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Reflectance spectra of RAMI forest stands in Estonia: Simulations and measurements

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ABSTRACT

Simulated reflectance spectra of three mature hemiboreal forests are compared to top-of-canopy reflectance factor from helicopter measurements in the spectral range of 400–1050 nm. Most of the input parameters of the forest reflectance model FRT used in the simulations have been measured in situ. The same data were used in the fourth phase of the Radiation Transfer Model Intercomparison (RAMI). The reasons of the discrepancies between simulated and measured spectra are analyzed.

1. Introduction

Reflectance models are being used in forest remote sensing, e.g., (Chen et al., 2005; Lang et al., 2007; Li et al., 1995; Nilson & Peterson, 1994), etc. To some extent, their effective use has been hindered by difficulties in model validation. Typically many of the needed input parameters are not measured or are measured with poor precision, the measured stand reflectance data have large uncertainties or the uncertainties are unknown, etc. This leads to a situation where existing reflectance models are never (and possibly will never be) properly tested against the measured reflectances. One of the consequences is that the reflectance modelers have too little information to further develop their models. The radiative transfer community has initiated the extremely useful RAMI model intercomparison initiative (Pinty et al., 2004; Widlowski et al., 2007), which has already improved the quality of several models participating in the project. However, the final goal should be creating the reflectance models capable to adequately reproduce the real reflectance spectra and directional reflectance with measurable input data. Fifteen years have passed since the first extensive field experiment BOREAS (Gamon et al., 2004) which provided a useful data set for such model testing activity. New experiments of the same kind of quality to further proceed with the model validation and development have been scarce.

Recently, a new data set with a potential to be used in model validation purposes was created for a few hemiboreal forests in Järvselja, Estonia (Kuusk et al., 2009a,b). The data set includes detailed stand structure data, nadir reflectance spectra measured from a helicopter, multi-angular CHRIS PROBA spectral data reduced to the top-of-canopy hemispheric-directional reflectance, understorey reflectance spectra, as well as leaf and trunk bark reflectance spectra. The Järvselja database offers a comprehensive dataset for the reconstruction of both the spectral and structural properties of hemi-boreal forests. It was designed for the benchmarking of forest radiative transfer models in efforts similar to the RAdiative transfer Model Intercomparison (Widlowski et al., 2007). Two of these stands were used as the basis for defining test cases in the fourth phase of the Radiation Transfer Model Intercomparison (RAMI, 2009).

This paper presents results on comparison of simulated and measured canopy spectral reflectance in the interval between 400 nm and 1050 nm. Data from the three Järvselja forest stands are used as input parameters for model simulations with the hybrid geometrical optics and radiative transfer forest reflectance model FRT (Kuusk & Nilson, 2000). Model reflectance spectra are compared to the helicopter measurements of the visible-NIR nadir reflectance spectra of these three forests. An emphasis is given to understanding discrepancies between simulated and measured reflectance spectra. The paper contains information needed to understand radiative energy closure in the shortwave spectrum.

2. Data

The study site is located in South-East Estonia, 27.3°E, 58.3°N. Three 100 × 100 m sample plots — a 124 year old pine stand, a 59 year old spruce stand, and a 49 year old birch stand are described in the Järvselja data base (Kuusk et al., 2009a,b).

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2.1. Forest structure

Forest structure measurements described in (Kuusk et al., 2009a,b) were carried out in the summer of 2007. The summary of tree and stand parameters is given in Table 1. For the measured dimensions along with mean value the standard deviation of the measure is given in brackets. As the geometric–optics models cannot handle every tree separately, for model simulations the trees in a stand are grouped into n_{cl} classes of trees (Kuusk et al., 2009b).

The pine stand is very homogeneous; only 6 young birch trees exist within the regeneration layer, and no bushes. Forest understorey vegetation is composed of sparse labrador tea and cotton grass, and continuous sphagnum moss layer.

In the birch stand two layers of mature trees can be distinguished. Birch trees dominate but there is 30% of alder trees in the upper layer. In the second layer are numerous lime trees, about 20% of total number of trees. Also, there is a few aspen, maple, and ash trees in the stand. The understorey has rich grass cover and the regeneration layer has young limes and a few young spruces.

Two layers of tall trees with almost equal number of trees can be distinguished in the spruce stand. About 17% of trees are deciduous, mainly birches. Tree canopy is dense, therefore, there is almost no grass in the understorey, only moss.

Detailed stand structure data can be found in the Technical Report (Kuusk et al., 2009b).

2.2. Optical properties

The measurements of leaf, needle and stem bark reflectance spectra, leaf transmittance spectra, understorey reflectance spectra, and top-of-canopy reflectance spectra were carried out in the summers of 2007 and 2008. A custom-designed spectrometer UAVSpec was used for spectral measurements (Kuusk & Kuusk, 2010; Kuusk et al., 2009a; Kuusk et al., 2010). The spectrometer has 256 bands in the spectral range of 306–1140 nm with 10 nm spectral resolution.

Reflectance spectra of tree leaves/needles, stem and branch bark, and transmittance of tree leaves were measured with the UAVSpec, equipped with an integrating sphere. We did not measure biochemistry of leaves and needles. Instead, the PROSPECT leaf optics model (Jacquemoud & Baret, 1990) was fitted to the measured spectra of leaf/needle hemispherical reflectance factor (and transmittance). The PROSPECT model serves as a submodel of the forest reflectance model FRT.

Table 1
Stand descriptions.

Stand:	Birch	Pine	Spruce
Species:	*Betula pendula* and *Alnus glutinosa*	*Pinus sylvestris*	*Picea abies* and *Betula pendula*
N	990	1115	1436
H	22 (5.5)	16 (1.5)	19 (5.2)
DBH	18 (6.2)	18 (4.4)	17 (7.3)
L	8 (2.0)	4 (1.0)	8 (3.3)
R_{cr}	1.8 (0.46)	1.5 (0.47)	1.5 (0.46)
n_{cl}	7	2	9
LAI_{eff}	2.9 (0.35)	1.8 (0.15)	3.8 (0.62)
LAI_{all}	3.9	1.9	4.4
CrCl	1.1	0.8	1.3
$CaCl_C$	0.80	0.74	0.90
$CaCl_L$	0.85	0.74	0.92

N — number of trees.
H — mean tree height, m.
DBH — mean breast-height-diameter, cm.
L — mean depth of live crown, m.
R_{cr} — mean maximum radius of crown, m.
n_{cl} — the number of size&species classes.
LAI_{eff} — effective LAI (LAI-2000).
LAI_{all} — allometric LAI.
CrCl — crown cover.
$CaCl_C$ — canopy cover with Cajanus tube.
$CaCl_L$ — canopy cover from airborne lidar data.
In brackets is the standard deviation of a measure.

We had no tools to measure the reflectance and transmittance of a single conifer needle. Reflectance factor of a conifer shoot (a bunch of needles with the needles not detached from the shoot and laid densely side by side) was measured with an integrating sphere. Reflectance factor of a single needle was calculated using the layer model by Gausman et al. (1971) which relates reflectance factor of a layer to an infinitely thick stack of layers:

$$R_\infty = 1/a$$
$$a = (1 + r^2 - t^2 + \Delta)/2r \qquad (1)$$
$$\Delta^2 = (1 + r + t)(1 + r - t)(1 - r + t)(1 - t - r),$$

where R_∞ is the reflectance factor of the thick layer, r and t are the reflectance factor and transmittance of a single layer, respectively. Transmittance of a needle in 18 spectral bands from the RAMI website (RAMI, 2009) was used in Eq. (1). The reflectance factor reduced by Eq. (1) and the transmittance of spruce and pine needles in 18 Proba/CHRIS Mode 3 bands from the RAMI website (RAMI, 2009) was used for fitting the PROSPECT model.

The structure and optical properties of the ground vegetation leaves were not measured. We measured the reflectance spectra of understorey vegetation with 8° field-of-view from the height of about 1 m walking along nine nearly circular transects of 5 m radius in every stand. The two-layer homogeneous canopy reflectance model ACRM (Kuusk, 2001) was fitted to the measured spectra. The ACRM model serves as a submodel of the forest reflectance model FRT.

Stand spectral reflectance factor in nadir direction $\rho(\Omega,\lambda)$ was measured onboard a helicopter from the height of 80 m using a fore-optics of 2° field-of-view. Spectral total and diffuse irradiance was measured during helicopter measurements in a nearby clearing. The recorded nadir radiance in digital counts $n_\lambda(t)$ was compared to the radiance of a calibrated Spectralon panel measured in a nearby clearing at the test site just before the target measurements. This way the recorded signal was converted to the directional spectral reflectance factor of targets. To take into account the diurnal changes in illumination conditions, downward spectral flux density Q_λ was recorded during the measurements with a FieldSpec Pro VNIR spectroradiometer equipped with a cosine receptor:

$$\rho(\Omega,\lambda) = \frac{q_\lambda(t_0)}{n_\lambda(t_0)}\frac{n_\lambda(t)}{q_\lambda(t)} r_\lambda, \qquad (2)$$

where $q_\lambda(t)$ and $q_\lambda(t_0)$ are the signals of the FieldSpec spectrometer during target measurements and calibration, respectively, $n_\lambda(t)$ and $n_\lambda(t_0)$ are the signals of the UAVSpec spectrometer, and r_λ is the spectral reflectance factor of the reference panel.

All details of measurements and data processing are described in the Technical Report (Kuusk et al., 2009b).

3. Forest reflectance model FRT

Reflectance simulations were carried out with the forest reflectance model FRT (Kuusk & Nilson, 2000, 2009). The FRT model calculates the directional reflectance factor of a forest for a given solar direction in the wavelength range of 400–2400 nm. The model describes spectral radiances in a stand as a sum of the single scattering radiance of direct sun flux, and the radiance of the diffuse fluxes of multiple scattering and scattered diffuse sky flux (Fig. 1). The incident sky flux is supposed isotropic. Tree crown envelopes are modeled as ellipsoids or cones in the upper and as cylinders in the lower part. We did not measure the length of conical and cylindrical parts of spruce crowns separately. Instead, the length of the conical