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Measured spectral bidirectional reflection properties of three mature hemiboreal forests

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ABSTRACT

A combined spectrometer-BRF sensor was developed and built at Tartu Observatory, Estonia. The BRF sensor records angular distribution of target radiance with high angular resolution in red or near-infrared spectral band in a plain selected with sensor orientation up to 70° zenith angles. Bidirectional reflectance factor (BRF) measurements on board a low flying helicopter over three mature forest stands in South-East Estonia – a birch stand, a spruce stand, and a pine stand – are reported. Airborne measurements are supported by extensive ground truth data which have been reported in separate publications. The measurements revealed that both the BRF values and the BRF shape depend on the forest type and wavelength. The asymmetry of reflectance factor in the principal plane is strong and the hot-spot shape is very sharp in coniferous stands in the red spectral band. Multiple scattering of radiation in the NIR spectral band smooths the angular distribution of forest BRF. The collected data allow to validate forest radiative transfer models.

1. Introduction

Directional reflectance characteristics of forests can be described based on concepts of the bidirectional reflectance distribution function (BRDF) (Schaepman-Strub et al., 2006). Field measurements generally record the hemispherical–directional reflectance factor which is the ratio of the radiant flux reflected by a sample surface to the radiant flux reflected into the identical beam geometry by an ideal (lossless) and diffuse (Lambertian) standard surface, irradiated under the same conditions as the sample surface. However, when measuring radiation scattering in red or near-infrared (NIR) spectral domain, most of the incident flux is directional sun radiation, therefore, the measurements in such spectral bands are almost identical to the bidirectional reflectance factor (BRF).

Reflection properties of low vegetation (field crops, grasses) and soil can be measured from ground. An overview of ground-based measurements of BRDF of vegetation canopies is provided by Schönermark et al. (2004). Directional properties of forest reflectance are difficult to measure. Such data are rare, and as a rule, are not supported by detailed ground truth measurements.

Milton et al. (1994) describe early attempts to measure BRF of forests. The preliminary directional characteristics of forest reflectance were obtained through provisional airborne measurements using existing instruments for radiation measurements. Kriebel (1977, 1978) measured bidirectional reflection properties of four vegetated surfaces at seven visible and NIR wavelengths by means of an airborne scanning radiometer. Data were averaged over solid angle regions of 30° azimuth and 10° zenith angle. One of the targets was a coniferous forest.

Field measurements at finite angular intervals in azimuth and zenith or by integrating over solid angles of several degrees may conceal the true BRDF features which may fall into the gaps between observations or are lost in the averaging process. BRF profiles of high angular resolution in the solar principal plane of a few Estonian forests were measured by Kuusk et al. (1985) by manual scanning using a narrow field-of-view (FOV 20') four-band radiometer on-board a low flying airplane. Kuusk (1986) provides a full hemispherical distribution of BRF of a birch stand in red spectral band recoded on-board a low flying airplane using a photo-camera equipped with a fish-eye lens. The metrological accuracy of these measurements was rather low for several reasons discussed in the original publications. Nevertheless, such provisional measurements revealed the most informative areas of BRDF for further more detailed studies.

BRDF measurements of forests by Deering et al. (1999) at a BOREAS test site using the PARABOLA instrument (Deering and Leone, 1986) are supported by extensive ground truth data (Sellers et al., 1995). The PARABOLA instrument measured radiance for almost complete (4π) sky-and-ground-looking hemispheres in 15° instantaneous FOV sectors from a tram at the height about 13–15 m

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above the canopy. Airborne POLDER data at an altitude of 5500 m are also available for these stands (Leblanc et al., 1999).

There are two options for the measurement of forest BRF from an airborne carrier: using a down-looking imaging spectral sensor of wide field of view (FOV) which records the radiance of a forest stand at all view angles simultaneously (the fixed platform method), and using the goniometer principle where the sensor is pointed to a target from different directions (the fixed target method). The former method assumes the target is laterally homogeneous and the precision may be limited by the spatial variability of the target. The precision of the latter method may be limited by the pointing accuracy of the sensor.

For the study of forest reflectance a special combined airborne instrument – the spectrometer and BRF-sensor – UAVSpec was designed and built at Tartu Observatory by Kuusk (2011b). Angular distribution of hemispherical–directional reflectance of forests at Järvselja test-site in South-East Estonia was measured in flight campaigns in July–August of 2008–2011. In the BRF measurements using the UAVSpec instrument the two abovementioned principles are combined. The BRF-sensor of UAVSpec measures the angular distribution of reflectance along the flight path. The azimuth angle of the recorded BRF relative to the sun azimuth is determined by the flight direction. Spectral band is selected with a band-pass filter.

The BRF of the stands at Järvselja, Estonia which are described in the Järvselja data-base (Kuusk et al., 2009, 2013) has been measured several times at various azimuths. This data-base contains many optical and structural parameters of three 1 ha stands required for modeling radiative transfer in forest canopies. By comparing the modeled and measured BRF, forest radiative transfer models can be validated.

Knowledge of the angular distribution of forest reflectance is also necessary for the interpretation of off-nadir looking satellite images and for the estimation of albedo of forests using close to nadir reflectance data acquired with airborne or satellite sensors.

2. Materials and methods

2.1. Instrumentation

For the study of forest reflectance a series of special combined airborne instruments UAVSpec was designed and built at Tartu Observatory by Kuusk (2011b). The UAVSpec-series spectrometer system combines a spectrometer, a BRF-sensor, a GPS-receiver, a web camera, a position sensor, and a controlling computer. The instrument is lightweight and fully autonomous, it does not need any operator's intervention during the flight.

The BRF sensor is based on a 256-band Si linear sensor array. The array is connected via a preamplifier DZA-S3901-4 to a front-end-electronics (FEE) board FEE-HS, both have been manufactured by Tec5 AG. Low-level control of the BRF sensor is handled by a custom-designed controller electronics which controls the integration time of the sensor and functions as an interface between the controlling computer and the FEE. It also measures the temperature with two thermistors. One of them is placed under the sensor array, the other one is glued to the analog-to-digital converter integrated circuit on the FEE. With a wide-angle lens (DSL203 by Sunex Inc., FOV 140°), a transect along the flight path is projected through a band-pass filter onto the sensor. The cross-track FOV is limited to about 10° with a slit that is glued to the window of the sensor. The along-track FOV is 140°, instantaneous field-of-view (iFOV) of sensor array cells is 0.5–1° depending on the view polar angle (the angle between the view direction and the optical axis of the BRF-sensor), being smaller in the center of the linear sensor array. The spectral band is selected either by a red (660 nm, half width 11 nm) or NIR (850 nm, half width 25 nm) band-pass filter.

The GPS receiver Globalsat BU-353 (with SiRF Star III chipset) is used for the georeferencing. The 2D position error of the GPS-receiver is 10 m (Globalsat, 2007).

The nadir-looking web camera Philips SPC-900NC is used for the support of georeferencing and visual control of measurements.

The UAVSpec system includes a MTi-G attitude and heading reference system by XSens Technologies B.V. The MTi-G uses various sensors for determining attitude angles of the instrument. While the errors of roll and pitch values are estimated to be less than one degree, the heading measurements of MTi-G based on a magnetic sensor are unreliable and these have not been used during the data processing. Azimuth angles of the acquired BRFs were extracted from the GPS track instead and verified from the shadows visible in the web camera images. In measurements on-board a helicopter the azimuth accuracy is still rather low – the yaw angle of a helicopter is varying and may systematically deviate from the GPS track.

A PC/104-Plus single-board computer (SBC) Puma by VersaLogic Corporation Ltd. is used as the high-level controlling computer. It is running with a Linux operating system. The signal from the whole linear sensor array is sampled at the rate of 8 s^{-1} (red filter) or 16 s^{-1} (NIR filter). The position (x, y and z coordinates) and the webcam image are recorded at the rate of 1 s^{-1}, attitude of the instrument at the rate of 10 s^{-1}. The software and acquired data are stored on a Compact Flash card.

For the measurements of incident spectral radiation the HR-1024 VIS-NIR spectrometer by Spectra Vista Corporation equipped with a cosine receptor RCR/A124505 by Analytical Spectral Devices, Inc. was used. Diffuse sky radiation was measured by obscuring the direct irradiance with a disk (Yanishevsky, 1957).

2.2. Measurements

The UAVSpec instrument was mounted to the chassis of a Robinson R22 helicopter so that the long axis of the sensor's footprint was parallel to the flight direction and field of view was almost symmetrical in forward and backward directions. Average flight altitude was 80–100 m above ground level, flight speed 60 km h^{-1}.

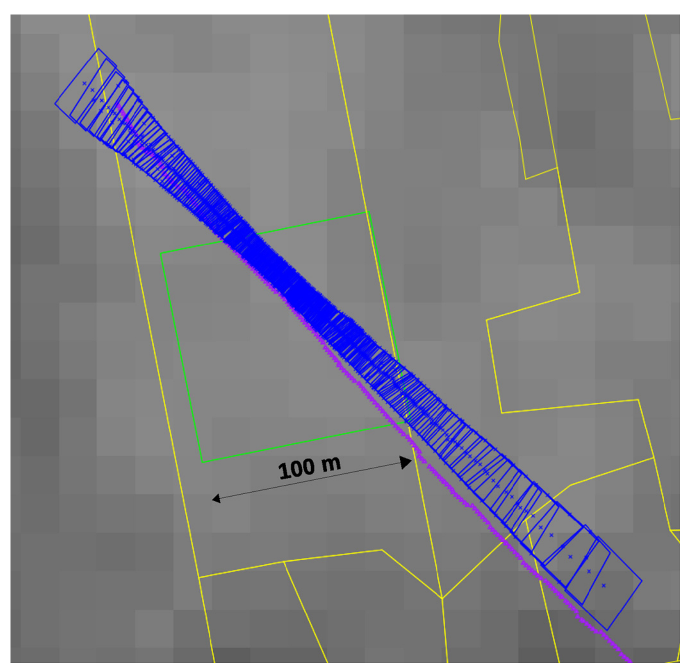

Fig. 1. A sample footprint of the BRF sensor (blue). The green square is the boundary of the birch stand in the Järvselja data-base (Kuusk et al., 2013), yellow lines are stand boundaries, and red dots are the positions of helicopter during BRF sampling. The background is a nadir-looking NIR CHRIS image (Barnsley et al., 2004) of 5 July 2010.