OPTIMAL SAMPLING CONFIGURATIONS FOR THE ESTIMATION OF CANOPY PROPERTIES FROM BRDF DATA ACQUIRED WITH THE EGO/JRC

Cédric BACOUR[1], Stéphane JACQUEMOUD[1], Peter VOGT[2], Brian HOSGOOD[2], Giovanni ANDREOLI[2], Jean-Pierre FRANGI[1]

*[1]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
*[2]Space Applications Institute, Joint Research Centre,
via E. Fermi, 21020 Ispra (VA), Italy*

ABSTRACT: *A database gathering bidirectional and hyper-spectral reflectances of artificial and natural plant canopies was acquired in 1996 at the Joint Research Centre (Ispra, Italy) with the European Goniometer facility (EGO). It is analyzed with the idea of determining optimal measurement configurations for the retrieval of architectural canopy parameters by iterative inversion techniques: first, the sensitivity of the PROSAIL canopy reflectance model to its input parameters is studied, both spectrally and directionally, with experimental designs; second, a statistical framework based on the simulated annealing method is developed.*

1 − INTRODUCTION

The expansion of onboard systems dedicated to Earth monitoring has made many data on vegetation cover available. The extraction of pertinent information on the state and evolution of plant canopies has long been governed by the spectral features of the observations. Since the late 80's, retrieval techniques have also taken advantage of their directional properties with the inversion of bidirectional canopy reflectance (CR) models (Goel, 1989; Myneni and Ross, 1991). Coupling both spectral and directional information should favour the operational use of CR models to infer canopy key properties (Jacquemoud et al., 1994). The inverse problem is often over-determined because the number of measurements M is higher than the number m of parameters Θ to infer. Furthermore it is ill posed in the sense that 1) there is no unique solution, 2) the M data are subject to variations. Consequently, rather than searching for the "true" solution of the parameter set, the "best" solution is sought (Verstraete et al., 1996). The question is then: how to choose, among M measurements available, the N ones that lead to the "best" estimation of the parameters? Defining optimal data sets, both spectrally and directionally, to better retrieve canopy biophysical parameters, is still a point at issue. Basically, two approaches can be found in the literature: those based on model sensitivity (Goel and Thomson, 1985; Privette et al., 1996; Combal et al., 2000) with respect to some criterion, and those using statistics to explore the data space (Maggion, 1995; Gao and Lesht, 1997; Solheim et al., 2000; Weiss et al., 2000). These two aspects are undertaken here with the help of experimental reflectances measured in the laboratory.

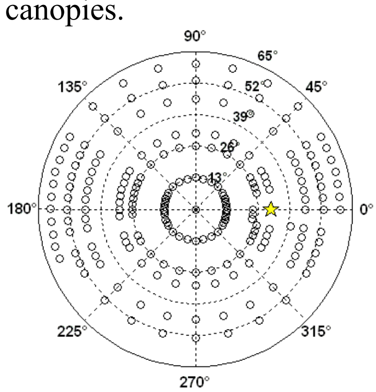
A campaign conducted in 1996 at the European Goniometer facility (EGO) − Joint Research Centre (Ispra, Italy) − gathered directional and hyper-spectral measurements of canopy Reflectance Factors (RF). The data are analyzed so as to determine possible optimal configurations with iterative inversion techniques. This paper first describes the experiment and the data set. Then, a sensitivity analysis of the PROSAIL parameters according to the acquisition constraints (wavebands and viewing directions) is tackled by use of experimental designs. Finally, a Monte-Carlo like method is applied during the inversion process to determine the optimal viewing directions.

Proc. 8th International Symposium Physical Measurements & Signatures in Remote Sensing, Aussois (France), 8-12 January 2001, CNES, pages 481-486.

2 – EXPERIMENT AND DATA SET

2.1 – Experimental setup

The EGO instrument allows automated sampling of the Bidirectional Reflectance Distribution Function (BRDF) of small targets with a nearly total coverage of the upper hemisphere (Solheim et al., 1996). The light source, a 1000W Tungsten halogen collimated lamp, was positioned at θ_s = 31.6° all along the experiment. A Spectron Engineering SE590 spectroradiometer was used for the radiance measurements. Directional and spectral signals reflected by different kinds of canopies were recorded. Three artificial canopies, made of 300 identical plants, each one with 6 rotatable leaves, were first considered. They differed from the LAI values created by various stem spacings; the leaf orientation was following an ellipsoidal leaf angle distribution (Campbell, 1990) with a mean leaf inclination angle θ_l of 30°; the hot spot parameter was assessed from the leaf surface and the stem height: s_l = 0.21; a polystyrene plate was finally used as underlying soil. Two natural canopies of clover (*Trifolium repens L.*) and marigold (*Tagetes ssp L.*) were also studied in the same configuration (Vogt, 1997). Their LAI was determined with the Licor LAI2000 instrument. Leaf reflectance and transmittance spectra were measured both for the artificial and natural canopies.



The BRDF of the targets was acquired in 229 viewing directions (Figure 1) and in 89 narrow wavebands (from 460 to 900 nm). The observation processing over the scenes required a Gore-Tex™ reference panel, due to the large size of the illuminated surface. View zenith angles exceeding 60° were discarded (Solheim et al., 2000).

Fig. 1: Directional sampling of the viewing geometry over the canopies in polar coordinates. The star (☆) indicates the light source position.

2.2 - Bidirectional Reflectance Factors estimation

The Bidirectional Reflectance Factor (BRF) of a surface has been defined by Nicodemus et al. (1977) as the ratio of the radiant flux reflected by this surface to that reflected by a perfect diffuser in the same configuration. The BRF of the target $\hat{\rho}_t^\lambda(\theta_s,\theta_v,\phi_v)$ is given by:

$$\hat{\rho}_t^\lambda(\theta_s,\theta_v,\phi_v) = \frac{\hat{s}_t^\lambda(\theta_s,\theta_v,\phi_v)}{\hat{s}_{GT}^\lambda(\theta_s,\theta_v,\phi_v)}.\hat{\rho}_{GT}^\lambda(\theta_s,\theta_v,\phi_v)$$

where $\hat{s}_t^\lambda(\theta_s,\theta_v,\phi_v)$ and $\hat{s}_{GT}^\lambda(\theta_s,\theta_v,\phi_v)$ are the digital counts measured for the target and the Gore-Tex™ panel, respectively, under identical illumination and observation geometry. The latter is itself calibrated with a Spectralon™ reference panel, the BRF of which is derived both from the directional-hemispherical reflectance factor $\rho_H^\lambda(8°,2\pi)$ provided by the manufacturer and the signals measured by the detector:

$$\hat{\rho}_H^\lambda(31.6°,\theta_v,\phi_v) = \frac{\pi.\hat{s}_H^\lambda(31.6°,\theta_v,\phi_v).\rho_H^\lambda(8°,2\pi).\cos(8°)}{\int_{2\pi}\hat{s}_H^\lambda(8°,\theta_v,\phi_v).\cos(\theta_v).d\omega_v.\cos(31.6°)}$$

where $d\omega_v$ denotes an element of solid angle in the direction (θ_v,ϕ_v). $\hat{s}_H^\lambda(8°,\theta_v,\phi_v)$ is obtained from measurements of the Spectralon™ panel acquired for θ_s=10° (Solheim, 1998). Deduced values of

$\hat{s}_H^{\lambda}(8°,\theta_v,\phi_v)$ were then fitted by the Modified Rahman Pinty Verstraete model (Rahman et al., 1993; Engelsen et al., 1996), without the hot spot factor, before numerical integration over the upper hemisphere. Figure 2 shows spectral and directional reflectance of the artificial canopy (#3).

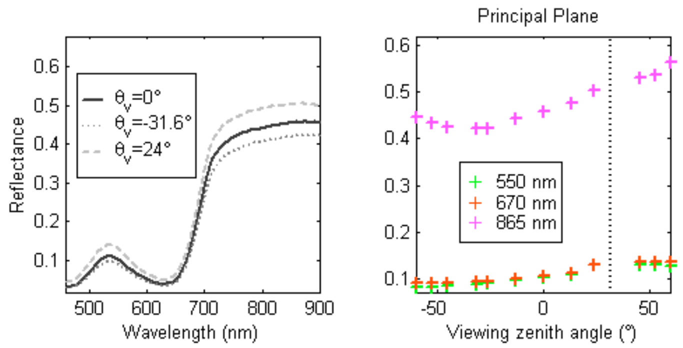


Fig. 2: Spectral **(a)** and directional **(b)** reflectance of the artificial canopy (#3) (negative viewing angles indicate forward scattering).

3 – SAIL SENSITIVITY

3.1 – The models

The radiative transfer model used here is the 1-D bidirectional CR model SAIL (Verhoef, 1984) which offers a good compromise between low computation time and quality of the simulated reflectances as compared to other CR models (Bacour et al., 2000a; 2000b). We use two versions of SAIL: one which requires the leaf reflectance and transmittance as input parameters (§4), and another one coupled with the latest version of the PROSPECT model (Jacquemoud et al., 2000) to compute the leaf optical properties (§3.2), and called PROSAIL. The other input parameters are: the leaf area index LAI, the mean leaf inclination angle θ_l according to the ellipsoidal leaf angle distribution, the hot spot parameter s_l (Kuusk, 1985), a spectral soil parameter α_{soil} that controls the reflectance levels of a given soil, and the measured soil reflectances. PROSPECT requires the leaf structure parameter N, the chlorophyll a+b content C_{ab} (μg cm^{-2}), the equivalent water thickness C_w (cm), and the dry matter content C_m (g cm^{-2}).

3.2 – Designs of experiments – model sensitivity

Design of experiments have proved to investigate well the response of a model to variations of its input parameters (Bacour et al., 2000a) by statistically determining a limited – but representative – number of simulations (Benoist et al., 1994). The joint study of the 6 PROSAIL parameters (LAI, C_{ab}, N, θ_l, s_l, and α_{soil}), each one taking seven levels, would traditionally lead to 7^6 = 117649 simulations whereas an experimental design made of 343 numerical simulations can be found. The values taken by the parameters are provided in Table 1.

Parameter	Variation range	Levels
LAI	0 – 5	0.3, 1, 1.8, 2.5, 3.3, 4, 4.8
C_{ab}	1 – 80	5, 17, 29, 41, 52, 64, 76
θ_l	5 – 85	9, 21, 33, 45, 57, 69, 81
s_l	0.01 – 1	0.06, 0.21, 0.36, 0.51, 0.65, 0.80, 0.95
α_{soil}	0.5 – 2	0.57, 0.80, 1.02, 1.25, 1.48, 1.70, 1.93
N	1 – 2.5	1.1, 1.3, 1.5, 1.8, 2.0, 2.2, 2.4

Table 1. Values of the input parameters used for the simulations.

The simulations were conducted for the 229 EGO configurations plus one viewing angle in the direction of the hot spot. The spectral and directional effects $\hat{\alpha}_{v_p,m}$ of a factor v_p are inferred from the [343 × 89 × 230] array of results after averaging the responses over viewing directions and wavebands: $\hat{\alpha}_{v_p,m} = \overline{\rho}_{v_p,m} - \overline{\rho}$, where $\overline{\rho}$ is the general averaged reflectance over the 343 numerical experiments, and $\overline{\rho}_{v_p,m}$ is the mean of the responses for which v_p is at the level m. The model is all the more sensitive to one of its input parameters v_p since the variation of $\hat{\alpha}_{v_p,m}$ between two levels of v_p is important. Sensitivity indices are consequently based on the effect gradient: $S_{v_p} = \sum_n \sqrt{\Delta\hat{\alpha}_{v_p}^{\ 2}}$. They are then scaled between the extremum values found for the whole configuration set, spectrally (Figure 3) and directionally (Figure 4), and expressed as a percentage.

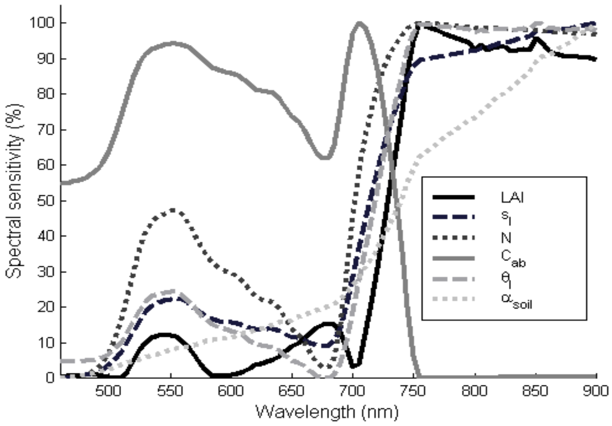


Fig. 3: Spectral sensitivity indices for canopy parameters

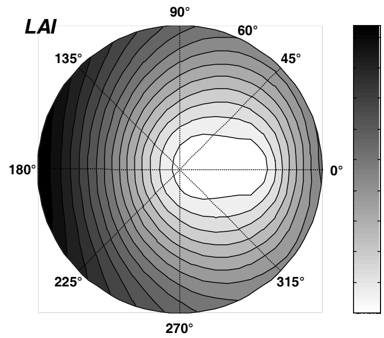


Fig. 4: Directional sensitivity of LAI

4 – ESTIMATION OF CANOPY BIOPHYSICAL PARAMETERS

Consider a sub-sample of n directions among M. The combinatorial problem that consists in determining which ones satisfy the best a criterion that gauges the goodness of the solution, was undertaken dynamically, during the inversion process, with a simulated annealing method.

4.1 – Inversion technique

Inversion consists in exploring numerically the parameter space until the best solution is reached, i.e. in finding the minimum of the merit function χ^2, defined as $\chi^2 = \sum_{j=1}^{n_v} \sum_{\lambda=1}^{89} \left[\frac{\rho^j_{\text{meas}}(\lambda) - \rho^j_{\text{mod}}(\lambda,\Theta)}{\rho^j_{\text{meas}}(\lambda)} \right]^2$. n_v is the number of selected viewing directions, and Θ the vector of parameters to retrieve.

4.2 – Simulated annealing

The simulated annealing method is an improved Monte-Carlo method designed to look randomly for the global minimum of a function of n variables (Kirkpatrick et al., 1983). Starting from an initial guess of the measurement configuration, the function to minimize χ^2 is evaluated with a Quasi-Newton algorithm (routine E04JAF of the NAG library). Any downhill solution is accepted and the algorithm takes up from this new point. An uphill step may be accepted, which allows the algorithm to escape from local minima, if it complies with the Metropolis criterion (Metropolis et al., 1953); as the optimization process proceeds, the acceptance probability of such points decreases and the algorithm converges to the global minimum (Goffe, 1996).
The initial temperature has been chosen so that the initial acceptance probability equals 0.9. The method has been applied for a number of viewing directions *No* increasing from 10 to 220 (10 step), and repeated twice. Figure 5a shows an example of the performance of the algorithm to find 60 optimal viewing directions. The latter are preferentially located in the backward scattering direction, along the principal plane.

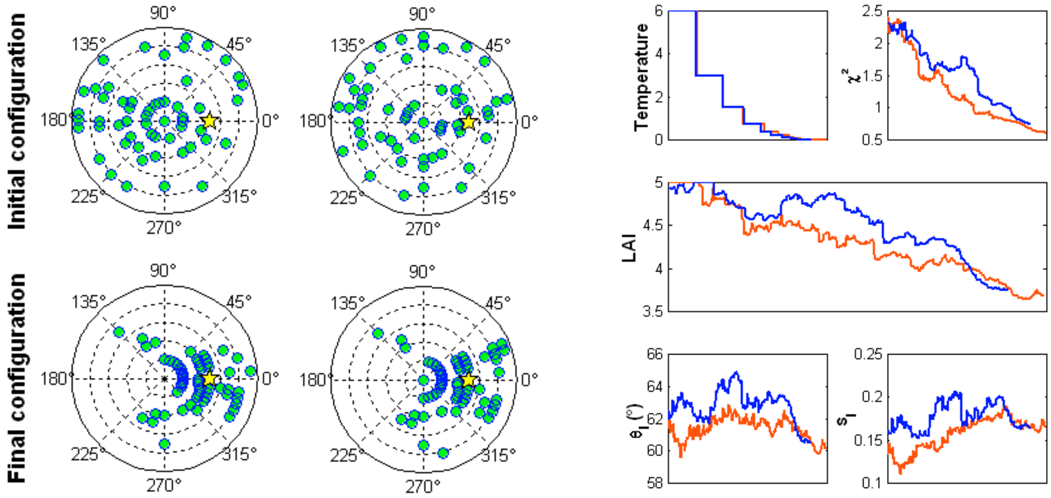
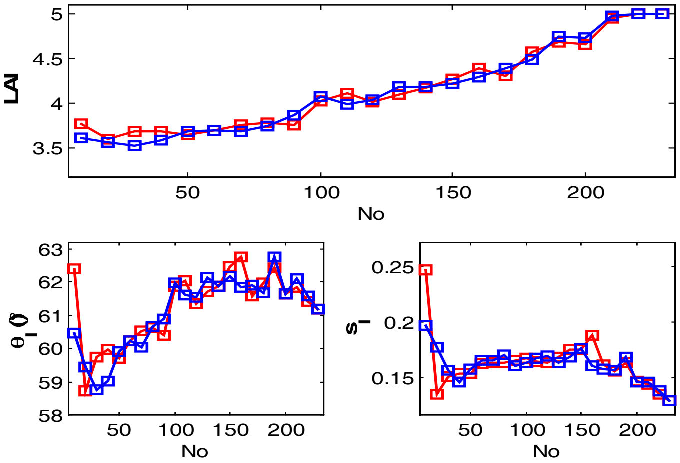


Fig. 5: a) Compared initial and final viewing configurations for *No*=60. **b)** Variation of T, χ^2, LAI, θ_l, and s_l, as a function of the iteration number along the algorithm progress.



The number of viewing directions (*No*) initially chosen greatly influences the performance of the SAIL inversion to estimate the parameters related to the canopy structure, as can be seen in Figure 6.

Fig. 6: a) LAI, **b)** θ_l, and **c)** s_l, final values as a function of the number of viewing directions, *No*.

5 – CONCLUSION

The potential of the BRDF database acquired with the EGO over artificial and natural canopies has not been fully exploited yet. This study was initiated to derive an optimal sampling configuration for the use in CR model inversion. It has provided some encouraging results. The use of experimental designs to assess sensitivity indices for PROSAIL input parameters points out what configurations should be the most informative on the canopy structure and should permit to determine weighting schemes of the merit function during the inversion process. These results, coupled with those obtained with the simulated algorithm, should give clues in a near future to determine minimum numbers of viewing configurations (spectrally and directionally) to retrieve canopy key properties.

ACKNOWLEDGEMENTS: *The authors thank Dr. Inger Solheim who provided valuable advices and data, and Dr. Alois Sieber who allowed full access to the EGO facility.*

REFERENCES

Bacour C., Jacquemoud S., Tourbier Y., Dechambre M., Frangi J.-P. (2000a), Design and analysis of numerical experiments to compare four canopy reflectance models, *Remote Sens. Environ.*, submitted.

Bacour C., Jacquemoud S., Leroy M., Hautecoeur O., Weiss M., Prévot L., Bruguier N., Chauki H. (2000b), Estimation of vegetation characteristics by inversion of three canopy reflectance models on airborne POLDER data, *Phys. Chem. Earth*, submitted.

Benoist D., Tourbier Y., Germain-Tourbier S. (1994), *Plans d'expériences: construction et analyse*, coll. Tec & Doc, Lavoisier, Paris, 693 pp.

Campbell G.S. (1990), Derivation of an angle density function for canopies with ellipsoidal leaf angle distribution, *Agric. For. Meteorol.*, 49:173-176.
Combal B., Oshchepkov S.L., Sinyuk A., Isaka H. (2000), Statistical framework of the inverse problem in retrieval of vegetation parameters, *Agron.*, 20(1):65-77.
Engelsen O., Pinty B., Verstraete M.M., Martonchik J.V. (1996), Parametric bidirectional reflectance factor models: evaluation, improvements and applications, report EUR16426EN, European Commission, Joint Research Centre, Space Applications Institute, Ispra, Italy, 120 pp.
Gao W., Lesht B.M. (1997), Model inversion of satellite-measured reflectances for obtaining surface biophysical and bidirectional reflectance characteristics of grassland, *Remote Sens. Environ.*, 59:461-471.
Goel N., Thompson R.L. (1985), Optimal solar/viewing geometry for an accurate estimation of leaf area index and leaf angle distribution from bidirectional canopy reflectance data, *Int. J. Remote Sensing*, 6(9):1493-1520.
Goel N. (1989), Inversion of canopy reflectance models for estimation of biophysical parameters from reflectance data, in *Theory and Applications of Optical Remote Sensing* (G. Asrar, Ed.), Wiley Interscience, New York, pp. 205-250.
Goffe W.L. (1996), SIMANN: a global optimization algorithm using simulated annealing, *Studies in Nonlinear Dynamics and Econometrics*, 1(3):169-176.
Jacquemoud S., Flasse S., Verdebout J., Schmuck G. (1994), Comparison of several optimization methods to extract canopy biophysical parameters – Application to CAESAR data, in *Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing*, Val d'Isère (France), 17-21 January 1994, pp. 291-298.
Jacquemoud S., Bacour C., Poilve H., Frangi J.-P. (2000), Comparison of four radiative transfert models to simulate plant canopies reflectance - Direct and inverse mode, *Remote Sens. Environ.*, 74:471-481.
Kirkpatrick S. (1983), Optimization by simulated annealing, *Science*, 200:671-680.
Kuusk A. (1985), The hot spot effect of a uniform vegetative cover, *Sov. J. Remote Sensing*, 3(4):645-658.
Maggion S. (1995), Etude de l'estimation des paramètres d'un modèle de réflectance bidirectionnelle et planification optimale des observations depuis l'espace, Thèse de doctorat, Université Paul Sabatier, 267 pp.
Metropolis N., Rosenbluth A.W., Rosenbluth M.N., Teller A.H., Teller E. (1953), Equations of state calculations by fast computing machines, *J. Chem. Phys.*, 21:1087-1092.
Myneni R.B., Ross J. (1991), Photon-Vegetation interactions: applications in optical remote sensing and plant ecology, *Springer-Verlag*, New York, 565 pp.
Nicodemus F.E., Richmond J.C., Hsia J., Venable W., Ginsberg I., Limperis T. (1997), Geometrical considerations for reflectance nomenclature, *National Bureau of Standards,* Report 160:1-52, NIST, Boulder, CO.
Privette J.L., Myneni R.B., Emery W.J., Hall F.G. (1996), Optimal sampling conditions for estimating grassland parameters via reflectance model inversions, *IEEE Trans. Geosci. Remote Sens.*, 34(1):272-284.
Rahman H., Pinty B., Verstraete M.M. (1993), Coupled Surface-Atmosphere Reflectance (CSAR) model. 2. Semi-empirical surface model usable with NOAA Advanced Very High Resolution Radiometer Data, *J. Geophys. Res.*, 98:20791-20801.
Solheim I., Hosgood B., Andreoli G., Piironen J. (1996), Calibration and characterization of data from the European Goniometer Facility (EGO), Report EUR 17268 EN, Joint research Center,Ispra, Italy, 38 pp.
Solheim I. (1998), Bidirectional and spectral reflectance properties of the *Cladina stellaris* and *Flavocetraria nivalis* lichens and the *Racomitrium lanuginosum* moss, PhD Thesis, University of Tromso, Department of Physics, Tromsr (Norway), 169 pp.
Solheim I., Engelsen O., Hosgood B., Andreoli G. (2000), Measurement and modeling of the spectral and directional reflection properties of lichen and moss canopies, *Remote Sens. Environ.*, 72:78-94.
Verhoef W. (1984), Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model, *Remote Sens. Environ.*, 16:125-141.
Verstraete M.M., Pinty B., Myneni R.B. (1996), Potential and limitations of information extraction on the terrestrial biosphere from satellite remote sensing, *Remote Sens. Environ.*, 58:201-214.
Vogt P. (1997), Bestimmung des Blattflächenindexes und der absorbierten, photosynthetisch aktiven Strahlung der Vegetation aus bidirektionalen Reflexionsfaktoren am Oberrand der Pflanzendecke, DLR Forschungsbericht 97-25, ISSN 0939-2963, 119 pp.
Weiss M., Baret F., Myneni R.B., Pragnère A., Knyazikhin Y. (2000), Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data, *Agron.*, 20:3-22.