Influence of Vegetation Canopy Heterogeneity on the Interpretation of Remotely Sensed Reflectance Measurements

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Abstract – A ground-based experiment to analyze influence of canopy heterogeneity on the estimation of the canopy bi-hemispherical-directional reflectance from data sampled by a single-angle sensor is presented. The approach is based on comparing both the three-dimensional field of the upward radiation and the sensor response to this field. The simulation results are compared with measurements in the field.

I. INTRODUCTION

Land surface processes are important components of the terrestrial climate system. Accurate descriptions of the interaction between the surface and the atmosphere require reliable quantitative information on the fluxes, mass, and momentum, especially over terrestrial areas, where they are closely associated with the rates of evapotranspiration and photosynthesis. Many of these processes can be related to the spectral reflectance of the surface [1]-[3]. The vegetation canopy is classified as a special type of surface not only due to its role in the energy balance but also due to its impact on the global carbon cycle [4], [5]. Its reflection results from biophysiological, chemical and physical processes, and is characterized by spatial, seasonal and diurnal variations. Specification of the canopy reflectance, therefore, is also used to quantify the forest functioning in models e.g. on tree competition for light [6], [7], on sustainable forest management [8], on bio-physiological processes of trees and tree growth [9], [10]. Reflectance measurements, which can be acquired through remote sensing, are therefore particularly useful to describe and predict these surface-atmosphere interactions.

The bi-Hemispherical-directional Reflectance (BHR) of vegetation canopy at a given spectral band is the ratio of the mean canopy-leaving irradiance to the irradiance incident on the canopy. In order to evaluate BHR, a fraction of upward radiance which is transferred from pixels to a satellite sensor is measured. If the influence of the atmosphere is accounted correctly, the ratio of the surface irradiance sampled by the sensor from different pixels over a sensed area to that incident on the surface is usually assigned to the BHR. Angular signatures of pixels can be characterized by large spatial and temporal variations. Even in the case when the single-angle radiance is of a wide field of view, with minimal atmospheric effect, it is not clear that the sensor registers a reflected radiation representative of the whole upward radiation field from the sensed
area. The goal of the present paper is to demonstrate and quantify the effect of forest heterogeneity on the estimation of the BHR at the photosynthetically active region of the solar spectrum (400nm-700nm) from data sampled by a single-angle sensor. Our approach is based on comparing both the three-dimensional field of the upward Photosynthetically Active Radiation (PAR) and the sensor response to this field. The simulation results are compared with measurements in the field.

II. MATERIALS AND METHOD

A coniferous (Picea abies (L.) Karst) tree stand in Solling, ca. 50 km North-West of Göttingen, FRG, was chosen for simulation and measurements („F1 Fläche“, 52.77°N, 9.58°E). This forest is at present about 110 years old. A site covering an area of 25x30 m² was selected for our investigation. There were 35 trees in the base plot (corresponding to a tree density of 467 trees per hectare). The trees are, on average, 29m in height with a crown height of about 11m. Tree locations were mapped, and total height, height to crown base and crown widths were measured on all trees. The projections of the tree crowns are shown in Fig. 1. Since 1990, the upward and downward PAR fluxes have been continuously registered at a height of 39 m above ground (10m above the forest) by LICOR quantum sensors mounted on a 50 m tall tower in this base plot (Fig. 1). These sensors measure the quanta between 400 and 700 nm (in µE m⁻² s⁻¹) which were cabled to a multi-port data recorder programmed to sample each sensor 6 time a minute for 60 min. The mean and standard deviation of these 360 measurements were then recorded on a computer. These data are the subject of our analysis.

The monochromatic steady-state transport equation [11] was used to simulate the three-dimensional distribution of PAR in this base plot at a given instant of time. The radiation field is defined as the solution of this equation. A computational technique developed in reactor physics for the numerical solution of the transport equation [12]–[14] was applied to numerically solve the transport equation. A parallelepiped of dimension 25m by 30m by 29m with trees was simulated to describe the interaction of solar radiation with the forest canopy elements. Within this space, we utilised 174000 cells of 50cm by 50cm by 50cm as the basic spatial resolution. At a given instant of time, the spectral distribution of PAR intensity with wavelength band width of 15 nm was evaluated with the radiation model [15] in 80 directions distributed over the unit sphere according to the Carlson quadrature rule [16] in each cell. The simulated radiation field at the top of the canopy represent all possible features of the directional and spectral distributions of the upward solar radiation field above the forest canopy [17]. A response of the hemispherical sensor to the simulated radiation field was then quantified.

In the application of transport theory, three important input variables must be quantified [11]. They are, the architecture of an individual tree and the canopy, optical properties of the vegetation elements (leaves, stem, etc.) which depend on physiological conditions (water status, pigment concentration, etc.) and of the soil, and atmospheric conditions which determine the input radiation field at the canopy boundaries. Special sub-models for simulating these input variables were incorporated in the canopy-radiation model which were parameterized in terms of tree-trunk coordinates, tree and crown heights, crown projections, spectral transmittance and reflectance of one-year shoots, soil spectral reflectance and the diffuse and global short-wave radiation, and global PAR incident at the forest canopy [15]. All these parameters were measured
for the base plot. The full model of the three-dimensional radiation regime provided good agreement when compared with radiation measurements from the base plot [15].

III. SENSOR RESPONSE AND THE BHR: THEORY

Consider a horizontal plane above the base plot. We use a Cartesian coordinate system, with origin \( O=(0,0,0) \) on this horizontal plane, with the \( Z \) axis directed upwards (Fig. 2), i.e. the position of a space point \( r \) denotes the triplet \((x,y,z)\). The direction \( \Omega=(\mu,\phi) \), \(-1\leq \mu \leq 1, 0 \leq \phi \leq 2\pi, \) is expressed in spherical coordinates and has an azimuth \( \phi \) measured in the horizontal plane from the positive \( X \) axis in a counterclockwise fashion, and a polar angle \( \theta=\cos^{-1}(\mu) \) with respect to the polar axis that coincides with the \( Z \) axis. Let \( J(r,\Omega) \) be the intensity of the upward PAR at a point \( r=(x,y,0) \) on the top boundary of the base plot in the upward direction \( \Omega \) (i.e. \( \mu>0 \)). It depends both on the points of the horizontal plane and on the upward directions. These spatial and directional dependencies result from interaction between PAR and the base plot, and thus include the complex influence of the forest structure on the canopy-leaving radiation field.

Now, consider a hemispherical sensor located at a height \( h \) relative to the horizontal plane (Fig. 2) which registers the upward radiant flux into the atmosphere. We denote by \( r_S=(x_S,y_S,h) \) and \( J_S(\Omega) \) the sensor spatial coordinates and the intensity of the PAR radiance at \( r_S \) in the upward direction \( \Omega \sim (\mu,\phi) \), \( \mu>0 \). Here we examine the sensor response on a clear sunny day. The downward PAR flux from the atmosphere to the sensor can be assumed to be horizontally homogeneous. Therefore, its value \( E^\downarrow \) (in \( \mu E \text{ m}^{-2} \text{ s}^{-1} \)), at any space point above the forest is identical to the mean downward radiant flux incident on the forest. This variable is available from measurements made continuously at the base plot.

The upward PAR flux reflected by the canopy and captured by the sensor can be expressed as

\[
E_S = \int_{2\pi} J_S(\Omega) \cdot h \cdot d\Omega = \int_0^{2\pi} d\phi \int_0^1 J_S(\Omega) \mu d\mu . \tag{1}
\]

The ratio \( A_S \) of the flux \( E_S \) to the incident flux \( E^\downarrow \) is termed the effective BHR, i.e.

\[
A_S = 100 \% \cdot E_S/E^\downarrow . \tag{2}
\]

The mean amount \( E_F(S_0) \) of PAR reflected by a horizontal surface \( S_0 \) of area \( |S_0| \) belonging to a horizontal surface \( z=0 \) is

\[
E_F(S_0) = \frac{1}{|S_0|} \int_0^{2\pi} d\phi \int_0^1 \mu d\mu \int dx dy J(r,\Omega) . \tag{3}
\]

The BHR \( A_F \) can be written as

\[
A_F = 100\% \cdot \lim_{S_0 \to \infty} E_F(S_0)/E^\downarrow . \tag{4}
\]
If $S_0$ is a representative area for the whole stand, then the sign „lim“ in Eq. (4) can be omitted. Our aim is to evaluate the BHR and the effective BHR in order to estimate their difference.

The intensity $J_S(\Omega)$ of PAR at $r_S$ in an upward direction can be expressed via the intensity of upward PAR at a point $r_t=(x_t,y_t,0)$ on the $XY$ plane as (Fig. 2):

$$J_S(\Omega) = J(r, \mu, \phi),$$

where $r_t=r_S-l[r_S,\Omega]$, $l[r_S,\Omega]$ denotes the distance between the point $r_S$ and the horizontal plane $z=0$ along the direction $-\Omega$. Points on the horizontal plane can also be expressed in terms of polar coordinates with the pole at $O_S=(x_S,y_S,0)$, and with polar axes parallel to $OX$ (Fig. 2). Let $\rho_t$ and $\phi_t$ be the polar coordinates of $r_t$. The azimuth, $\phi$, and the polar angle $\theta=\cos^{-1} \mu$ of the direction $\Omega$ are

$$\mu = \cos \theta = \frac{h}{\sqrt{h^2 + \rho_t^2}}, \quad \phi_t = \pi + \phi.$$

Substituting these equations into Eqs. (1) and (3) one obtains:

$$E_S = \int_0^{2\pi} \int_0^\infty \frac{h^2 \rho_t}{(h^2 + \rho_t^2)^2} J(O_S + \rho, \Omega; \mu, \phi) d\phi_t d\rho_t, \quad (4)$$

$$E_F(S_0) = \int_0^{2\pi} \int_0^\infty \frac{h^2 \rho_t}{(h^2 + \rho_t^2)^2} \left[ \frac{1}{\text{mes}(S_0)} \int J(O_S + r; \mu, \phi) dx \right] d\phi_t d\rho_t, \quad (5)$$

where $\Omega=(\cos \phi, \sin \phi, 0)$ is a unit direction at point $r_t$ (Fig. 2).

Equation (4) depends on the spatial point $O_S$ on the horizontal plane. Its horizontal coordinates are the $XY$ coordinates of the sensor. Equation (5) is independent of this point because the integration in the square brackets is performed over all points on the surface $S_0$. Averaging Eq. (4) over points $O_S$ and accounting for Eqs. (2) and (4), one gets the following relationship between the effective BHR and the BHR

$$\lim_{S_0 \to \infty} \frac{1}{S_0} \int_{S_0} A_S dO_S = A_F.$$

Thus, the BHR is equal to the mean effective BHR which results from averaging the responses of „a large number of sensors“ located at several points on the horizontal plane $z=h$. If a forest stand can be idealised as a horizontally homogeneous medium, i.e., $J(r,\Omega)$ does not depend on points $r_t$ of the horizontal plane, then, it follows from Eqs. (4) and (5), that the effective BHR coincides with the true BHR. In reality, however, such an idealisation is usually unrealistic. To demonstrate this we evaluate the effective and true BHR (Eqs. 4-5) with the three-
IV. SENSOR RESPONSE AND THE BHR: EXPERIMENT

The sample stand described in section 2 and plotted in Fig. 1 was chosen to compare the simulation results with field measurements. Two PAR sensors were mounted 10m ($h=10$ m) above the forest in order to measure the incident ($E^↓$ in $\mu E \ m^{-2} \ s^{-1}$) and reflected ($E_{SM}$ in $\mu E \ m^{-2} \ s^{-1}$) PAR. The horizontal plane $z=0$ is at height 29m relative to the soil, which coincides with the maximum tree height. A clear sunny day (14.10.94) was chosen to carry out these measurements. The dimension of the base plot was 25m by 30m. Its center coincided with horizontal coordinates of the sensor location. According to our estimations [15], this sample plot could be taken as representative of the whole stand. The area of the sample stand therefore was also taken as the surface $S_0$ for which the BHR was evaluated [see Eqs. (3) and (5)]. The sensor response $E_S$ [see Eq. (4)] can be represented by the sum of two components, viz.

$$
E_S = \int_{0}^{\rho_0} \int_{0}^{2\pi} \frac{h^2 \rho_1}{(h^2 + \rho_1^2)^2} J(O_S + \rho_1 \Omega_1; \mu, \phi) d\rho_1 d\phi_1 +
$$

$$
+ \int_{\rho_0}^{\infty} \int_{0}^{2\pi} \frac{h^2 \rho_1}{(h^2 + \rho_1^2)^2} J(O_S + \rho_1 \Omega_1; \mu, \phi) d\rho_1 d\phi_1 = E_{S,0}(\rho_0) + E_{S,\infty}(\rho_0).
$$

The first component, $E_{S,0}(\rho_0)$, is the irradiance of PAR field transferred to the sensor at angles between 0 and

$$
\theta_0 = \cos^{-1}\left(\frac{h}{\sqrt{h^2 + \rho_0^2}}\right)
$$

to the upward normal of the sensor surface, and the second is the PAR energy reaching the sensor from other directions. The hemispherical sensor [18] provides the best cosine correction for photons incident at angles between 0 and about 63°. In the interval between 63° and 80° the error for this sensor is about $\pm 5\%$ [18]. If $\rho_0=19.5$ m then, it follows from Eq. (7), $\theta_0=63°$. The component $E_{S,0}(\rho_0)$ in Eq. (6) accounts for the PAR reaching the sensor from the surface $S_0$ in this case. The second component, $E_{S,\infty}(\rho_0)$, describes the rest captured by the sensor.

The intensity $J(O_S + \rho_{1} \Omega_1; \mu, \phi)$ in $E_{S,\infty}(\rho_0)$ is replaced by the mean intensity $J_M$ of PAR radiance reflected by the surface $S_0$ and captured by the sensor, i.e. $\pi J_M = E_{S,0}(\rho_0)$. Substituting $J_M$ in $E_{S,\infty}(\rho_0)$, we approximate $E_S$ by

$$
E_S \approx E_{S,0}(\rho_0) + \pi J_M \frac{h^2}{h^2 + \rho_0^2}.
$$
This equation was used to simulate the sensor response. The intensities \( J(r, \Omega) \) at points \( r = O_S + \rho_t \Omega_t \) (cf. Eq. 6) on the horizontal plane as well as \( J_M \) were evaluated from the three-dimensional canopy radiation model.

Fig. 3 demonstrates the daily variation of the effective BHR derived from measurements \( (A_{SM}(T)\text{=}100\% \cdot E_{SM}/E_\downarrow) \) and from simulations \( (A_S(T)\text{=}100\% \cdot E_S/E_\downarrow) \). The daily variation of the true BHR \( A_F(S_0,T)\text{=}100\% \cdot E_F(S_0)/E_\downarrow \), is plotted in this figure also. The daily difference, \( \delta(A_S,A_F) \), between the simulated effective BHR [i.e. derived from Eq. (8)] and the true BHR, defined as

\[
\delta(A_S,A_F) = 100\% \times \frac{\int_{T_1}^{T_2} |A_S(T) - A_F(S_0,T)| dT}{\int_{T_1}^{T_2} A_S(T) dT}
\]

is about 45%. Here \( T_1 \) and \( T_2 \) are the times of sunrise and sunset respectively. Similar daily variations were observed for other available sunny days [19]. The daily means of the simulated effective BHR and the BHR are 3.1% and 4.5% respectively. Their difference makes up \( 100\% \times (4.5-3.1)/3.1=45\% \). Evaluation of the BHR by the daily mean response of one fixed sensor above the forest stand does not average the forest heterogeneity.

The daily difference \( \delta(A_{SM},A_S) \) between the measured and simulated effective BHR’s, as was derived from Eq. (9), is 25%. The same difference evaluated from Eq. (9) for \( T_1=9:30 \) and \( T_2=14:30 \) only is 6%. The daily difference therefore is mainly caused by inaccuracies in the evaluation of exitances during the early morning and the late evening hours. We think that the model evaluates the upward PAR field reaching the sensor during these hours more accurately than an actual sensor measurement. This hypothesis is based on the following argumentations. A sensor can only register the radiant energy which exceeds a threshold value \( \epsilon \) of sensor sensitivity, i.e., when \( E_{S,\infty}(\rho_0) = \pi J_M h^2/(h^2+\rho_0^2) > \epsilon \). It follows from this inequality that decreasing \( J_M \) results in decreasing the angle \( \theta_0 \) defined by Eq. (7). Because the incoming PAR radiance is rather weak during the early morning and the late evening hours, the mean intensity of reflected PAR radiance \( J_M \) is small and, as a consequence, the sensor can only measure the radiance reaching the sensor from a rather small solid angle about the upward normal to the sensor surface. As a result, a fraction of the reflected PAR radiance is not registered by the sensor. Note at a low solar elevation, the direction of reflected PAR radiation caused by the hot spot is also low. Because the intensity of radiation decreases with the square of the distance [Eq. (4)], this energy therefore may not be registered by the sensor in spite of the fact that the intensity of reflected radiation reaches its maximum value about hot spot directions [20]. Clearly these argumentations do not prove our hypothesis about the sensor response during the early morning and the late evening hours precisely. However, the problem of accurately the BHR needs special attention.
V. CONCLUSIONS

The directional distribution of canopy-leaving PAR field is characterized by large spatial variation. The three-dimensional structure of the vegetation canopy is the cause of this heterogeneity. The mean upward radiation flux therefore results from averaging this heterogeneous radiation field over spatial and angular variables. The single angle sensor can record only that fraction of this field which is transported from pixels in the direction to sensor. This fraction may not represent the whole upward radiation field. Therefore, the mean radiation flux cannot be derived from data sampled by this sensor. Daily mean response of one fixed sensor does not average the effect of the canopy heterogeneity. A special arrangement of several single angle sensors, or the use of special weights accounting for the heterogeneity effect [21], or the use of multi-angle sensors, e.g., POLDER (Polarization and Directionality of the Earth’s Reflectance, [22]) and MISR (Multi-angle Imaging SpectroRadiometer, [23], [24]), are needed to correctly derive the BHR. It follows from this, as well as from Eqs. (4) and (5), that the use of one-dimensional canopy radiation models can cause an essential misinterpretation of canopy reflectances. Indeed, such models are usually designed to evaluate mean angular signature of heterogeneous canopies. Because the single-angle sensor registers only part of the canopy-leaving radiation, i.e., a somewhat different radiation field, simulated and measured reflectances may not be incomparable. For example, a location of a PAR sensor (selected randomly) above a coniferous forest stand at the scientific research station “Solling”, near Göttingen (FRG), leads to an underestimation of the reflected PAR energy by 45%. This finding suggests that the radiation balance over the entire short and long wavelength interval may be overestimated. This is often observed in field measurements [25]. An analysis of about 40 field experiments presented in [26] showed that the turbulent fluxes of the sensible and latent heat and the fluxes of the short wave and thermal radiation were only balanced within the range of 80-100%. The forest heterogeneity in short wave radiation measurements was not taken into account in all these experiments.

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Figure 1. Spatial distribution of crown projections in the base plot. The coordinate system is aligned such that the angle between the positive X axis and the direction to north is 75°. Tree stems are numbered. The location of the 50m tall tower is shown as shaded square. The path of a moving LICOR sensor at the canopy bottom is marked as a shaded elongated rectangle. This moving sensor was used to test our three-dimensional canopy radiation model [15]. The cross symbols denote the vertices of 10x10m grids.
Figure 2. Solar energy intercepted by the downward looking sensor. Here, $r_s$; the point of sensor location; $n$ is upward normal to the sensor surface; $\Omega$ is a direction of radiance captured by the sensor; $\theta = \cos^{-1}\mu$ is the angle between the direction $\Omega$ and the normal $n$; $l[r_s, \Omega]$ is the distance between the sensor and the top canopy boundary along the direction $-\Omega$; $r_t = r_s - l[r_s, \Omega] \Omega$ is a point of the top canopy boundary; $O_s$ is the projection of the point $r_s$ onto the top canopy boundary. Points of the top canopy boundary are expressed in polar coordinates, $\rho_t$ and $\phi_t$, with its pole at the point $O_s$ and polar axes $O_sX_s$ parallel to $OX$; $\Omega_t$ is a unit vector at the point $O_s$ directed to $r_t$. 
**Figure 3.** Daily variation of the effective BHR obtained by measurements (○) and model calculations (×). The curve * corresponds to daily variation of the BHR derived from model calculations.
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