COUPLING SPECTRAL AND BIDIRECTIONAL INFORMATION TO ESTIMATE CANOPY BIOPHYSICAL PARAMETERS BY MODEL INVERSION

Cédric BACOUR & Stéphane JACQUEMOUD

Laboratoire Environnement et Développement, Université Paris 7,
Case 7071, 2 place Jussieu, 75251 Paris Cedex 05, France,
tel: +33 1 44 27 60 47, fax: +33 1 44 27 81 46, email: bacour@ccr.jussieu.fr

1 – INTRODUCTION

The expansion of onboard systems dedicated to Earth monitoring has made many data available on vegetation cover. The estimation of the continental biosphere properties with optical remote sensing data has long been governed by the spectral features of the observations. Empirical or semi-empirical methods, like vegetation indices, are still largely used for remote sensing estimation purposes in the solar domain. Because these methods are often poorly physically based, this limits their reliability although they bear upon most of the operational applications. Since the late 80's, the anisotropy properties of terrestrial surfaces came out for the assessment of key characteristics of plant canopies (Kimes and Sellers, 1985). Inversion of bidirectional canopy reflectance (CR) models emerged as a promising alternative for retrieval issues (Goel, 1989; Myneni and Ross, 1991). The new generation of spaceborne instruments (POLDER / ADEOS, MISR / TERRA, among others) is designed to study both the spectral and directional characteristics of the Earth surfaces. This trend depicts one of the scientific stakes to come in remote sensing, which is to take advantage both of the spectral and the directional signatures of vegetation in order to retrieve the biophysical parameters that reveal its functioning. Among the different retrieval methods usually applied (neural networks, look up tables), iterative optimization techniques are the most widespread in the literature.
We address here the issue of the choice of the physical model to represent the radiative field within the canopy. Then the inverse problem is settled and illustrated with some results.

2 – THE MODELS

2-1. At the canopy level

All physical canopy reflectance models are not invertible. An "ideal" model for inversion purposes should comply both criteria of accuracy (in the sense it should represent correctly the radiative field within the canopy) and speed. These conditions may seem contradictory because the most realistic models are also the most demanding in computer ressources. For these reasons, ray-tracing models are so far used only in the direct mode to compute reflectances. One-dimensional models appear as a good compromise of accuracy and efficiency. The canopy is described by one or several plane parallel layers, composed of a gas where the only diffusing and absorbing elements are small leaves, homogeneously distributed. The other plant organs are generally ignored. Many models can be found in the literature; they differ from their description of the canopy architecture and from the approximation level of the radiative transfer equation. In general, the main parameters used to describe the canopy architecture are: the leaf area index (LAI), the distribution of leaf orientations described here by the mean leaf inclination angle θ_l, a hot spot parameter (s_l) – ratio of the leaf length to the height of the canopy – that explains the increase of the canopy reflectance in the backward direction, when leaves hide their own shadow.

2-2. At the leaf level

These models also require the soil reflectance and the leaf optical properties as input parameters. The latter can be computed by the PROSPECT model (Jacquemoud et al., 2001) where the leaf is considered as N staked-up layers, which specific absorption coefficients and refractive index are known. To compute the hemispherical leaf reflectance and transmittance between 400 and 2500 nm (5 nm step), the model depends upon:

- the leaf structure parameter N, which typically ranges between 1 and 2.5. Although it affects the leaf optical properties over the whole spectrum, the main effects can be seen in the near infrared plateau,
- the chlorophyll a+b content C_{ab} (μg cm^{-2}) that affects the reflectance and transmittance in the visible (400-700 nm),
- the equivalent water thickness C_w (cm or g cm^{-2}) that takes into account light absorption by leaf water content in the middle infrared (1100-2500 nm),
- the dry matter content C_m (g cm^{-2}) that is responsible of light absorption between 800 and 2500 nm.

2-3. Coupling and comparison

Among all 1-D canopy bidirectional reflectance models of the literature, we focused on the comparison of four ones: SAIL (Verhoef, 1985) which is the most commonly used for operational uses, KUUSK (Kuusk, 1995), IAPI (Iaquinta and Pinty, 1994), and NADI (Gobron et al., 1997). Their input parameters have been settled as coherent as possible.

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They mainly differ by the way the radiative transfer equation is solved and by the way the canopy structure is described. They have been coupled with the PROSPECT model and renamed PROSAIL, PROKUUSK, PROSIAPI, and PRONADI, respectively (Figure 1).

A classical model intercomparison showed good agreement both spectrally and directionally, for a standard canopy (N = 1.5, C_{ab} = 35 µg cm^{-2}, C_w = 0.015 cm, C_m = 0.01 g cm^{-2}, LAI = 2, spherical leaf angle distribution, s_l = 0.25) and an illumination viewing angle θ_s of 30° (Figure 2).
Such comparisons are limited as far as they concern only restricted canopy diversity. They can be improved by using designs of experiments. The latter allow model comparison not only on the basis of computed reflectances but also on the input parameter effects. Moreover they permit a better exploration of the parameter space (the input variables vary simultaneously in a restricted number of computations), and therefore provide a wider range of reference canopies (Bacour et al., 2001a). Figure 3 shows the effects of the LAI and θ_l parameters for each model, when taking 7 values within the range [0;7]. The results come from simulations performed with the sampling scheme of a Hyper Graeco Latin Geometric experimental design made of only 343 different simulations to study the effects of 6 parameters, taking 7 levels each. Note that a complete set of simulations, studying all possible combinations between the parameter levels, would require 7^6 simulations. These methods have made possible the identification of the parameters that induce the largest differences between the four models.

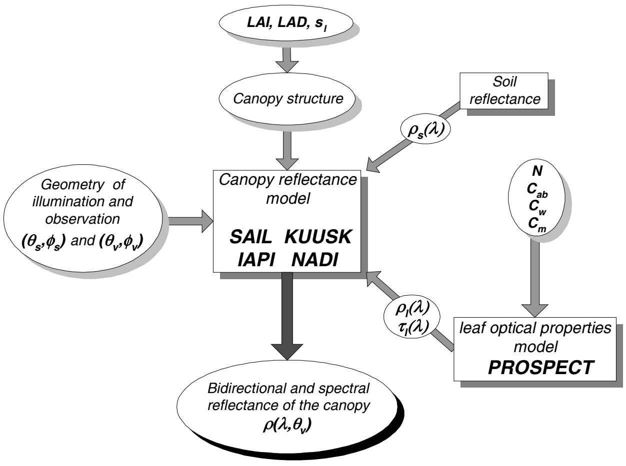

Figure 1. Coupling of the models

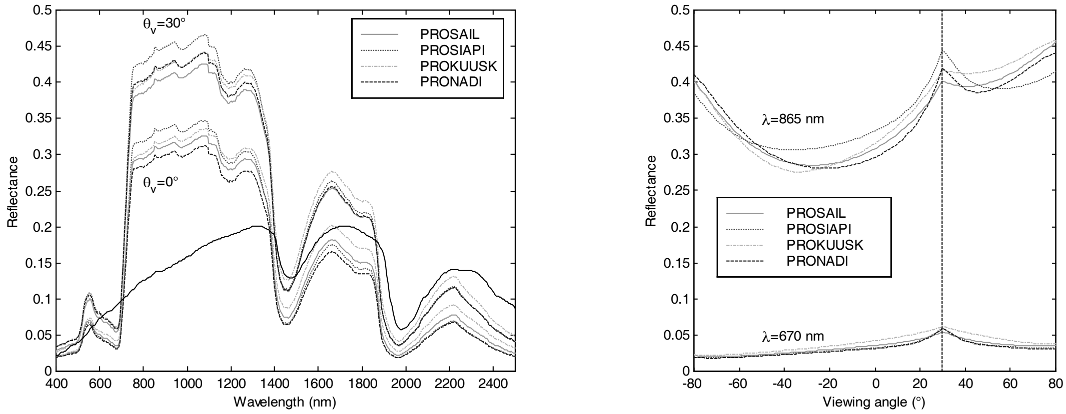

Figure 2. a) Spectral and **b)** directional reflectances computed by PROSAIL, PROSIAPI, PROKUUSK, and PRONADI.

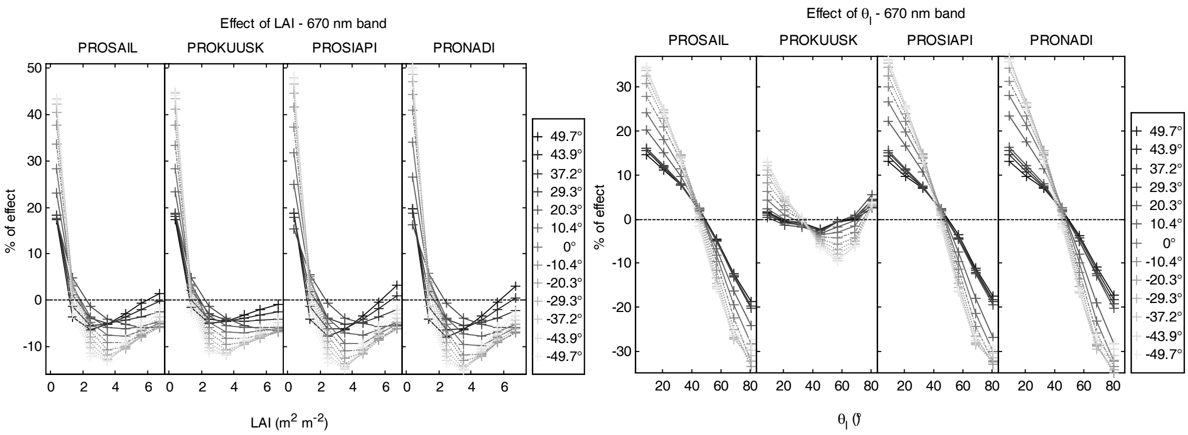

Figure 3. Comparison of the effects of **a)** LAI and **b)** θ_l, for PROSAIL, PROKUUSK, PROSIAPI and PRONADI, at 670 nm.

3 – ESTIMATION OF CANOPY BIOPHYSICAL PARAMETERS

3-1. The Inverse Problem

Iterative inversion consists, from a collection of measured directional and spectral reflectances, in determining the set of independent input parameters for which the reflectance computed by the model best fits the measurements. This is achieved by numerically exploring the parameter space until the best solution is reached, *i.e.* the one that minimizes a merit function χ^2 characterizing the "goodness" of the fit. Typically χ^2 is defined as: $\chi^2 = \sum_{j=1}^{n_v} \left[\rho^j_{\text{meas}}(\lambda,\Omega) - \rho^j_{\text{mod}}(\lambda,\Omega,\Theta)\right]^2$, or as $\chi^2 = \sum_{j=1}^{n_v} \left[\dfrac{\rho^j_{\text{meas}}(\lambda,\Omega) - \rho^j_{\text{mod}}(\lambda,\Omega,\Theta)}{\rho^j_{\text{meas}}(\lambda)}\right]^2$, which doesn't favor one spectral band with respect to another. Here, λ and Ω are respectively the wavelength and configuration (illumination and viewing directions) of the n_v observations, and Θ is the set of parameters to retrieve.

3-2. Applications

Inversion of these models have been already applied on experimental data (Jacquemoud et al., 2001). Bacour et al. (2001b) analyzed airborne POLDER data collected during the Alpilles-ReSeDA campaign this way: 16 flights were carried out over the Alpilles (France) test site from January to October 1997. Atmospherically and geometrically calibrated reflectances have been acquired at 550, 670, and 865 nm, with a 20 m ground resolution. PROSAIL, PROKUUSK, and PROSIAPI inversions were performed (quasi-Newton method) over validation crops of wheat, maize, sunflower, and alfalfa, for which ground measurements of LAI were available. Figure 4 shows the compared performance of the models to estimate the LAI.

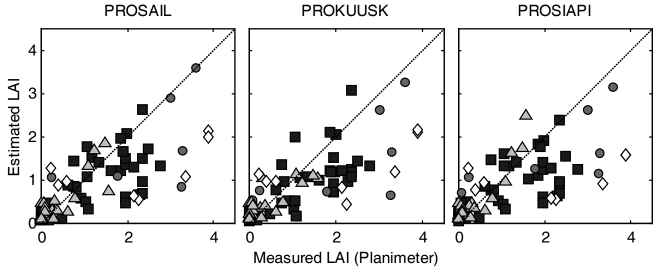

Figure 4. Comparison between LAI values measured with the planimeter, and LAI values estimated by inversion of PROSAIL, PROKUUSK, and PROSIAPI, on ■ wheat, ● maize, △ sunflower, and ◇ alfalfa.

A map of the estimated parameters has been established over a subimage of the Alpilles test site, by inversion of the PROSAIL model pixel per pixel (Figure 5). The fields distinguish well from each other by their LAI values; the wheat fields exhibit the highest ones.

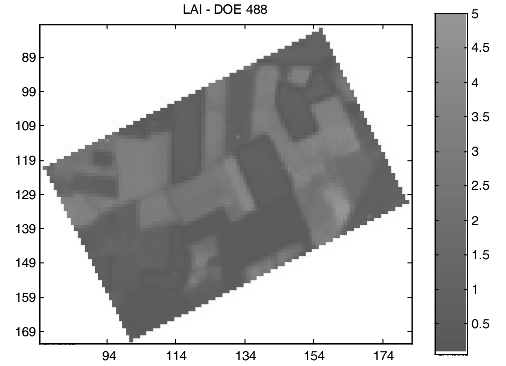

Figure 5. LAI estimation by PROSAIL inversion for the acquisition made the 2nd of May 1997.

4 – CONCLUSION

Inversion techniques to estimate canopy key properties from remote sensing data have great potential for operational uses. The quality of the estimation relies on i) the inversion technique itself, ii) a good physical representation of the absorption and reflection processes within plant canopies, and iii) the measurements. Iterative methods have already shown proof for providing reliable estimates of canopy state, and despite some low computer execution speed with respect to neural networks or look-up tables, they remain very flexible and quite easy to use. 1-D radiative transfer models are a good alternative for inversion purposes and concern most of the operational applications. The quality of the measurements is still a point at issue. In particular, it has to be determined which configurations (spectrally and directionally) lead to the best estimation of the parameters of interest. This problem underlies the determination of instrument characteristics and important financial stakes depend on it.

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