

## CONCEPT FOR FOREST PARAMETER ESTIMATION BASED ON COMBINED IMAGING SPECTROMETER AND LIDAR DATA

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### ABSTRACT

Both Imaging Spectrometry and LIDAR have been already investigated as independent data sources to describe and quantify forests properties. While Imaging Spectrometry provides information on the biochemical and biophysical properties of the canopy, LIDAR resolves the spatial and vertical distribution of the canopy structure (1, 2). The presented contribution outlines a concept how these two complementary information sources can be combined for an improved estimation of forest parameters based on radiative transfer modelling.

### INTRODUCTION

Vegetation plays a major role in the terrestrial land surface processes such as the exchange and storage of water, energy and CO<sub>2</sub>. Driving parameters of the physiological processes, such as foliar biochemistry and the green leaf area, can be derived by remote sensing platforms such as Imaging Spectrometers and LIDAR sensors enabling an assessment of the terrestrial ecosystem functioning on a spatial scale. The characterization and quantification of biophysical and biochemical forest properties by remote sensing could thus provide spatial information on tree growth and canopy condition essential to foresters, fire and resource managers (3, 4).

Remote sensing of vegetated surfaces, especially for forests, relies on the understanding of the interaction of the electromagnetic radiation within the canopy described by physically-based radiative transfer models (RTM). The radiative transfer within a forest canopy is dependant on the spectral properties, the spatial distribution of the canopy elements and on the subsequent complex radiative processes, such as multiple scattering, mutual shading of the crowns and shading of the understory (5, 6). Appropriate radiative transfer models can be used to explicitly exploit our knowledge of the physical processes governing the signal of a forest canopy recorded by an imaging spectrometer or LIDAR (7, 8).

The information dimension observed by LIDAR provides information about the vertical canopy structure describing the canopy height and the vertical distribution of canopy elements. Whereas, the spectral information dimension provided by imaging spectrometers contains information about the biochemical composition of the canopy foliage such as chlorophyll and water content. Biophysical canopy parameters such as LAI (Leaf Area Index) and fractional cover are also inferable. Nevertheless, the leaf optical properties, which are directly related to the foliage biochemistry, scales to the canopy as function of canopy structure and spatially arrangement of canopy elements. Consequently the LIDAR signal, e.g. recorded as full waveform, can improve the accuracy and robustness of canopy parameter retrieval, especially the foliage biochemistry, 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 dimension are thus mutually dependant and can complement each other. A simultaneous exploitation of the information dimensions observed by Imaging Spectrometry and LIDAR based on radiative transfer modelling will therefore provide a new approach to optimize the retrieval of forest foliage biochemical composition and the canopy structure.

In this contribution two separate case studies demonstrate the feasibility of Radiative Transfer Modelling for IS and LIDAR independently, a prerequisite for the proposed approach (9, 10). Further on a concept of combining these two sensors and their data content by joining the two employed RTM is presented.

## TEST SITE OF CASE STUDIES

The test site for this study is located in the eastern Ofenpass valley, which is part of the Swiss National Park (SNP). The Ofenpass represents an inner-alpine valley on an average altitude of about 1900 m a.s.l with 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*) and some stone pine (*Pinus cembra* L.) (11, 12). These forest stands can be classified as woodland associations of *Erico-Pinetum mugo* (11). Unique ground based characterization of the canopy structure, biochemistry and optical properties of the canopy elements were conducted in summer 2002 using various instruments, ranging from non-destructive spectroradiometric measurements to dry biomass estimation of needles (10).

## RADIATIVE TRANSFER MODELLING: IMAGING SPECTROSCOPY

The spectral reflectance of a vegetation canopy, provided by air- or spaceborne imaging spectrometer, is known to be primarily a function of the foliage optical properties, canopy structure, background reflectance of understory and soil, illumination conditions and viewing geometry (5, 6). The complex radiative transfer within a canopy governing the signal recorded by imaging spectrometers can be described by physically based radiative transfer models (RTM), which take into account the above mentioned factors (7, 13). The use of such a RTM for a comprehensive retrieval of the biophysical and –chemical canopy properties from imaging spectrometer data was demonstrated in the following regional test case (1).

During a large campaign in the Swiss National Park, in summer 2002, DAIS 7915 and ROSIS imaging spectrometer flights were carried out along with intensive ground measurements of the vegetation properties. Canopy structure was described by two canopy analyzers LAI2000 and hemispherical photographs following well known methods for the characterization of heterogeneous canopies such as coniferous forest (14, 15). Standard wet-laboratory procedures were used for determination of foliage water content and dry matter.

### Radiative Transfer Model

The hybrid radiative transfer model (RTM) GeoSAIL (16) was employed to describe canopy reflectance at scene level. GeoSAIL was chosen due to its low computational costs and its comparable performance to the more sophisticated RTM FLIGHT (Kötz et al. 2004). The radiative transfer at foliage level was characterized by the model PROSPECT (17), which provided the foliage optical properties as a function of the biochemistry and was then subsequently coupled with the canopy RTM. GeoSAIL describes the canopy reflectance of a complete scene including discontinuities in the canopy and shadowed scene components. GeoSAIL is a combination of a geometric model with the SAIL model (18), that provides the reflectance and transmittance of the tree crowns. The geometric model determines the fraction of the illuminated and shadowed scene components as a function of canopy coverage, crown shape and illumination angle. All trees are assumed to be identical with no crown overlap nor does the model account for mutual shading.

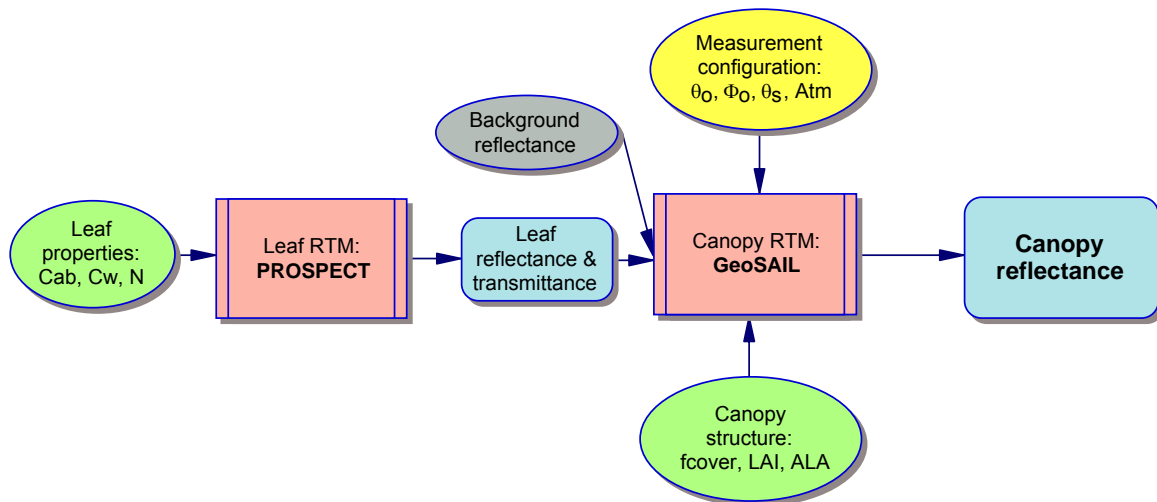


Figure 1: Schematic description of the coupled RTM PROSPECT/GeoSAIL and their input parameters for the simulation of the canopy reflectance

### RTM inversion

The inversion of coupled models PROSPECT and GeoSAIL was based on look up tables (LUT), whose generation consisted in precomputing the canopy reflectance for 130'000 canopy realizations and considering the measurement configuration. The parameters corresponding to each canopy realization were randomly drawn following a uniform distribution. The range of each variable was defined based on ground measurements performed in this study and on experimental data presented in literature (19-21) (Table 1). The selected ranges corresponded to a distribution of the respective variable typical for the observed coniferous canopy. The generation of the LUT allowed consequently for the implementation of general prior information depending on the specific vegetation type. Tree geometry and spectral properties of the understory and woody parts were also specified by the forest stand characteristics and ground measurements.

Table 1: Specific ranges for each parameter describing the constraining space for canopy realizations used for the generation of the look up table.

RTM parameter	Unit	Minimum	Maximum
LAI	unitless	1	5
Fractional cover	%	0.4	0.85
Wood fraction	%	0.25	0.45
Chlorophyll content	$\mu\text{g}/\text{cm}^2$	55	80
Water content	$\text{g}/\text{cm}^2$	0.025	0.065
Dry matter	$\text{g}/\text{cm}^2$	0.02	0.05
N	unitless	2	5

The model inversion was carried out by minimizing the merit function  $\chi^2$ , as depicted in eq. 1, and is defined as the distance between the canopy reflectance  $\rho_{\text{mes}}$  acquired by the DAIS 7915 and the simulated reflectance  $\rho_{\text{sim}}$  found in the LUT. The distance criterion was weighted using the uncertainty of the spectroradiometric measurements ( $\delta_{\text{DAIS}}$ ), which is related to the calibration of the DAIS 7915 sensor and the atmospheric correction of the imaging spectrometer data.

$$\chi^2 = \sum_{i=1}^{n_\lambda} \frac{1}{\delta_{DAIS}^i} (\rho_{mes}^i - \rho_{sim}^i)^2 \quad (1)$$

where  $n_\lambda$  is the number of finally included imaging spectrometer bands (e.g., 34). Canopy realizations found within a tolerance of 20% of the minimal calculated distance  $\chi^2$  were considered as possible solutions; their median defined the final solution and their standard deviation the uncertainty of the inversion.

Based on a case study in a mountain coniferous forest, we demonstrate the successful canopy variable estimation in a heterogeneous canopy, such as fcover, LAI, leaf water content and leaf dry matter (Figure 2). The coupled model approach using PROSPECT and GeoSAIL allow a quantitative approach for the extraction of relevant vegetation variables. The canopy variables provide information on the vegetation status vital to the management of forests with respect to ecological modelling.

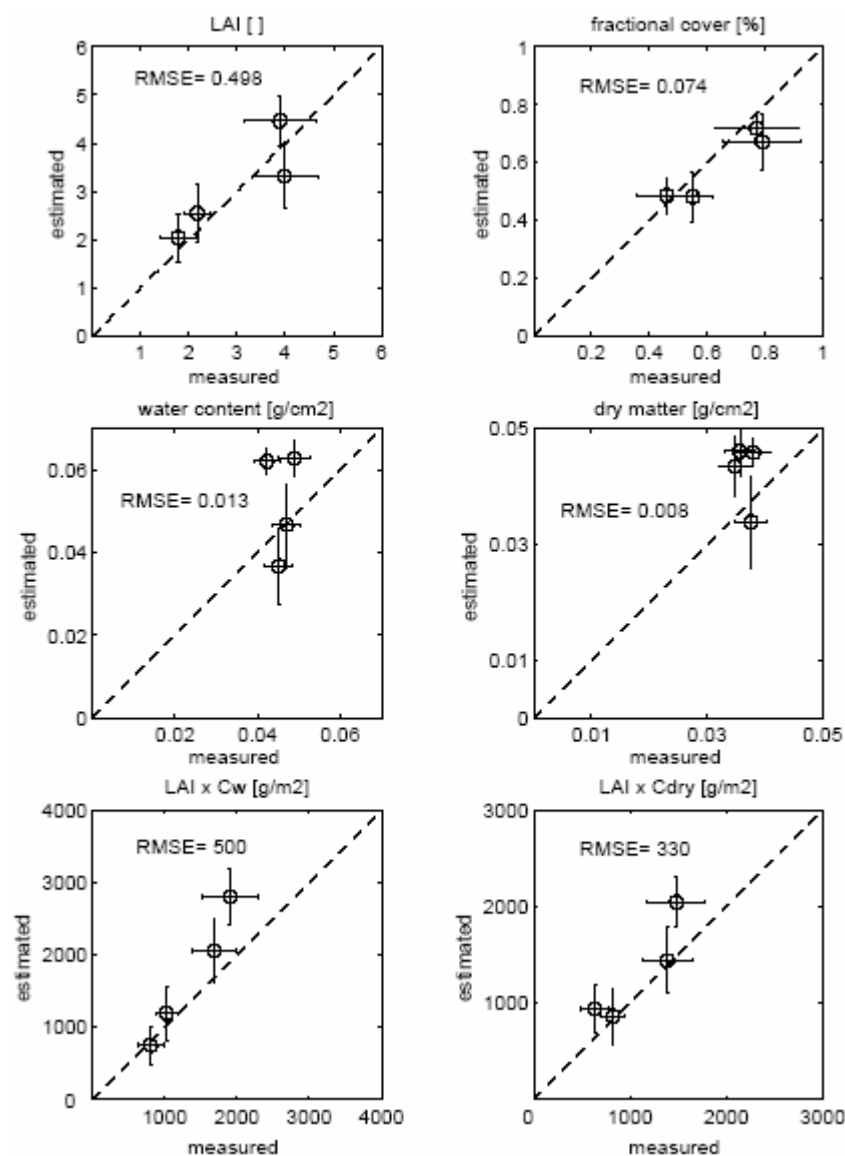


Figure 2: Performance of radiative transfer model inversion: Estimates and measurements of canopy parameters related to the four test sites, error bars represent the uncertainties related to the ground measurements (e.g. the nine plots summarised into the four test sites) and model inversion respectively. (LAI x Cw: canopy water content, LAI x Cdry: Canopy dry matter content, RMSE: root mean square error in corresponding units) (10).

## **RADIATIVE TRANSFER MODELLING: LIDAR**

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 aboveground biomass. A number of studies have shown the sensitivity of small and large footprint LIDAR systems relative to forest canopy structure (2, 22-25). 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 (26).

However, for the retrieval of forest parameters based on LIDAR data the interaction of the laser with the complex 3D canopy structure has to be adequately understood and interpreted. For this purpose several radiative transfer models (RTM) have been developed, incorporating a realistic forest stand representation, LIDAR sensor specifications as well as the involved physical processes (8, 27, 28). The inversion of such a physically-based model is presented in the following case study demonstrating the feasibility of retrieving biophysical parameters from LIDAR data by radiative transfer modelling (9).

For the case study an airborne LIDAR survey was carried out in October 2002 over the test site in the SNP (2). The FALCON sensor, a small-footprint push-broom laser altimeter operated by the company TopoSys, was used. The system provided both first and last reflection of the laser signal (first/last pulse) in a point density of more than 20 points per m<sup>2</sup> with a footprint size of about 50 cm in diameter. The single pulse data of the small-footprint LIDAR were converted into digitized waveforms following the approach described in (29). The LIDAR return waveform was modeled as the sum of reflections within a footprint of 25 meters in diameter. Instrument-specific characteristics have been taken into account emulating the specifications of the large footprint LIDAR system LVIS (30).

### **Radiative Transfer Model**

A three-dimensional waveform model was used to simulate LIDAR waveforms as a function of forest stand structure and sensor specifications (8). The model constructs a 3D-representation of the observed forest stand taking into account the number and position of trees, tree height, crown geometry and shape as well as the exposition of the underlying topography (Figure 3). The crown itself is described as a turbid scattering medium parameterized by its foliage area volume density, the Ross-Nilson G-factor (31) and the foliage reflectance. Finally, the ground reflectance needs to be defined for an accurate waveform simulation.

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.

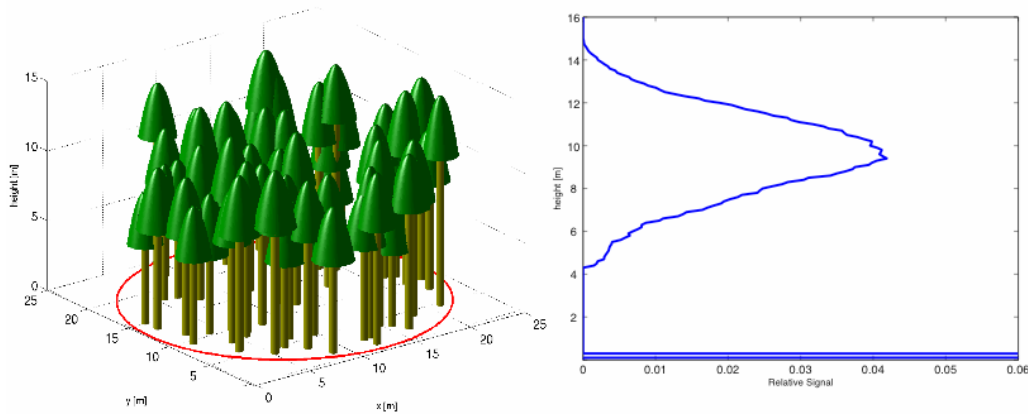


Figure 3: Example of a 3-D forest stand representation for waveform simulations, parameterization: 60 trees, max. tree height: 15 m, crown length: 4m, crown width: 3 m, crown shape: hemi-ellipsoid, LAI: 2.5, G-factor: 0.5, leaf reflectance: 0.215, background reflectance: 0.152, footprint: 25 m

### RTM inversion

The inversion of the LIDAR waveform model was based on a LUT (Look Up Table) approach. A LUT model inversion comprises two parts, the generation of the LUT itself and the selection of the solution corresponding to a given measurement.

Simulating LIDAR waveforms for a total number of 100'000 canopy realizations, while considering the sensor configuration, generated a comprehensive LUT. For each of these canopy realizations a forest stand representation had to be constructed following the respective input parameters of the waveform model. The input model parameters were sampled randomly within defined ranges and following generally a uniform distribution (Table 2). The terrain was assumed to be flat since terrain variations were already taken into account before the waveform conversion.

The solution of the model inversion was found by minimizing the merit function  $\chi^2$ , defined as the distance between the reference waveform  $\omega_{ref}$  acquired by the LIDAR system and the simulated waveform  $\omega_{sim}$  found in the LUT. Simulated waveforms are normalized relative to their maximum peak for conformity with the measured signal.

$$\chi^2 = \sum_{i=1}^{n_{bin}} (\omega_{ref}^i - \omega_{sim}^i)^2 \quad (2)$$

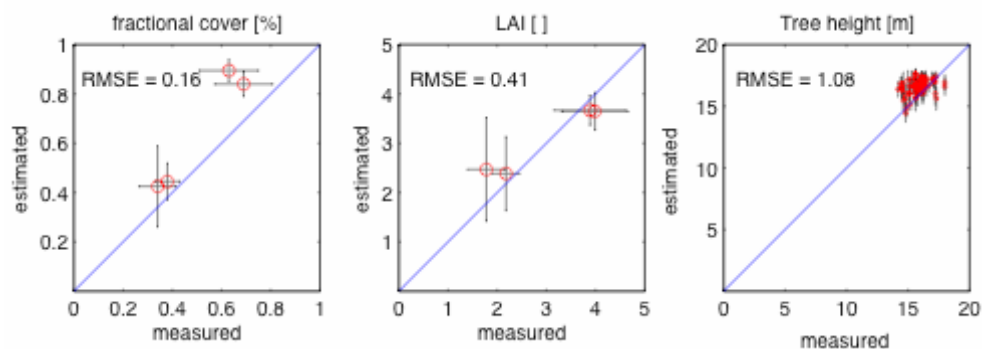
where  $n_{bin}$  is the number of bins of the digitized waveform. The first ten canopy realizations relative to the minimal calculated distance  $\chi^2$  were considered as possible solutions; their median defined the final solution and their standard deviation the uncertainty of the inversion.

**Table 2: Parameter ranges and distribution describing the generation of the LUT. Additional parameters were fixed to default or field measurement values: foliage reflectance ( $\lambda$ : 1560 NM): 0.215, background reflectance ( $\lambda$ : 1560 NM): 0.152, crown shape: hemi-ellipsoid, G-factor: 0.5 and Tree number: 60.**

Parameter	unit	Min	Max	Distribution
max. Tree height	m	8	18	uniform
Crown length	m	2	6	uniform
Crown width	m	1	5	weighted
LAI	[m <sup>2</sup> /m <sup>2</sup> ]	1	4	uniform
fcover <sup>a</sup>	%	0.09	0.95	uniform

a. No direct model input parameter but calculated for each canopy realization.

The feasibility of the proposed parameter estimation by inversion of a waveform model has been tested and validated on two different data sets (9). A synthetic data set showed first the general invertibility of the model and the parameter potentially deducible (not shown, refer to (9)). Furthermore a realistic data set acquired over the Swiss National Park assessed the actual retrieval performance of specific biophysical forest parameters (Figure 4).



**Figure 4: Performance of the model inversion for the SNP data set, error bars represent the uncertainties related to the field measurements and model inversion (9).**

## CONCEPT OF FUSION

As presented in the above sections both information dimensions provided by Imaging Spectrometry and LIDAR can be exploited by physically-based radiative transfer models independently. As stated in the introduction the independent exploitation of each data source separately can neither take into account the dependency of the LIDAR response on the spectral properties of canopy elements and background nor the uncertainties induced by the indirect relationship between canopy reflectance and foliage biochemistry. For an improved retrieval performance the two information dimension should thus be simultaneous and synergistically used. For this purpose the two different models describing the radiative transfer within the canopy, recorded by the respective instrument, need to be combined. As both RTM are based on the same basic physical concept and share common input parameters, an interface between the two models can be established (Figure 5). Common 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 simulated canopy (Figure 6). The spectral properties of the background are also identical for the parameterization of both models.

The interface between the two RTM allows the generation of a Look Up Table (LUT) consisting of the simulated combined signatures of the Imaging Spectrometer and LIDAR as a function of the

common forest stand parameterization. Simulations will have to cover the full range of structural as well as biochemical possible realizations of the parameter space of the two RTM. The retrieval of forest parameters will subsequently rely on the comparison of the simulated combined signature to the measurements of the Imaging Spectrometer and LIDAR sensor simultaneously. An appropriate LUT search algorithm has to be identified which is capable of exploiting the full information content of the two signatures.

Additional to the direct synergy of the two information dimension in the retrieval of forest parameters there are several other advantages of a combined use of Imaging Spectrometry and LIDAR. On the one hand a LIDAR derived digital surface or terrain model can improve the pre-processing of Imaging Spectrometer data resulting in higher geometric accuracy and improved correction of illumination effects. On the other hand aerosol optical thickness provided by the Imaging Spectroscopy could help to account for aerosol scattering processes affecting the LIDAR signal.

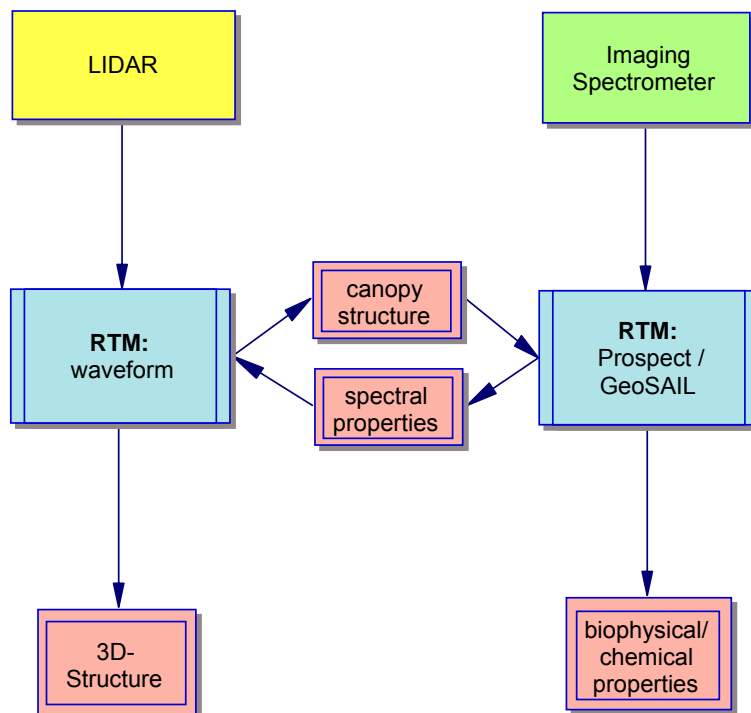


Figure 5: Concept of the combined retrieval of forest parameters by simultaneous RTM inversion.

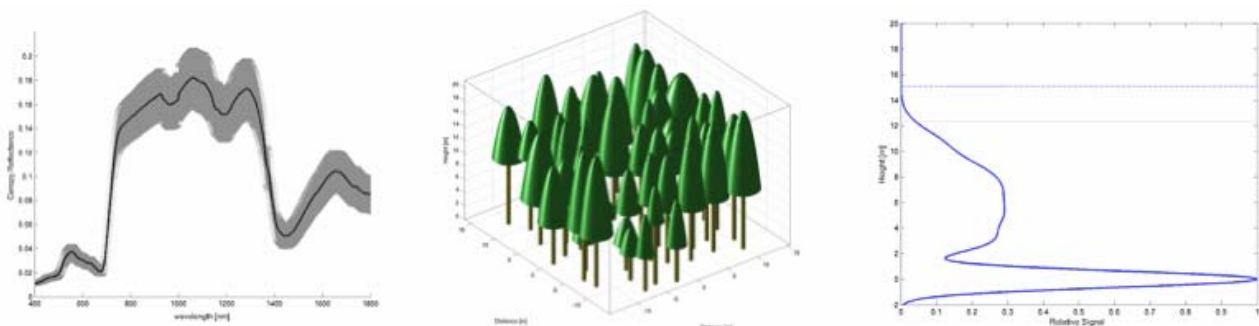


Figure 6: Combined signature for a common parameterization of a forest stand (middle), left the canopy reflectance spectrum and right the vertical signal of the LIDAR waveform.



## CONCLUSIONS AND OUTLOOK

The outlined concept of a combined inversion of two linked radiative transfer models for imaging spectrometer and LIDAR data will provide a comprehensive and quantitative characterization of a forest stand, including the foliage biochemical content as well as the horizontal and vertical canopy structure. As the approach relies on physically-based RTM the parameter retrieval will be robust over time and space accounting for changes in illumination, vegetation types and phenology. Ongoing research is focusing to test this concept on a synthetic but nevertheless realistic data set.

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