UNIVERSITAT JAUME·I

Título artículo / Títol article:	On Hyperspectral Remote Sensing of Leaf Biophysical Constituents: Decoupling Vegetation Structure and Leaf Optics Using CHRIS–PROBA Data Over Crops in Barrax
Autores / Autors	Pedro Latorre Carmona, Yuri Knyazikhin, Luis Alonso, Jose F. Moreno, Filiberto Pla, Yang Yan
Revista:	Geoscience and Remote Sensing Letters, IEEE, 2014, vol. 11, nº 9
Versión / Versió:	Post-print autor
Cita bibliográfica / Cita bibliogràfica (ISO 690):	LATORRE-CARMONA, Pedro, et al. On Hyperspectral Remote Sensing of Leaf Biophysical Constituents: Decoupling Vegetation Structure and Leaf Optics Using CHRIS–PROBA Data Over Crops in Barrax. Geoscience and Remote Sensing Letters, IEEE, 2014, vol. 11, no 9, p. 1579-1583.
url Repositori UJI:	http://hdl.handle.net/10234/127465

On Hyperspectral Remote Sensing of Leaf Biophysical Constituents: Decoupling Vegetation Structure and Leaf Optics Using CHRIS-PROBA Data Over Crops in Barrax

Pedro Latorre Carmona, Yuri Knyazikhin, Luis Alonso, Jose F. Moreno, Filiberto Pla, Yang Yan

Abstract— **Scattering from a leaf responds differently at different wavelengths to changes in leaf properties such as pigment concentrations, chemical constituents, internal structure and leaf surface properties. Radiation scattered by leaves and exiting the vegetation canopy toward the sensor is affected by canopy structure. The concept of canopy spectral invariants is used to decompose multi-angular hyperspectral CHRIS-PROBA surface reflectances over agricultural crops during peak growth season into structural and optical components. The former called the Directional Area Scattering Factor is determined by the canopy geometrical properties and varies with crop type. The latter is a function of the leaf scattering properties and more directly related to the leaf interior. For dense crops the decomposition technique does not require the use of canopy radiation models, prior knowledge, or ancillary information regarding the leaf scattering properties and thus provides a powerful means to remove canopy structural influences in hyperspectral remote sensing of leaf biochemical constituents. Our results also suggest that leaf-surface characteristics can increase canopy scattering spectra. This may decrease the ability to remotely sense leaf biochemistry.**

Index Terms— **hyperspectral remote sensing; leaf optics; canopy structure, leaf biochemical constituents, spectral invariants.**

I. INTRODUCTION

D ETECTION of early signs of ecosystem changes through altered physiology, including agricultural systems, has long been among one of the main objectives for hyperspectral remote sensing [1, 2]. Most of existing methods to relate canopy reflectance and leaf biochemical constituents use statistical approaches. Their largest weakness is the lack of causal mechanisms that relate satellite data and leaf biochemistry: statistical relationships although significant can be spurious [3,4]. This can lead to misinterpretation of satellite data [4]. Radiative transfer based approaches provide physically consistent linkage between biophysical parameters and canopy reflectance, and can naturally distinguish causality from correlation. Their development is required to take full advantage of available and future satellite data.

Remote sensing of leaf biochemistry is based on the fact that the spectral distribution of radiation scattered by a leaf is governed by the leaf properties such as pigment concentrations, chemical constituents, internal structure, and leaf surface characteristics. The leaf scattering spectrum therefore is the only optical variable that conveys information about leaf biochemistry. It however cannot be directly measured from space because the radiation scattered by leaves and exiting the vegetation is strongly affected by the 3D canopy structure. Reflectance data should be corrected for canopy structure effects to extract information about leaf properties. A new structural variable, the Directional Area Scattering Factor (DASF), as a means to achieve this correction has recently been identified and its critical role in decoupling the contribution from canopy structure and leaf optics has been demonstrated over a wide range of forests [4]. Accurate analyses of how radiation interacts with foliage and traverses in the 3D vegetation canopy underlay this result. Our goal is to demonstrate the applicability of this radiative transfer based approach to agricultural systems. We focus on data acquired over dense crops. This represents the most complicated case in remote sensing because reflectances are saturated and thus insensitive to various structural parameters such as Leaf Area Index (LAI), plant density, height, etc. Small changes in canopy structure, e.g., LAI, however can alter how canopy reflectance responds to changes in leaf optical properties [5]. This indirect effect makes retrieval of leaf properties a challenging task.

The paper is organized as follows. A description of study area and database are given in Sect. II. The decomposition technique exploits similar spectrally invariant behavior of the scattering process at the leaf and canopy scales, which are discussed in Sect. III. Decoupling contributions from canopy

P. Latorre Carmona and Filiberto Pla are with the Departamento de Lenguajes y Sistemas Informáticos, Universidad Jaume I, 12071, Castellón de la Plana, Spain (e-mail: latorre@uji.es, pla@uji.es).

Y. Knyazikhin and Yang Yan are with the Department of Earth and Environment, Boston University, Boston, MA 02215 USA (phone: 617-353-8843; fax: 617-353-8399; e-mail: jknjazi@bu.edu, yangyannn@gmail.com).

L. Alonso and J. Moreno are with the Departamento de Física de la Tierra y Termodinámica, Universidad de Valencia (e-mail: luis.alonso@uv.es, jose.moreno@uv.es).

structure and leaf optics is outlined in Sect. IV. Some radiation is scattered at the surface of leaves, and, therefore, contains no information on leaf biochemistry. This decreases the ability to remotely sense leaf biochemistry. Equations that account for this additional confounding factor are included in this section. Finally, results and conclusions are presented in Sects. V -VI.

II. STUDY AREA AND DATA USED

Data used in our research were acquired during the international Spectra Barrax Campaign (SPARC) in Barrax, Spain, July 14-17, 2004 with the objective of collecting data needed for validation of satellite based and ground measurement systems and technologies [6].

The SPARC dataset includes spectra of Conical Reflectance (HCRF) and Transmittance (HCTF) Factors (as defined in [7]) of abaxial and adaxial sides of corn, sugar beet and potato leaves in the spectral interval between 350 and 2500 nm at 1 nm spectral resolution. Leaf optical properties were measured under laboratory conditions using an Analytical Spectral Devices (ASD) FieldSpec Pro(FSFR) spectroradiometer with a field of view (FOV) of 25°. The ASD FSFR was positioned so that entrance aperture was perpendicular to the leaf surface [6].

Five spectral images of the Barrax site were acquired by the Compact High Resolution Imaging Spectroradiometer (CHRIS) on the PROBA platform on July-16, 2004. The CHRIS instrument was configured in Mode 1 to register radiance in 62 spectral bands, from 400 nm to 1050 nm, along track zenith angles of $\pm 55^o, \pm 36^o$ and 0° at a spatial resolution of 36 m [8]. Actual view zenith angles (azimuths) from -55° to $+55^o$ were 56.79^o (198.39^o), 37.32^o (202.43^o), 8.8^o (224.28^o), 31.64^o (0.23^o) and 53.22^o (6.91^o), respectively. The solar zenith angle and azimuth were 20.81^o and 145.5^o. Spectra of the Bidirectional Reflectance Factor (BRF) at a spatial resolution of 36 m were derived from these images after removal of instrumental and atmospheric perturbations [9]. We excluded noisy data below 450 nm and focus on the 450 to 855 nm spectral interval.

In our analyses we will also use mean BRF (MBRF) over view directions weighted by $\cos(VZA_k)/\sum_{k=1}^{5}\cos(VZA_k)$ where VZA_k represent view zenith angles. The MBRF is an accurate estimate of the Directional Hemispherical Reflectance if variation in BRF with azimuth can be neglected. The Normalized Difference Vegetation Index (NDVI) is defined here as the difference between mean BRF at 804 nm and 683 nm normalized by their sum.

Four patches of alfalfa, corn, potato and sugar beet were selected. The patch sizes of 180x216m (5x6 CHRIS pixels) coincide with the maximal area of the potato field. We used the mean spectral BRF to characterize the reflectance of a patch. Ground measurements of leaf area index (LAI) and fractional ground cover on the patches were made within 3 days of CHRIS data acquisition using LI-COR LAI 2000 instrument and hemispherical photos [6]. Fractional ground covers were 0.83 (alfalfa); 0.85 (corn); 0.86 (potato) and 0.94 (sugar beet). The corresponding LAIs were estimated as 3.73±0.12 (alfalfa), 2.57±0.10 (corn), 3.99±0.24 (potato) and

4.48±0.21 (sugar beet). The selected patches represent sufficiently dense canopies. Our analyses of variation of NDVI (mean =0.82 std=0.03) as well as BRF over dense crops with wet and dry soils suggested negligible impact of canopy background on reflectance. This condition facilitates the retrieval of DASF from hyperspectral data.

We used the Relative Root Mean Square Error (RRMSE) to quantify the proximity between observed, **X**, and estimated, **Y**, vectors, $RRMSE[\mathbf{X},\mathbf{Y}] = \sqrt{M^{-1}\sum_{\lambda=1}^{M}(x_\lambda - y_\lambda)^2 y_\lambda^{-2}}$ where x_λ, y_λ and M represent components of **X** and **Y**, and their lengths.

III. LEAF AND CANOPY SCATTERING

A. Leaf Scattering: observations

The sum of measured HCRF and HCTF describes the fraction of the incident diffuse radiation that have been reflected from, or transmitted through, the leaf within a solid angle corresponding to a FOV=25^0 around the nadir and zenith directions. We term this variable a hemispherical conical leaf scattering albedo (HCSA).

Let symbol h_λ represents measured HCSA spectrum of either abaxial, or adaxial sides of corn and sugar beet leaves, or their mean over the sides. We denote mean HCSA spectrum over abaxial and adaxial sides of the potato leaf by $h_{\lambda,p}$. Fig. 1 illustrates linear relationships between the ratio $h_\lambda/h_{\lambda,p}$ of two HCSA spectra and h_λ for the 710 to 790 nm spectral interval. All measured HCSAs in this spectral interval therefore can be expressed via one HCSA spectrum of potato, $h_{\lambda,p}$ as

$$h_\lambda = h_{\lambda,p} \frac{b}{1-kh_{\lambda,p}}, \qquad (1)$$

where k and b are the spectrally invariant slope and intercept of the $h_\lambda/h_{\lambda,p}$ vs. h_λ linear relationship (Fig. 1). We found that the use of any measured spectrum in place of $h_{\lambda,p}$ led to Eq. (1). From a mathematical standpoint, this is a consequence of the validity of Eq. (1). Thus our analyses illustrate that in the 710 to 790 nm spectral interval any two measured HCSA spectra are related via spectrally invariant relationship (1).

B. Leaf scattering:theory

Radiation reflected from or transmitted through a leaf results from photon interactions with leaf surface and its interior, i.e.,

$$h_\lambda = e_L + i_L \varpi_\lambda . \qquad (2)$$

Here e_L is the fraction of radiation reflected at the surface of leaf in given directions. Specular reflectance is the principal cause of light reflection at the leaf surface [10]. This portion of reflected radiation is partly polarized. The fraction of incident radiation that enters the leaf interior is represented by i_L. Both i_L and e_L exhibit a weak wavelength dependency, e_L does not interact with pigments inside the leaf, and is a function of the leaf surface properties [10]. The transformed leaf albedo, ϖ_λ, represents the diffuse component of the leaf

scattered radiation, which mainly results from radiation interacttions within the leaf interior. We use a bi-Lambertian model of the leaf diffuse scattering phase function [11] widely used in radiateve transfer calculations. In this model ϖ_λ is inde-pendent of leaf surface properties and varies with leaf anato-mical structure and leaf absorbing constituents [12]. Angular variation of ϖ_λ is neglected.

In the 710-790 nm interval, ϖ_λ is mainly determined by absorption spectra of dry matter and chlorophyll [13]. The former is flat in this interval while the latter varies with wavelength. The chlorophyll absorption spectrum therefore is a species independent spectral curve that relates spectra of the transformed albedos. Theoretical analyses [12] indicate that they are related via the spectrally invariant relationship given by Eq. (1) with $k = 1 - b = p_L$ (cf. Eq. S4.1 in [4]), where p_L is the within-leaf recollision probability. It follows from this result that the transformed albedos can be expressed in terms of one arbitrary selected spectrum, $\varpi_{0\lambda}$, called the refe-rence spectrum, and the within-leaf recollision probability p_L. We specified $\varpi_{0\lambda}$ using the Lewis and Disney approximation [12] of the PROSPECT model [13] with input parameters which provide a good dynamic range of $\varpi_{0\lambda}$: chlorophyll con-tent of $16\,\mu\text{g cm}^{-2}$; equivalent water thickness of $0.005\,\text{cm}^{-1}$ and dry matter content of $0.002\,\text{g cm}^{-2}$ [4]. The reference spectrum is mainly determined by chlorophyll absorption spectrum, whereas the wavelength independent within-leaf recollision probability becomes a function of leaf mesophyll structure, concentrations of chlorophyll and dry matter.

The following interpretation of the observed spectrally invariant behavior of leaf scattering (Fig. 1) can now be given. In 710-790 nm, the diffuse component, $i_L\varpi_\lambda$, in Eq. (2) dominates, i.e., $h_\lambda \approx i_L\varpi_\lambda$. The transformed albedo ϖ_λ in turn is related to the reference spectrum, $\varpi_{0\lambda}$, via Eq. (1) with $k = 1 - b = p_L$. It follows from this relationship that h_λ/ϖ_0 is linearly related to h_λ. Our data analyses confirmed this theoretical argument: all measured HCSA spectra (including $h_{\lambda,p}$) in the 710 to 790 nm interval perfectly follow h_λ/ϖ_0 vs. h_λ linear relationships with R^2>0.985; i.e., the measured HCSA spectra can be standardized to a single reference spectrum $\varpi_{0\lambda}$ via Eq. (1) with $k = p_L$ and $b = (1 - p_L)i_L$. As such, any two measured HCSA spectra are related via Eq. (1).

Note that normalization of HCSA by $i_L = b/(1 - k)$ gives an estimate, $\hat{h}_\lambda$, of the transformed albedo in the 710-790nm spectral interval, i.e., $\hat{h}_\lambda = \varpi_\lambda + e_\lambda/i_\lambda \approx \varpi_\lambda$. However, at strongly absorbing wavelengths, e.g., photosynthetically active radiation (400-700 nm), ϖ_λ is close to zero, $e_\lambda/i_\lambda \gg \varpi_\lambda$, and thus $\hat{h}_\lambda$ may become more sensitive to leaf surface properties rather than its interior. We will analyze this effect in Sect. V.

C. BRF spectrum and canopy structure

The canopy BRF can be approximated as [14-17]

$$\text{BRF}_\lambda(\Omega) = \omega_\lambda \frac{\varrho(\Omega)i_0}{1 - p\omega_\lambda} + S_\lambda . \tag{3}$$

Here p is the recollision probability, i.e., the probability that a photon scattered by material in the canopy will hit phyto-

element again. The wavelength independent ratio $\varrho(\Omega)/(1 - p)$ is the average directional escape probability density fun-ction of finding a free line of sight through the canopy from a point on the leaf surface element in the direction Ω [4]. The canopy interceptance, i_0, is the fraction of incident photons that are intercepted by the canopy. Finally, $\omega_\lambda = i_L + s_L\varpi_\lambda$ is the leaf albedo, i.e., the fraction of radiation incident on the leaf that is reflected or transmitted. Here s_L represents the sur-face reflected radiation and $i_L = 1 - s_L$, and ϖ_λ is the trans-formed albedo. The measured HCSA is an estimate of the leaf albedo and differs from ω_λ by the term describing the surface reflected radiation. The first term on the right hand of Eq. (3) describes reflectance of the vegetation canopy bounded at the bottom by a non-reflecting surface, while S_λ accounts for the additional radiation caused by interactions between the underlying surface and the vegetation canopy [16, 17]. For sufficiently dense vegetation, $S_\lambda \approx 0$. The ratio $\text{BRF}_\lambda(\Omega)/\omega_\lambda$ becomes linearly related to $\text{BRF}_\lambda(\Omega)$ with the slope and intercept given by p and $\varrho(\Omega)i_0$, i.e., BRF follows spectrally invariant relationship similar to Eq. (1).

The Directional Area Scattering Factor (DASF) is defined by Eq. (3), with $S_\lambda = 0$ and $\omega_\lambda = 1$. It describes the canopy BRF if leaves do not absorb radiation and is an estimate of the ratio of the leaf area that forms the canopy boundary, as seen along a given direction, to the total leaf area [4].

IV. DECOUPLING CONTRIBUTIONS FROM CANOPY STRUCTURE AND LEAF OPTICS

A. Retrieving DASF from BRF spectrum

Retrieving DASF exploits similar spectrally invariant behavior of the leaf and canopy scattering [4]. The former is illustrated and analyzed in Sects. III.A and III.B, while the latter is discussed in Sect. III.C. This technique can be outlined as follows (see [4] for details). In the 710-790 nm interval, $\omega_\lambda \approx i_L\varpi_\lambda$ where the transformed albedo ϖ_λ is related to the reference spectrum $\varpi_{0\lambda}$ via Eq. (1) with $k = 1 - b = p_L$. Substitution of $i_L\varpi_\lambda$ into Eq. (3) rearranges BRF to a new form (see Eq. S5.1 in [4] for more details). This results in a linear relationship between $\text{BRF}_\lambda(\Omega)/\varpi_{0\lambda}$ and $\text{BRF}_\lambda(\Omega)$ where the slope, k, and intercept, b, are given by $p_L + i_L p(1 - p_L)$ and $i_L\varrho(\Omega)(1 - p_L)i_0$, respectively (Eq. S5.2 in ref. [4]). The ratio $b/(1 - k)$ becomes independent on p_L (and consequently on the transformed albedo) and approximates the DASF as $\varrho(\Omega)i_L i_0/(1 - pi_L)$. Our analyses suggest validity of this technique for crops: CHRIS BRF spectra in the 710-790 nm interval perfectly followed $\text{BRF}_\lambda(\Omega)/\varpi_{0\lambda}$ vs. $\text{BRF}_\lambda(\Omega)$ linear relationship with R$^2 \geq 0.99$ where the slope and intercept vary with the sensor view direction and crop type. This also is true for the MBRF.

In general case of $S_\lambda \neq 0$, removal of the contribution, S_λ, from canopy background to BRF should precede retrieval of DASF using this algorithm. Radiative transfer based techniques for removing ground influences are well advanced in remote sensing (e.g., Green function approach, [16, 17]).

B. Canopy scattering coefficient

The deviation of canopy BRF from its non-absorbing counterpart DASF is determined by leaf optical properties. The $\text{BRF}_\lambda(\Omega)$ to DASF ratio is an estimate of the canopy

scattering coefficient, W_λ, i. e., the fraction of intercepted radiation that has been reflected from, or diffusely transmitted through, the vegetation [4, 12, 18]. Dividing Eq. (3) with $S_\lambda = 0$ by DASF $= \varrho(\Omega)i_L i_0/(1 - p i_L)$ one obtains

$$W_\lambda = \hat{\omega}_\lambda \frac{1 - p i_L}{1 - p i_L \hat{\omega}_\lambda} \qquad (4)$$

Here $\hat{\omega}_\lambda = \omega_\lambda/i_L = \varpi_\lambda + \delta$ where $\delta = s_L/i_L$. Substituting $\varpi_\lambda + \delta$ into Eq. (4) and letting $\theta = p i_L/(1 - \delta p i_L)$ one gets:

$$W_\lambda = \alpha W_{0\lambda}(\theta) + \beta \qquad (5)$$

where $\alpha = \gamma(1 + \delta\theta)$, $\beta = \gamma\delta(1 - \theta)$, and $\gamma = (1 - p i_L)/(1 - p i_L - \delta p i_L)$. Here $W_{0\lambda}(\theta) = \varpi_\lambda(1 - \theta)/(1 - \theta\varpi_\lambda)$ represents canopy scattering coefficient in the absence of scattering at the leaf surface and coincides with W_λ if $s_L = 1 - i_L = 0$. A deviation of α and β from unity and zero indicates an impact of leaf surface properties on the canopy scattering.

We use the measured leaf scattering spectra, $\hat{h}_\lambda$, as proxies of $\hat{\omega}_\lambda$ (i.e., $\hat{h}_\lambda \approx \hat{\omega}_\lambda$). The parameters θ, α and β in Eq. (5) were estimated as follows. Neglecting the second order term $[(p i_L \hat{\omega}_\lambda)^2]$, Eq. (4) at strongly absorbing wavelengths can be approximated as $W_\lambda = \widehat{h}_\lambda(1 - p i_L)[1 + p i_L \hat{h}_\lambda + (p i_L \hat{h}_\lambda)^2 + \cdots] \approx \hat{h}_\lambda(1 - p i_L)$. Thus, $W_\lambda = k_0 \hat{h}_\lambda + b_0$ where the non-zero intercept b_0 accounts for an error in the approximation of $\hat{\omega}_\lambda$ by $\hat{h}_\lambda$. The coefficients k_0 and b_0, are specified by plotting W_λ vs. $\hat{h}_\lambda$ for the 450-709nm interval. Because $\varpi_\lambda = \hat{h}_\lambda - \delta$, the term $W_{0\lambda}(\theta)$ is also linearly related to $\hat{h}_\lambda$, i.e., $W_{0\lambda}(\theta) = k(\theta)\hat{h}_\lambda + b(\theta)$ in this interval. By substituting $W_{0\lambda}(\theta)$ into Eq. (5) and accounting for the $W_\lambda(\theta)$ vs. $\hat{h}_\lambda$ relationship one gets $\alpha(\theta) = k_0/k(\theta)$, $\beta(\theta) = b_0 - k_0 b(\theta)/k(\theta)$. Finally, θ and corresponding values of α and β are specified by minimizing RRMSE $[\alpha(\theta)W_{0\lambda}(\theta) + \beta(\theta), W_\lambda]$ in the 450-855 nm interval.

To summarize, we have decomposed the measured BRF into the structural (DASF) and radiometric (W_λ) components. The former is a function of canopy structure, whereas the latter depends on the recollision probability (θ), leaf surface pro-perties (represented by α and β) and leaf inte-rior (represented by ϖ_λ). The decomposition is valid for the MBRF.

V. RESULTS

The DASF as a function of view zenith angle for different crop types is shown in Fig. 2. The leaf area from which photons can escape the vegetation through gaps in the near zenith direction is smallest for the corn patch. In the alfalfa patch leaves are less overlapped as seen from outside the canopy along the near nadir directions compared to other crop types. This increases the chance for scattered photons to escape the vegetation. The DASF varies with crop type, indicating a difference in their structural organization.

Figure 3 shows spectra of MBRF and the angular average canopy scattering coefficient. The removal of the effect of structural influences from MBRF involves changes in both the

magnitude of the spectral curves and their positions relative to each other, suggesting that canopy reflectance should be corrected for canopy structure effects to extract information about leaf properties.

The scattering coefficient represents canopy reflectance corrected for canopy structure effects and is more directly related to leaf biochemistry. However some radiation is scattered at the surface of leaves and therefore contains no information about leaf biochemistry. We use Eq. (5) to estimate the impact of leaf surface properties.
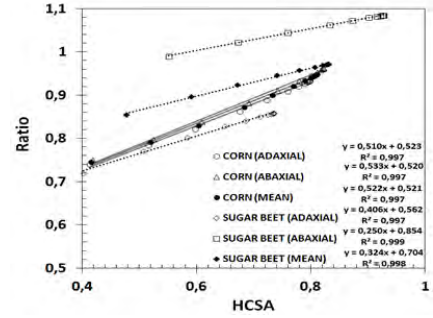

Fig.1 Measured hemispherical conical leaf scattering albedos follow spectrally invariant relationships. By plotting values of the ratio $h_\lambda/h_{\lambda,p}$ versus h_λ for the spectral interval [710, 790 nm], a linear relationship is obtained.
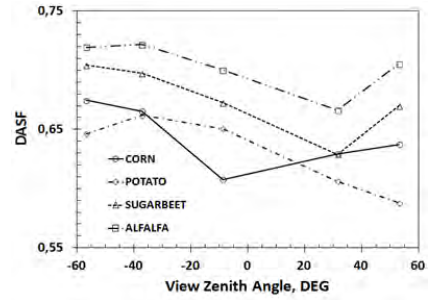

Fig.2. The Directional Area Scattering Factor (DASF) as a function of view zenith angle for corn, potato, sugar beet and alfalfa patches. Angles are shown with a negative sign if the view azimuth was greater than 180º. Averaging the DASF over view directions results in the following values: 0.64 (corn), 0.63 (potato), 0.67 (sugar beet) and 0.7 (alfalfa).

Figure 4 shows that Eq. (5) approximates measured angular average canopy scattering coefficient sufficiently well ($\theta = 0.66$, $\alpha = 0.96$, $\beta = 0.04$, RRMSE=7.4%). In the 710-855 nm interval where the contribution of surface reflected radiation can be neglected, W_λ can accurately be approximated by $W_{0\lambda}(\theta)$ alone (dotted line, $\theta = 0.66$, $\alpha = 1$, $\beta = 0$, RRMSE =4.3%). In the 422-710 nm interval $W_{0\lambda}(\theta)$ underestimates measured W_λ resulting in an underestimation of W_λ over 450-855 nm interval by RRMSE =37%. This is because $W_{0\lambda}(\theta)$ does not account for the contribution from the surface reflected radiation, which can exhibit a weak increase with an increase in the index of refraction from 600 down to 450 nm and consequently tends to enhance the leaf albedo. For other patches, $\theta = 0.82$, $\alpha = 1.0$, $\beta = 0.06$, RRMSE=8.3% (corn); $\theta = 0.66$, $\alpha = 0.97$, $\beta = 0.03$, RRMSE=9.9% (potato). If contribution of radiation reflected at the leaf surface is neglected, $W_{0\lambda}(\theta)$ approximates the measured

scattering coefficient in the 710-790 nm interval with a high accuracy: RRMSE=3.6%, $\theta = 0.77$, (corn); RRMSE =1.9%, $\theta = 0.65$ (potato). Its extrapolation to [450, 855nm] results in the following values of RRMSE (450-855 nm): 44% (corn); 19% (potato). These results suggest that neglecting leaf-surface characteristics may lead to an error in the relationship between canopy and leaf reflectance spectra of up to RRMSE=44%.
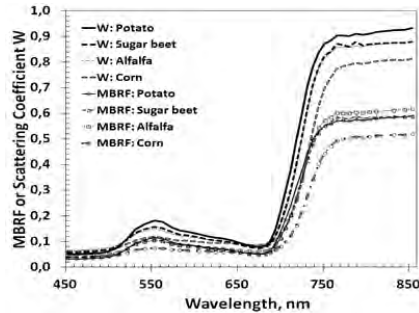

Fig. 3. Canopy scattering coefficient W and MBRF as functions of wavelength for alfalfa, potato, sugar beet and corn patches.
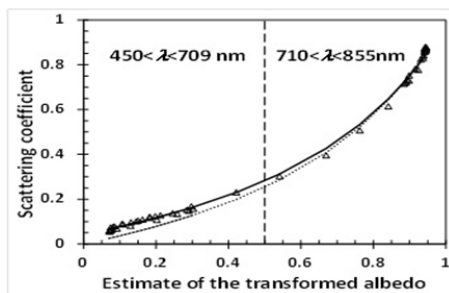

Fig. 4. Scattering coefficient, W_λ, of the sugar beet patch vs. $\hat{h}_\lambda$ (triangles) and its approximation (solid line) by Eq. (5). The dotted line shows $W_{0\lambda}(\theta)$ vs. $\hat{h}_\lambda$ relationship.

VI. CONCLUSIONS

The Directional Area Scattering Function (DASF), which is an estimate of the ratio of the leaf area that forms the canopy boundary, as seen along a given direction, to the total leaf area, is sensitive to crop type. It provides critical information to account for the impact of canopy structure on the relationship between hyperspectral data and leaf optical properties. For dense crops, the DASF can be estimated from the BRF spectrum in the 710 to 790 nm interval, without involving canopy reflectance models, prior knowledge or ancillary information regarding leaf scattering properties.

Some radiation is scattered at the surface of leaves, and, therefore, contains no information on leaf biochemistry. The leaf cuticle acts as a "barrier" for photons to enter the mesophyll and be absorbed; thus, tending to increase the leaf scattering. Our analysis suggests that leaf-surface characteristics can increase canopy scattering spectrum by up to 44%. This presents an additional confounding factor, unless it can be accounted for. It should be noted that polarization measurements may be useful to account for this factor because radiation reflected from the leaf surface is partly polarized whereas that from the leaf interior is not [10].

REFERENCES

[1] Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. Committee on Earth Science and Applications from Space: a community assessment and strategy for the future. National Research Council. Washington D.C.: The National Academies Press, 2007.

[2] S. L. Ustin, "Remote sensing of canopy chemistry," *Proc Natl Acad Sci USA*, vol. 110, pp. 804-805, January 15, 2013.

[3] J. Lloyd, K. Bloomfield, T. F. Domingues, and G. D. Farquhar, "Photosynthetically relevant foliar traits correlating better on a mass vs an area basis: of ecophysiological relevance or just a case of mathematical imperatives and statistical quicksand?," *New Phytologist*, vol. 199, pp. 311-321, Jul 2013.

[4] Y. Knyazikhin, M. A. Schull, P. Stenberg, M. Mõttus, M. Rautiainen, Y. Yang, et al., "Hyperspectral remote sensing of foliar nitrogen content," *Proc Natl Acad Sci USA*, vol. 110, pp. E185-E192, January 15, 2013.

[5] A. Samanta, Y. Knyazikhin, L. Xu, R. E. Dickinson, R. Fu, M. H. Costa, et al., "Seasonal changes in leaf area of Amazon forests from leaf flushing and abscission," *J. Geophys. Res-Biogeosciences*, vol. 117, pp. G01015, Feb 11 2012.

[6] J. Moreno. (2004, Oct. 4, 2012). SPARC data acquisition report. Available: http://earth.esa.int/campaigns/DOC/SPARC2004_Data_Acquisition_Report.pdf

[7] G. Schaepman-Strub, M. E. Schaepman, T. H. Painter, S. Dangel, and J. V. Martonchik, "Reflectance quantities in optical remote sensing definitions and case studies," *Remote Sens. Environ.*, vol. 103, pp. 27-42, Jul 15 2006.

[8] M. A. Cutter, "CHRIS Data Format," Surrey Satellite Technology Limited, https://earth.esa.int/c/document_library/get_file?folderId=23844&name=DLFE-592.pdf, Surrey UK,2008.

[9] L. Guanter, L. Alonso, and J. Moreno, "A method for the surface reflectance retrieval from PROBA/CHRIS data over land: Application to ESA SPARC campaigns," *IEEE Trans. on Geosci. Remote Sensing*, vol. 43, pp. 2908-2917, Dec 2005.

[10] V. C. Vanderbilt, L. Grant, and S. L. Ustin, "Polarization of light by vegetation," in Photon-vegetation interactions: applications in plant physiology and optical remote sensing, R. B. Myneni and J. Ross, Eds., ed Berlin Heidelberg: Springer-Verlag, 1991, pp. 191-228.

[11] J. Ross, The radiation Regime and Architecture of Plant Stands. The Hague: Dr. W. Junk, 1981.

[12] P. Lewis and M. Disney, "Spectral invariants and scattering across multiple scales from within-leaf to canopy," *Remote Sens. Environ.*, vol. 109, pp. 196-206, Jul 30 2007.

[13] J. B. Féret, C. Francois, G. P. Asner, A. A. Gitelson, R. E. Martin, L. P. R. Bidel, et al., "PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments," *Remote Sens. Environ.*, vol. 112, pp. 3030-3043, Jun 16 2008.

[14] D. Huang, Y. Knyazikhin, R. E. Dickinson, M. Rautiainen, P. Stenberg, M. Disney, et al., "Canopy spectral invariants for remote sensing and model applications," *Remote Sens. Environ.*, vol. 106, pp.106-122, 2007.

[15] Y. Knyazikhin, M. A. Schull, L. Xu, R. B. Myneni, and A. Samanta, "Canopy spectral invariants. Part 1: A new concept in remote sensing of vegetation," J. *Quant. Spectrosc. and Radiat. Transf.*, vol. 112, pp. 727-735, 2011.

[16] Y. Knyazikhin, A. Marshak, and R. B. Myneni, "Three-Dimensional Radiative Transfer in Vegetation Canopies and Cloud-Vegetation Interaction," in Three dimensional radiative transfer in the cloudy atmosphere, A. Marshak and A. B. Davis, Eds., ed Berlin Heidelberg: Springer-Verlag, 2005, pp. 617-652.

[17] S. Ganguly, M. A. Schull, A. Samanta, N. V. Shabanov, C. Milesi, R. R. Nemani, et al., "Generating vegetation leaf area index earth system data record from multiple sensors. Part 1: Theory," *Remote Sens. Environ.*, vol. 112, pp. 4333-4343, Dec 15 2008.

[18] S. Smolander and P. Stenberg, "Simple parameterizations of the radiation budget of uniform broadleaved and coniferous canopies," *Remote Sens. Environ.*, vol. 94, pp. 355-363, Feb 15 2005.