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Inversion of combined Radiative Transfer Models for Imaging Spectrometer and LIDAR Data

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I. INTRODUCTION

The spectral information domain provided by imaging spectrometers contains information about the biochemical composition of a vegetation canopy such as foliage chlorophyll and water content. The spectral information content also enables indirect assessment to the biophysical parameters LAI and fractional cover. On the other hand, the information domain observed by LIDAR provides direct measurements of the vertical and horizontal canopy structure describing the canopy height and the vertical distribution of canopy elements. The leaf optical properties, which are directly related to the foliage biochemistry, scale to the canopy as function of canopy structure and spatial arrangement of canopy elements. Further, the spatial heterogeneity and canopy structure dominate the radiative transfer especially within forest stands. Consequently the LIDAR signal, e.g. recorded as full waveform, can improve the accuracy and robustness of forest canopy parameter retrieval by reducing uncertainties related to the canopy structure. On the other hand the accurate interpretation of the LIDAR signal depends on the spectral properties of canopy elements as well as the background. The two sensors and their different information domains are thus mutually dependent but also complement each other. A synergistic exploitation of the information domains observed by Imaging Spectrometry and LIDAR based on radiative transfer modeling will therefore provide a new approach to optimize the retrieval of forest foliage biochemical composition and the canopy structure.

II. RADIATIVE TRANSFER MODELS

The remote sensing signatures of forest canopies as observed by an imaging spectrometer and a large footprint LIDAR have been simulated by two separate radiative transfer models (RTM). The use of the radiative transfer models has been twofold. They have been employed to generate by forward modeling an independent synthetic data set for validation purposes. Furthermore, the inversion of the two radiative transfer model provided the means for the proposed retrieval of vegetation canopy properties.

The hybrid radiative transfer model GeoSAIL [1] describes the spectral canopy reflectance of a forest stand. The radiative transfer at foliage level is characterized by the model PROSPECT [2], which provides the foliage optical properties as a function of the biochemistry and is subsequently coupled with the canopy RTM.

A three-dimensional (3D) waveform model was used to simulate LIDAR waveforms as a function of forest stand structure and sensor specifications [3]. 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 3D stand representation used for the waveform simulation.

III. GENERATION OF SYNTHETIC DATA SET

A synthetic but nevertheless realistic data set has been generated by linking the forest growth model ZELIG [4] to the two radiative transfer models described above. The linked models provided a comprehensive data set of the remote sensing signatures for an imaging spectrometer and a LIDAR over a wide range of forest stands.

ZELIG simulations over time (forest age: 5-250 years) and for ten different sites in changing environmental settings described in detail the highly variable canopy attributes, such as the canopy structure of the studied forest stands. A total of 3900 forest stand simulations (10 soil types x 15 replications x 26 time steps) were performed. ZELIG forest stand descriptions were used as parameterization of the radiative transfer models. Forward simulations of the two radiative transfer models subsequently generated the remote sensing signatures of the forest stands as observed by the imaging spectrometer APEX [5] and the large footprint LIDAR LVIS [6] (see Fig. 1 as example). Further, typical measurements errors of the remote sensing data and uncertainties related to the radiative transfer models were taken into account.

The synthetic dataset avoids limitations due to the number, variability and accuracy of field sampling as well as the co-registration errors between field data and remote sensing observations. The here used ZELIG data set has already served well for similar studies of model simulation and data analyses [7, 8]

IV. COMBINED RTM INVERSION BASED ON LUT

The inversion of the two introduced radiative transfer models for the synergistic vegetation parameter estimation from LIDAR and imaging spectrometer data is based on a LUT (Look Up Tables) approach. It is a conceptually very simple technique, which potentially overcomes computational limitations as well as the risk of local minimum convergence [9, 10]. The approach also allows due to its simplicity to construct a LUT comprising different remote sensing signatures of multiple sensors. Such a combined LUT is made possible by an interface between the two radiative transfer models. Common RTM parameters describing the canopy structure such as fractional cover, LAI and crown geometry establish a common forest stand parameterization used by each of the two models to generate a combined spectral and waveform signature of the respective canopy realization.

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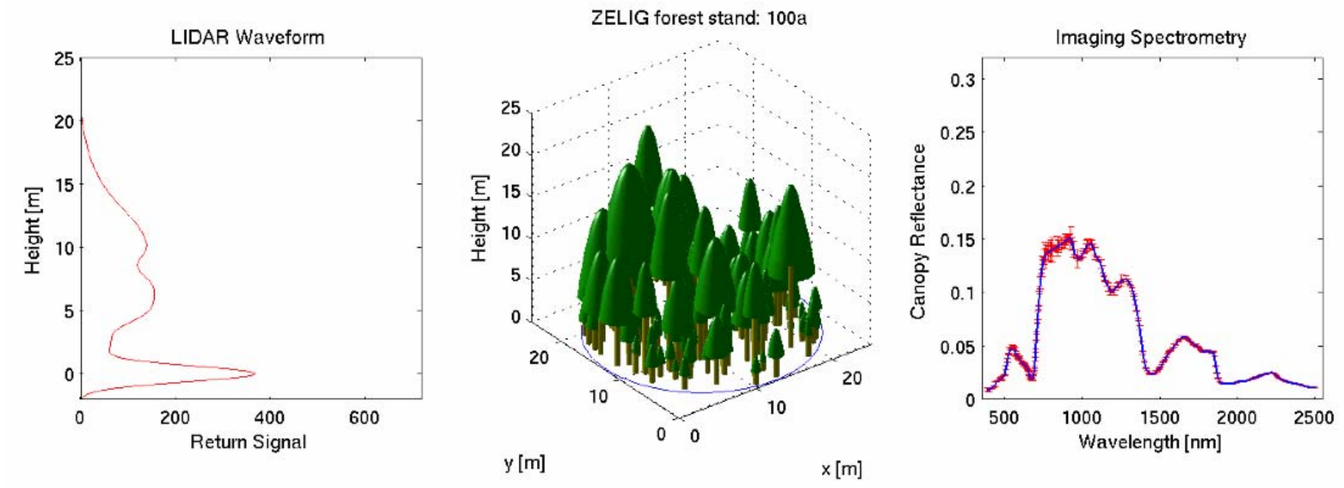

Figure 1. Simulated remote sensing signatures for the imaging spectrometer APEX and the large footprint LIDAR LVIS over a forest stand generated by the forest growth model ZELIG (stand age: 100 years, soil type ADAMS).

The LUT inversion approach can be split into two parts: (i) the generation of the LUT itself, and (ii) the selection of the LUT solutions corresponding to a given measurement. The selection of the LUT solutions followed here a sequential approach.

A. Generation of LUT

The generation of a look up table consists first to sample the space of the input variables V of the two involved radiative transfer models (LUT_V). A total of 100,000 canopy realizations have been generated following a uniform distribution and specific ranges for the respective canopy variable. Then, the two RTM linked by common vegetation variables were used to simulate the corresponding remote sensing signature table (LUT_S) for each canopy realization. The spectral properties of the background were also shared by both of the models.

The parameterization of the RTM for the LUT generation were in general defined accordingly to two previous experiments performed over a coniferous canopy, where each RTM was inverted separately [11, 12]. The LUT ranges were adapted to accommodate the conditions of the synthetic data set generated by ZELIG. Note that the generation of the LUT_V allows already to define some prior information on the respective variable by constraining it to vary within limited ranges.

B. Merit function

The selection of the solution within the LUT was achieved by a sequential approach consisting of two steps. The LIDAR waveform information was exploited in a first step delivering information on the vertical and horizontal canopy structure. Part of this information was used as prior information restricting possible solutions within the subsequent second step, the exploitation of radiometric information. In both steps the merit function was based on a simple distance criterion between measured and reference signature of the respective remote sensing sensor.

The coupling of the waveform and radiometric information was based on the hypothesis that LIDAR provided the most reliable estimates of the fractional cover, due to its direct measurement principle of canopy structure.

V. EVALUATION OF THE RTM COUPLING STRATEGY

The synthetic data set generated by the forest growth model ZELIG for a wide range of forest stands was used to evaluate the performance of the proposed method. First, the retrieval performance based solely on the information domain provided by the LIDAR sensor was discussed separately. The improvement of the combined radiometric and waveform information domains was subsequently evaluated relatively to the radiometric information performance.

The inversion of the waveform RTM provided reliable estimates of model parameters describing the vertical as well as the horizontal canopy structure. The parameters were all retrieved with high correlation coefficients and reasonable RMSE (Fig. 2). The two parameters describing the vertical canopy structure maximal tree height and the vertical crown extension showed similar performances. Both parameters were slightly underestimated, which was most likely caused by missing the signal start of the highest tree top. Due to the nature of the employed merit function low signals, as recorded from single tree tops extending over the canopy, received a relative low weight within the retrieval algorithm. The comparable values of the vertical crown extension relative to the maximal tree height indicated that the observed forest stands exhibited a rather continuous vertical distribution of crowns. The example of a ZELIG generated forest stand presented in figure 1 suggested such a vertical canopy structure. The horizontal structure represented by the canopy fractional cover showed some underestimation for low values as well as an overestimation for high values. Some of this behavior could be attributed to compensation for the fixed LAI parameter, which probably assumed a relative high crown density for sparse, younger stands and a relative low crown density for closed, mature stands. Nevertheless, this assumption was necessary for a stable inversion performance due to a strong inter-correlation between LAI and fcover. The overall high performance of the waveform model inversion has been only achieved by the implementation of a two strata canopy and a highly variable vertical tree height distribution into the LUT generation.

The combined RTM inversion performed well retrieving estimates of biophysical parameters, LAI and fcover, and biochemical parameters, foliage content of chlorophyll and water, with significant correlation coefficients and low RMSE (Fig. 3). The introduction of prior information on the fcover parameter derived from the waveform information content clearly improved the retrieval performance relative to estimates based only on radiometric information. The fcover estimates based on the combined RTM inversion resulted in a 24.4% lower RMSE and a 15.4 % increase of explanation power in terms of R^2, calculated over the total of all stands. The results for the soil type ADAMS, presented in figure 3, also indicated that most of the improvement was caused by the reduction of scattering for fcover greater than 0.5. Although the inversion uncertainty for low fcover has been also reduced. Relative to the fcover estimates based solely on waveform information content the combined retrieval showed a more linear relationship causing a lower RMSE. However, retrieval performance of the remaining parameters, especially the biochemistry, decreased by the introduction of prior information on the fcover. This had a number of different causes. First, the prior information on the fcover reduced considerably the number of available LUT entries, which consequently resulted in a lower probability to find a solution fitting the information content related to the biochemistry. Further, the prior information mostly improved the retrieval for closed canopies where estimation of foliage biochemistry is generally least affected by canopy structure [13]. Also the RTM GeoSAIL does not incorporate certain effects of canopy structure affecting the biochemistry estimation, such as mutual shading. Consequently indirect improvement of biochemistry retrievals by introduction of prior information on fcover was limited for this synthetic data set. Finally, the RTM inversion on the radiometric information already provided good results since prior information on all parameters was introduced implicitly during the LUT generation and the synthetic data set assumed ideal measurement conditions. Nevertheless, in reality an improved characterization of the canopy structure by prior information should also enhance the retrieval quality of biochemistry from imaging spectroscopy.

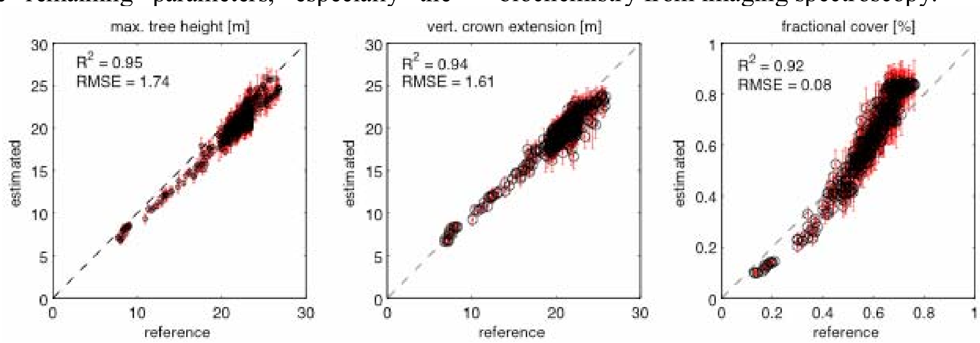

Figure 2. Vegetation parameter estimates describing the vertical and horizontal canopy structure retrieved by the inversion of the waveform RTM for forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion.

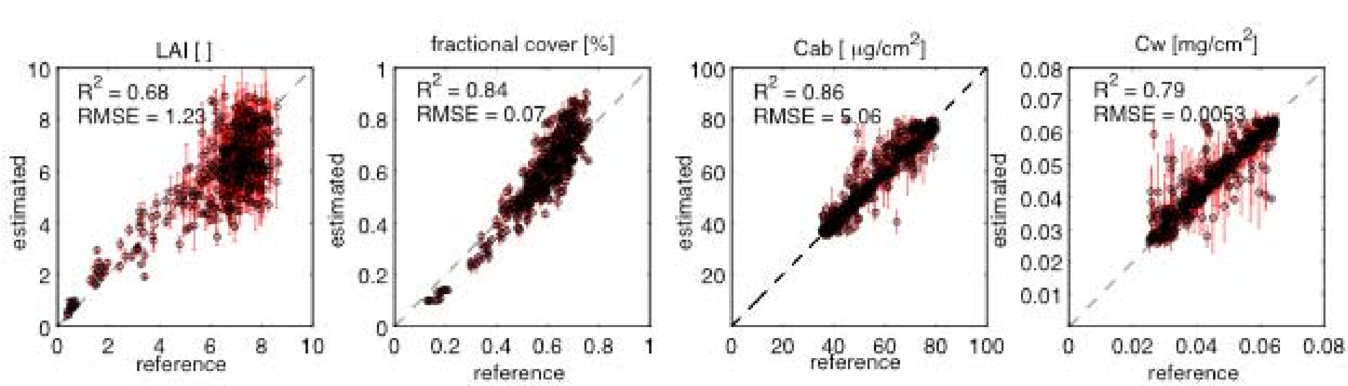

Figure 3. Estimates of biophysical and biochemical parameters retrieved by the coupled RTM inversion for forest stands generated by ZELIG over the soil type ADAMS (n=390 forest stands). Error bars represent the uncertainty of the model inversion.

VI. Conclusions

The remote sensing of vegetation properties is a generally ill-posed problem, partly due to the available indirect detection methods and measurement uncertainties but also due to the limited representation of the involved processes in the retrieval. Even physically based radiative transfer models are partly based on assumptions and parameterizations. Consequently the introduction of prior or ancillary information into the retrieval process is a necessary and useful approach to increase the robustness of canopy parameter estimation by remote sensing. One way of deriving prior information is to exploit different information domains provided by multiple sensors.

The presented study showed the potential for the combined exploitation of multiple sensors based on physically based radiative transfer modeling. The two information domains provided by imaging spectrometry and LIDAR were successfully used to derive a comprehensive canopy characterization. The results of the study provided robust estimates of the vertical and horizontal canopy structure as well as biophysical and –chemical canopy parameters for a wide range of forest stands. Although these findings are based on a synthetic data set, they bear a high significance for future space-borne Earth-Observation platforms such as the proposed mission Carbon-3D, which is supposed to provide global biomass estimates based on similar data observation techniques [14]. Also due to the simplicity of the coupled RTM strategy the approach could be easily extended to further information domains provided by multi-angle or RADAR observations.

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