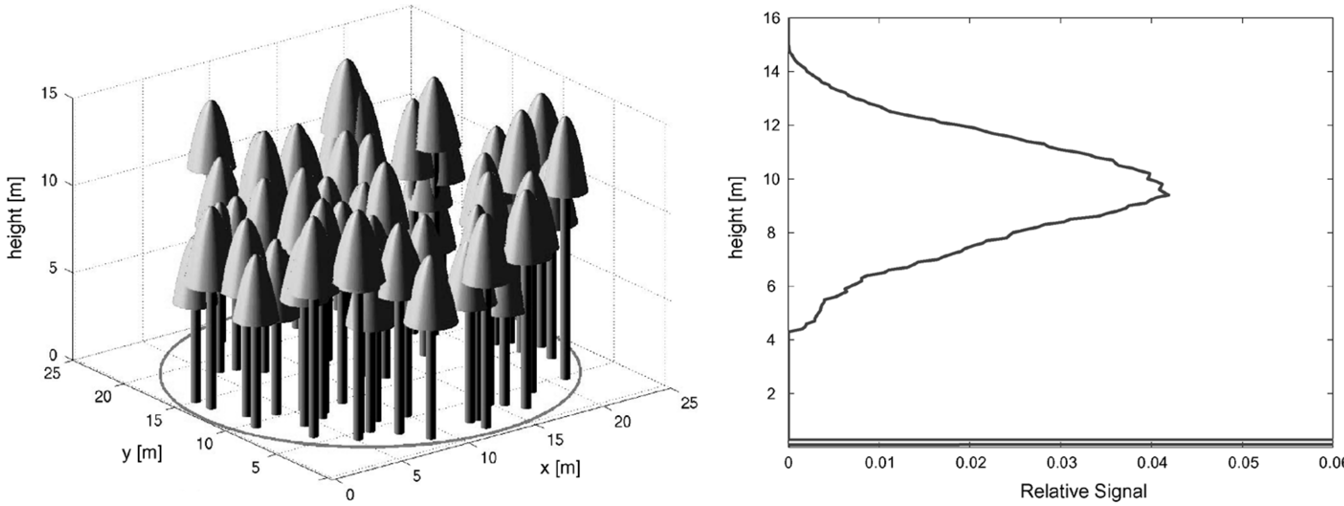

Fig. 1. Example of a 3-D forest stand representation for waveform simulations, parameterization: 60 trees, maximum tree height: 15 m; crown length: 4 m; crown width: 3 m; crown shape: hemi-ellipsoid; LAI: 2.5; G-factor: 0.5; leaf reflectance: 0.215; background reflectance: 0.152; footprint: 25 m.

Within this study, the original version of the waveform model was adapted to allow for the input of LAI instead of the foliage area volume density. The updated model also calculates the fractional cover of the respective 3-D stand representation used for the waveform simulation.

III. Data

A synthetic and an actual dataset, both comprising lidar waveforms and their corresponding canopy parameters, were available to validate the retrieval performances of the proposed approach.

A. Synthetic Dataset

A synthetic dataset was generated by simulating the lidar waveform response of 100 artificial forest stands using the above-described lidar waveform model. The stand parameters were chosen randomly within the ranges defined in Table II, creating an independent dataset for the validation of the proposed model inversion. Details of the model parameterization are described in Section IV. Uncertainties related to errors associated to the sensor and data processing could not be taken into account because of their insufficient characterization.

B. Swiss National Park Dataset

A field dataset was acquired over a study area located in the Eastern Ofenpass Valley, which is part of the Swiss National Park (SNP). Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l with an annual precipitation of 900–1100 mm. The south-facing Ofenpass forests, the location of the field measurement, are largely dominated by mountain pine (*Pinus montana ssp. arborea*).

Four core test sites were sampled intensively for their biophysical and spectral canopy characteristics. The sites were selected following a stratified sampling scheme to cover different canopy densities within the observed stand. Each site was defined by nine sampling points, evenly spaced in a grid of 10 m, covering a square area of 20 $\times$ 20 m. The LAI-2000 plant canopy analyzer was used to estimate the two canopy variables: LAI and fractional cover.

VI. Conclusion

The response of a large-footprint lidar over a forest canopy is governed by the complex forest structure and the involved physical processes. Consequently, a physically based radiative transfer model is an appropriate method to interpret and exploit the waveform recorded by such a system. Two separate datasets successfully demonstrated the potential of RTM inversion to retrieve horizontal and vertical forest structure from lidar data.

A synthetic dataset verified the invertibility of the proposed waveform model for forest parameters retrieval. Horizontal and vertical forest structure expressed as fractional cover, maximum tree height, and vertical extension of the crown layer could be estimated. LAI of the forest overstory was only retrievable for the coniferous canopy studied in the SNP. Estimates of fractional cover and maximum tree height could also be successfully validated with the *in situ* field data. However, model assumptions and data processing difficulties limited the accuracy of the obtained results. Model development and the use of waveform data obtained by a dedicated large-footprint sensor will further improve the retrieval performance. Although measured large-footprint lidar data will introduce new problems to the algorithm including the effect of varying terrain and laser illumination within the footprint.

Due to its physically based nature of the proposed concept and algorithm, there is no dependency on *in situ* calibration. However, it relies on ancillary information such as crown shape and both foliage and background reflectance. Imaging spectroscopy can provide spectral information on the relevant canopy components and can help to define the crown shape or G-factor by detecting the observed forest type. Consequently the combination of the two different sensor types, lidar and imaging spectrometers, could improve the stability and accuracy of the proposed forest parameters retrieval.