PROSPECT+SAIL: 15 Years of Use for Land Surface Characterization

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State of Science of Environmental Applications of Imaging Spectroscopy (in honor of Dr. Alexander F.H. Goetz)
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Why are we interested in plant canopies?

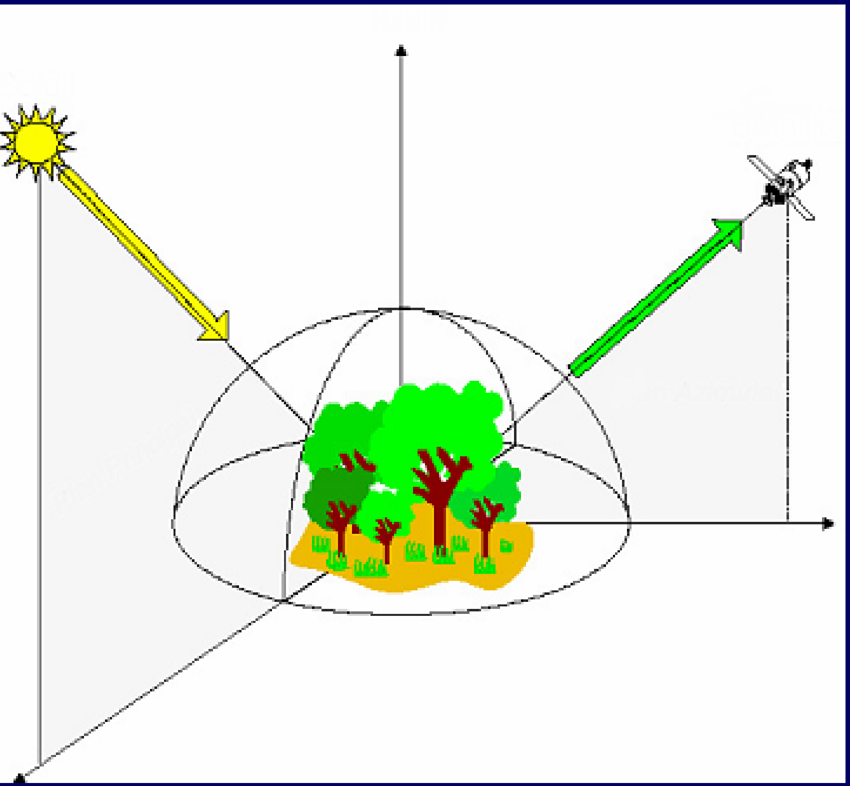
Vegetation provides foundations for life on Earth through ecological functions: regulation of climate and water resources, habitat for animals, supply of food and goods.

Physiological processes at different scales like photosynthesis, evapotranspiration, carbon storage, decomposition of organic matter, etc. partly depend on:

- plant species and age, canopy density and architecture, etc.
- leaf anatomy
- leaf biochemical composition, i.e. photosynthetic pigments, water, carbon, nitrogen, etc.

Plant canopy reflectance in the solar domain (0.4-2.5 µm)

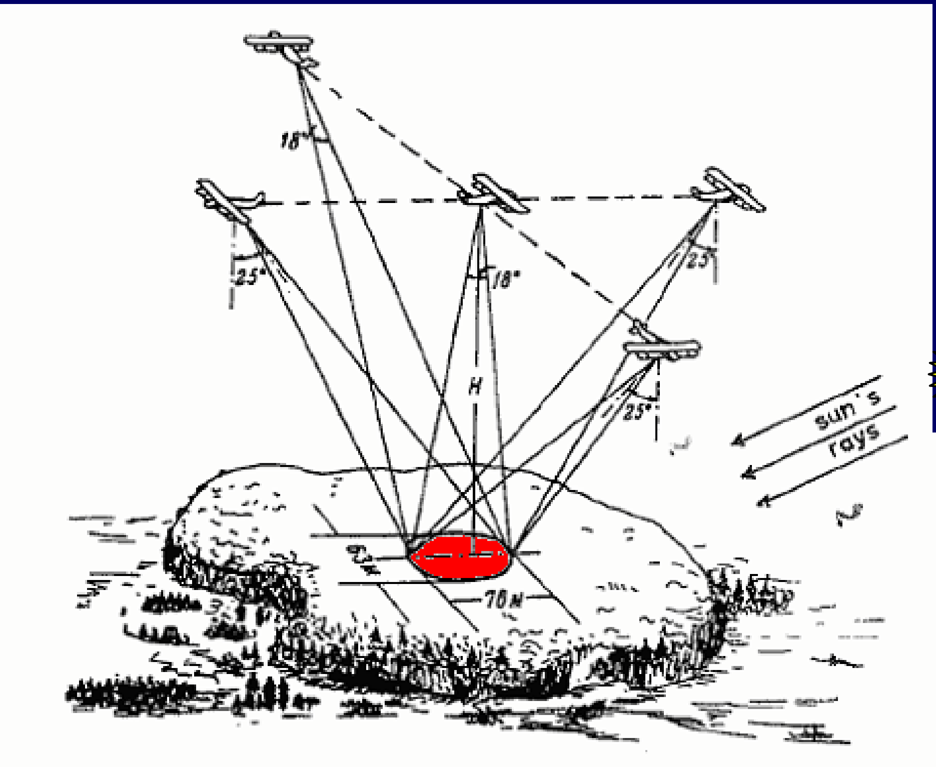
$$\rho(\lambda,\theta_s,\varphi_s,\theta_v,\varphi_v) = \pi \frac{L(\lambda,\theta_s,\varphi_s,\theta_v,\varphi_v)}{E(\lambda,\theta_s,\varphi_s)}$$



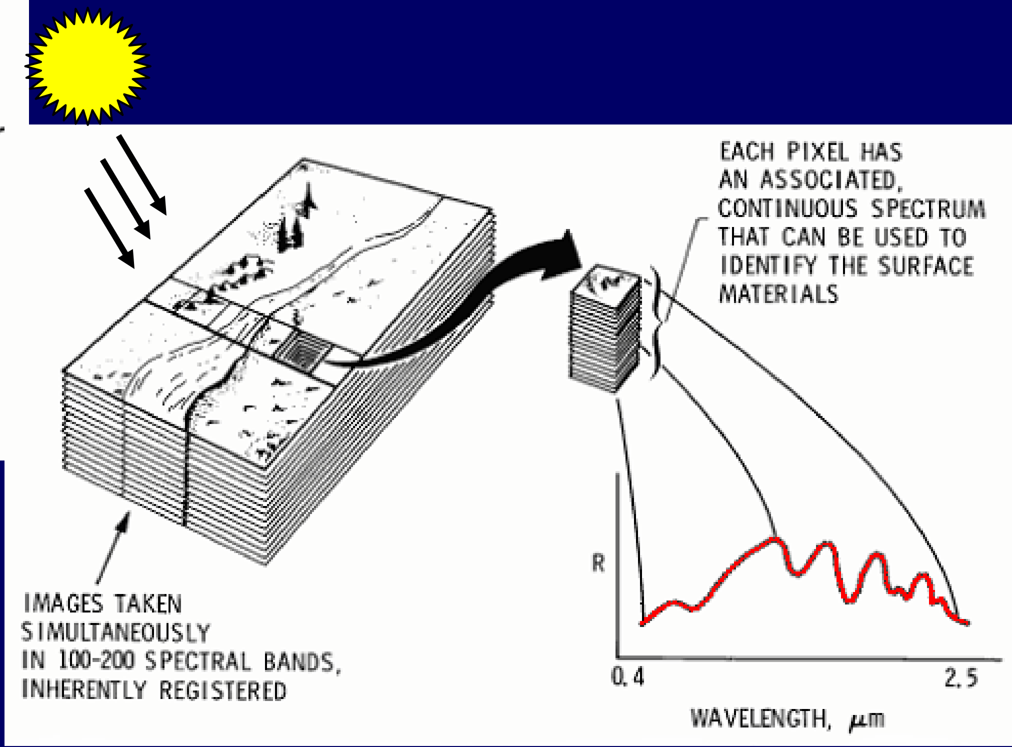
Plant canopy reflectance depends on:

- measurement configuration
- soil reflectance
- leaf reflectance and transmittance
- plant architecture
  - → Leaf Area Index
  - → Leaf Inclination Distribution Function
  - → leaf size / canopy height
  - → cover fraction
  - → etc.
- illumination conditions: diffuse / direct

Spectral or directional reflectance measurements?

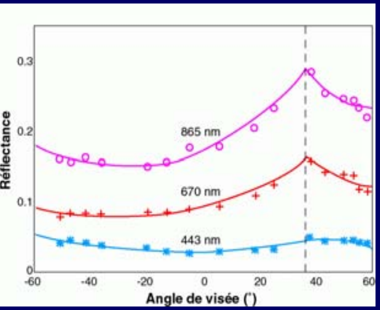


E.S. Arcybashev & S.V. Belov, 1958, The reflectance of tree species, In *Russian Data on Spectral Reflectance of Vegetation, Soil, and Rock Types* (D. Steiner & T. Guterman, eds), pp. 232. Juris Druck + Verlag Zurich.



G. Vane & A.F.H. Goetz, 1988, Terrestrial imaging spectroscopy, *Remote Sensing of Environment*, 24:1-29.

Information content

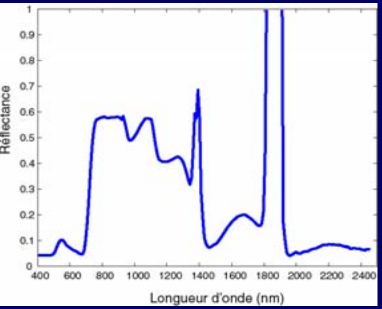


multi-angular measurements

1 wavelength, n viewing angles

information on plant architecture

$$\begin{cases} \rho\left(\lambda,\theta_s,\varphi_s,\theta_v^{(1)},\varphi_v^{(1)}\right) \\ \rho\left(\lambda,\theta_s,\varphi_s,\theta_v^{(2)},\varphi_v^{(2)}\right) \\ \cdots \\ \rho\left(\lambda,\theta_s,\varphi_s,\theta_v^{(n)},\varphi_v^{(n)}\right) \end{cases}$$



multi-spectral measurements

n wavelengths, 1 viewing angle

information on plant biochemistry

$$\begin{cases} \rho\left(\lambda^{(1)},\theta_s,\varphi_s,\theta_v,\varphi_v\right) \\ \rho\left(\lambda^{(2)},\theta_s,\varphi_s,\theta_v,\varphi_v\right) \\ \cdots \\ \rho\left(\lambda^{(n)},\theta_s,\varphi_s,\theta_v,\varphi_v\right) \end{cases}$$

Understanding the RT at different scales

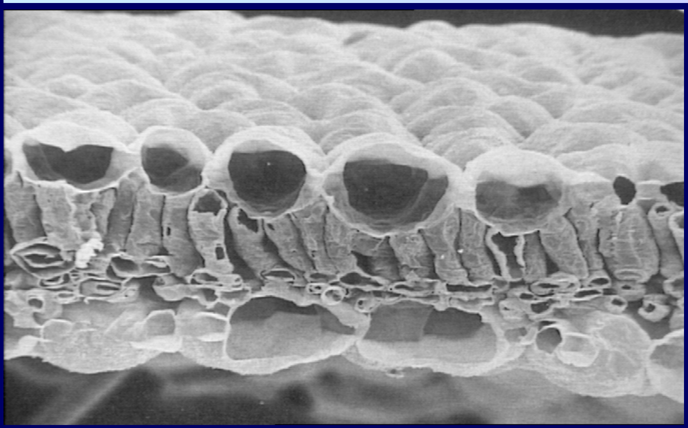
At the canopy level

5 m

At the satellite level

70 km

At the leaf level

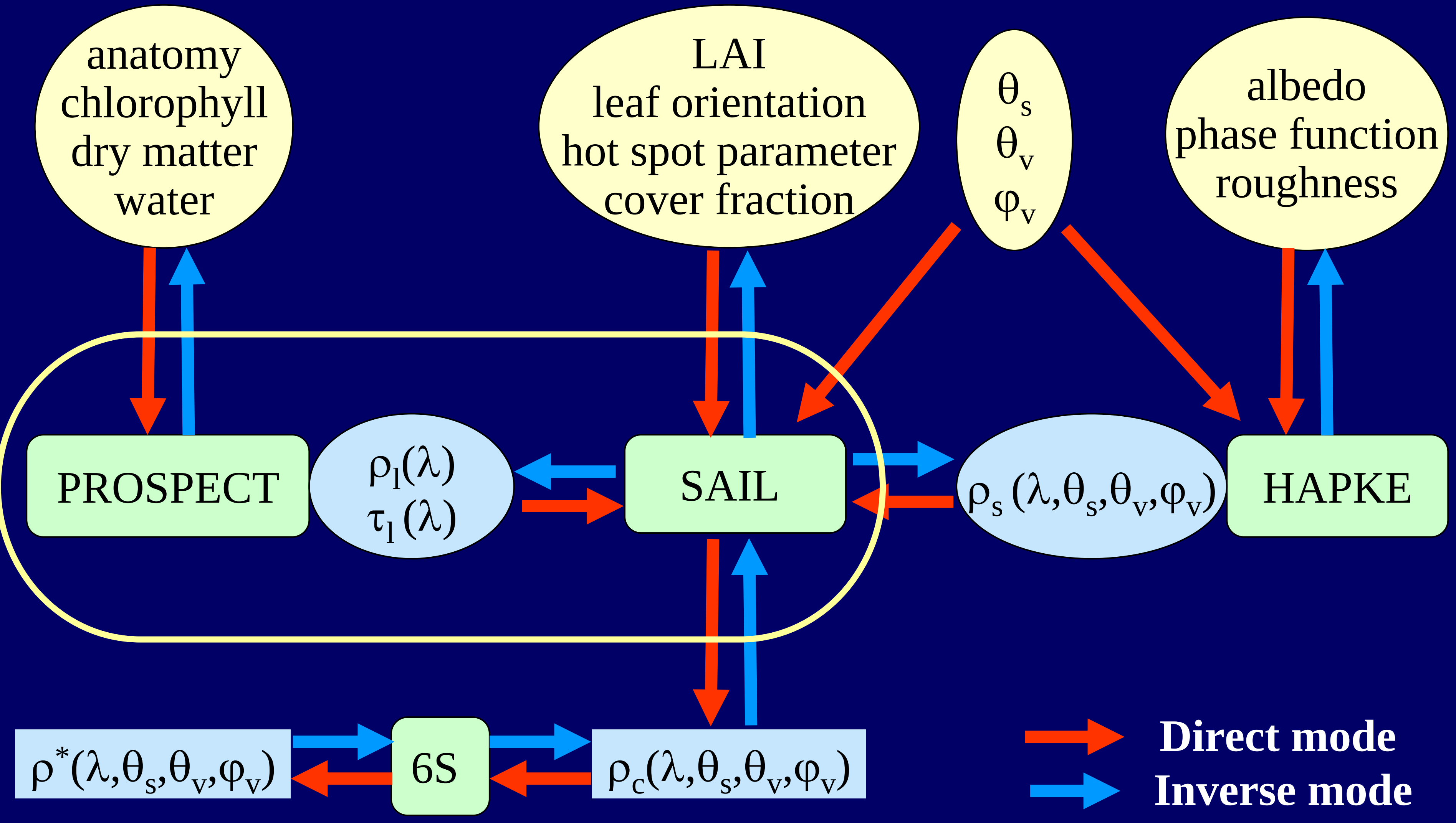


150 µm

At the soil level

50 cm

Coupling of RT models

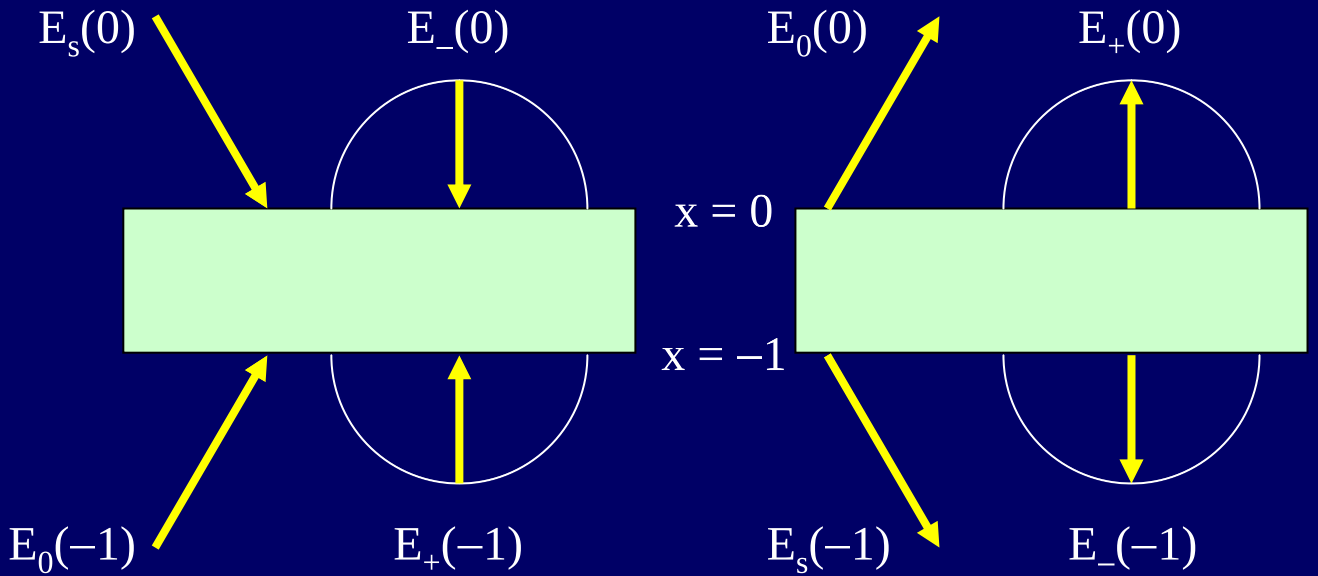


REMOTE SENSING OF ENVIRONMENT 16:125–141 (1984) 125

Light Scattering by Leaf Layers with Application to Canopy Reflectance Modeling: The SAIL Model

W. VERHOEF

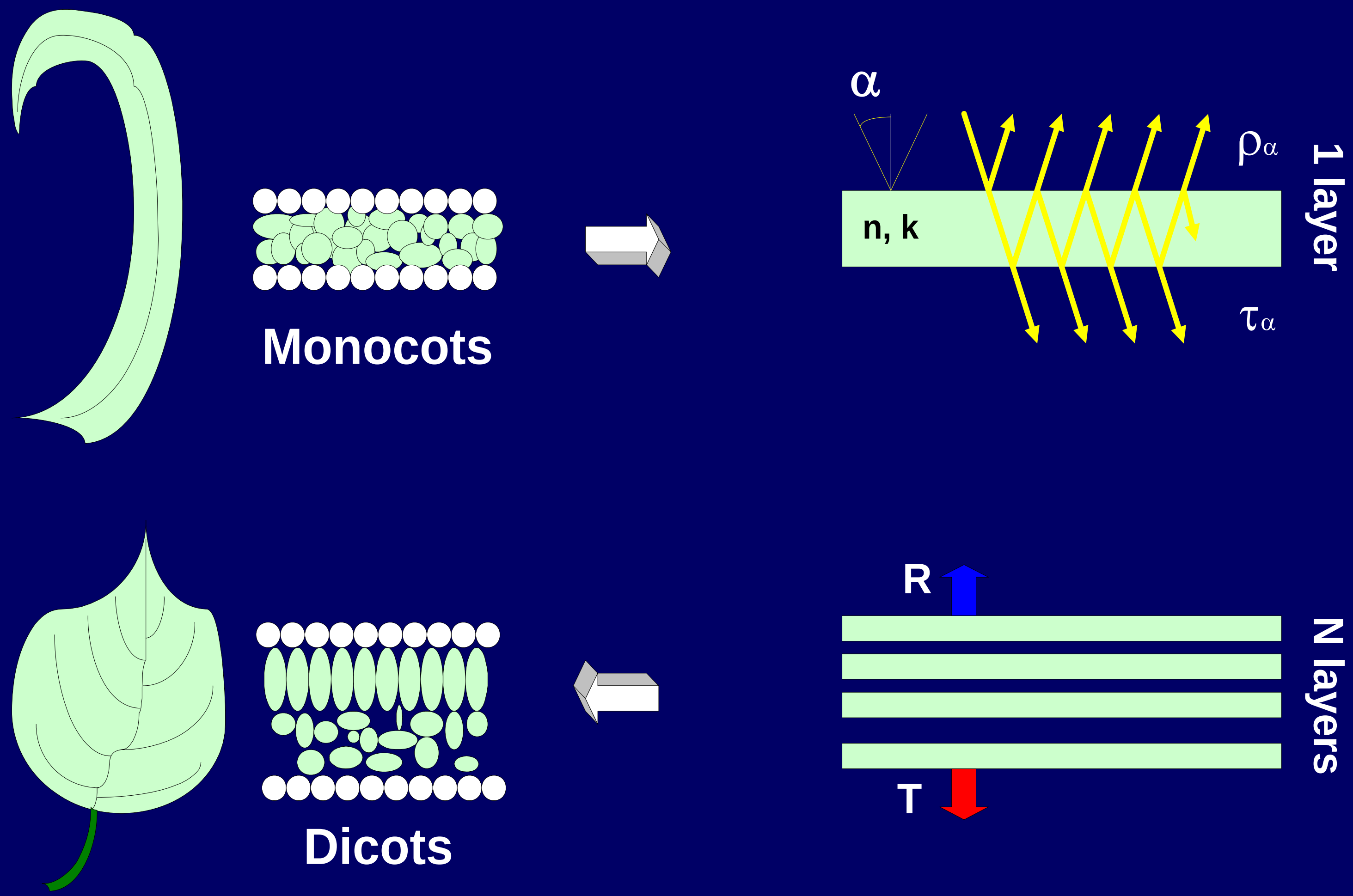
National Aerospace Laboratory NLR, 2 Anthony Fokkerweg, 1059 CM Amsterdam, The Netherlands



REMOTE SENS. ENVIRON. 34:75–91 (1990)

PROSPECT: A Model of Leaf Optical Properties Spectra

S. Jacquemoud and F. Baret
INRA, Station de Bioclimatologie, Montfavet, France



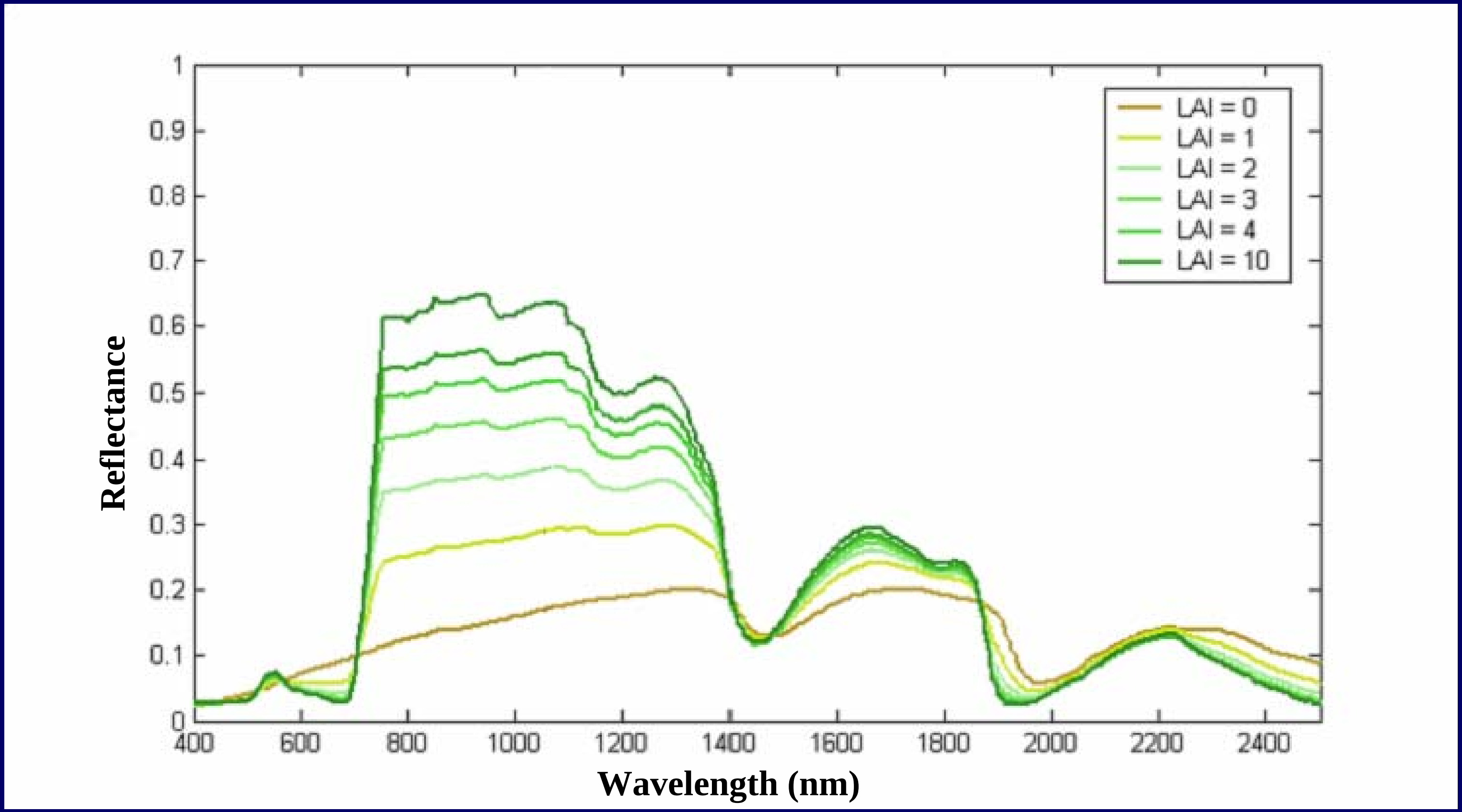
How PROSPECT+SAIL were used in direct mode?

- To study the spectral shifts (red-edge) and deformations as a function of the canopy input variables one-by-one.

- To design or test vegetation indexes:
  Weighted Difference Vegetation Index → LAI
  Transformed Chlorophyll Absorption in Reflectance Index → C_{ab}
  Simple Ratio Water Index → C_w

- To perform sensitivity analyses intended to quantify the contribution of the canopy input variables: selection of optimized spectral bands (number, position, width) and viewing directions (number, position) for new sensors.

Simulations with PROSPECT+SAIL

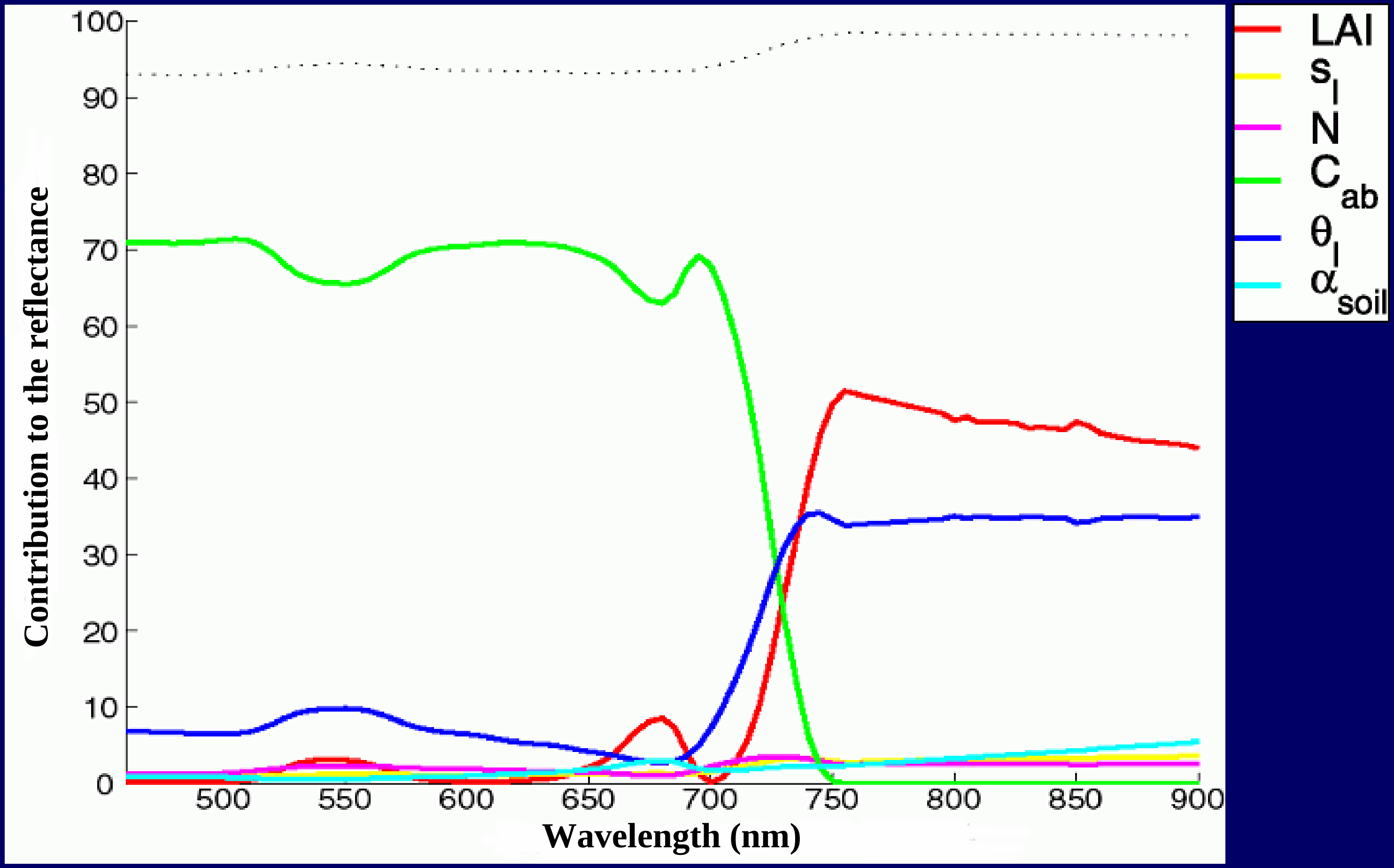


Solar zenith angle: $\theta_s = 20°$
Viewing zenith angle: $\theta_v = 0°$
Leaf orientation: spherical
Horizontal visibility: VIS = 100 km

Leaf structure parameter: N = 1.5
Total chlorophyll content: $C_{ab} = 50\ \mu g\ cm^{-2}$
Water content: $C_w = 0.01$ cm
Dry matter content: $C_m = 0.005\ g\ cm^{-2}$

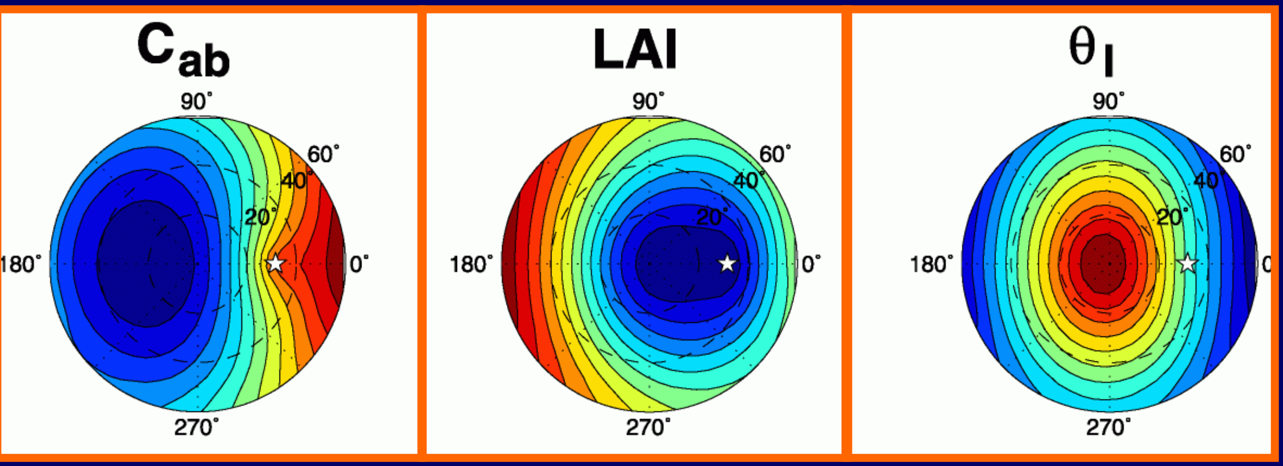
Spectral sensitivity analysis of PROSPECT+SAIL

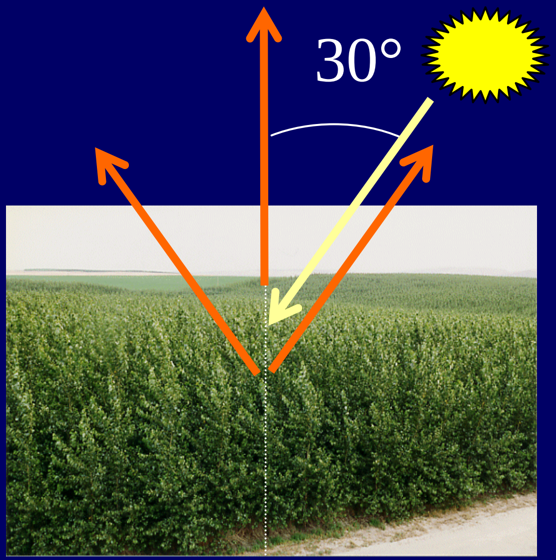
Design Of Experiments for Simulation



C. Bacour, S. Jacquemoud, Y. Tourbier, M. Dechambre & J.-P. Frangi, 2002, Design and analysis of numerical experiments to compare four canopy reflectance models, *Remote Sensing of Environment*, 79:72-83.

Directional sensitivity analysis of PROSPECT+SAIL





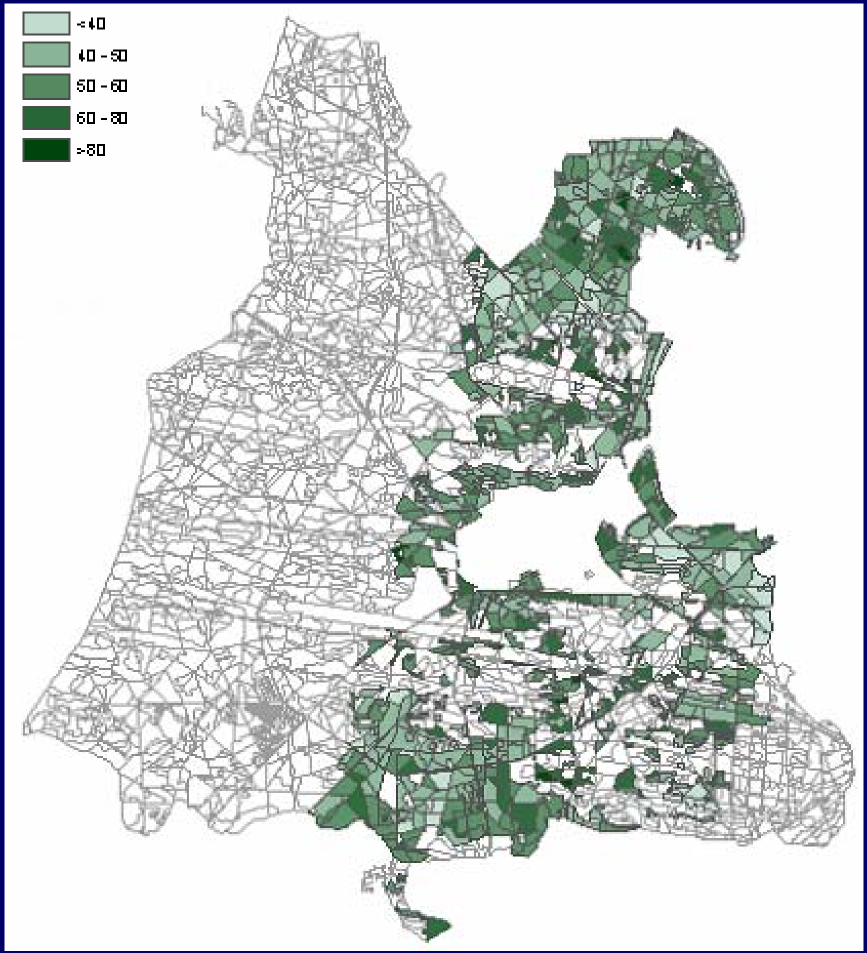
Chlorophyll content

Leaf Area Index

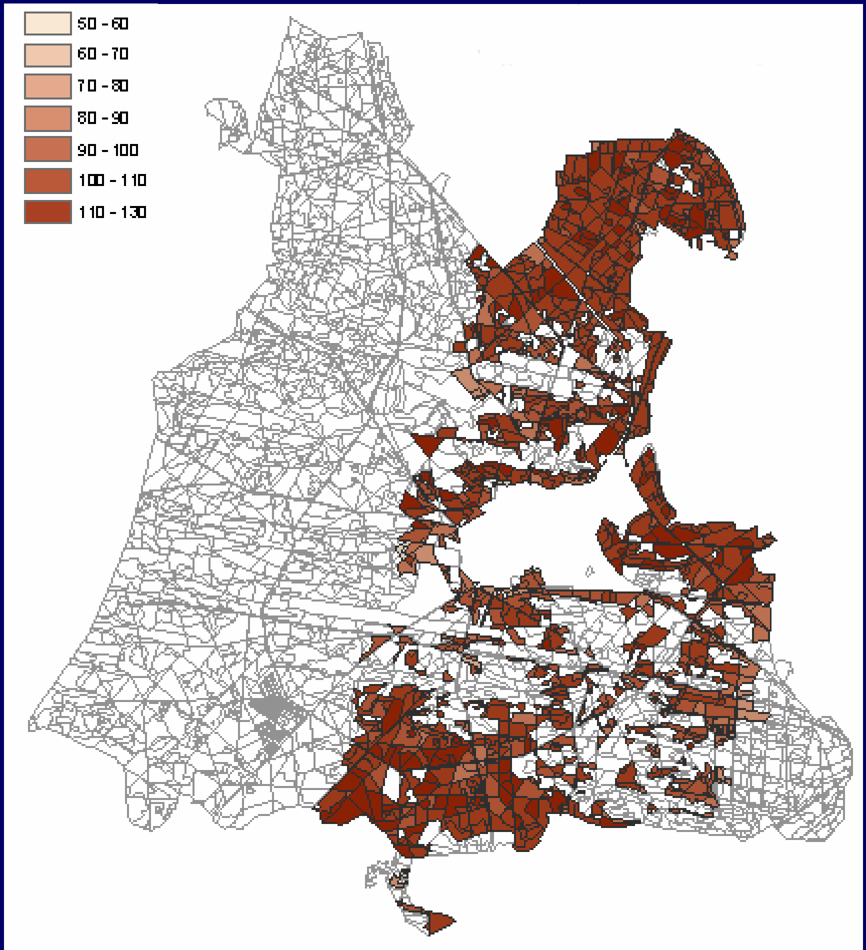
Mean leaf inclination angle

C. Bacour, S. Jacquemoud, Y. Tourbier, M. Dechambre & J.-P. Frangi, 2002, Design and analysis of numerical experiments to compare four canopy reflectance models, *Remote Sensing of Environment*, 79:72-83.

Chlorophyll content (µg cm^{-2})



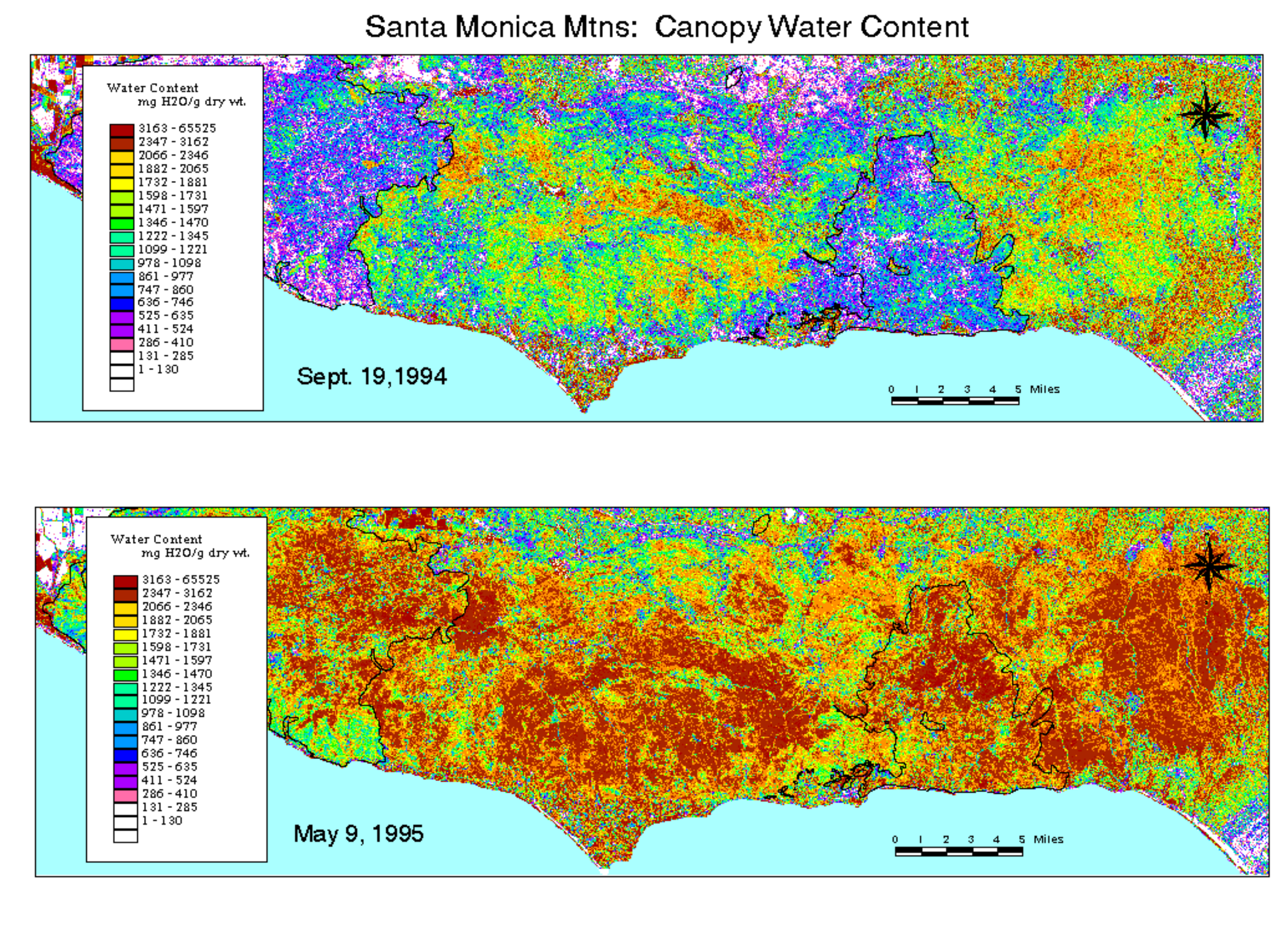
Leaf Mass per Area (g m^{-2})



G. Le Maire, H. Davi, K. Soudani, C. François, V. le Dantec & E. Dufrêne, 2005, Modelling annual production and carbon dioxide fluxes of a large managed temperate forest using forest inventories, satellite data and field measurements, *Tree Physiology*, 25:859-872.

AVIRIS
airborne • visible • infrared • imaging • spectrometer

Water content (mg H_2O / g dry weight)



S.L. Ustin, D.A. Roberts, J.E. Pinzón, S. Jacquemoud, M. Gardner, G. Scheer, C.M. Castañeda & A. Palacios-Orueta, 1998, Estimating canopy water content of chaparral shrubs using optical methods, *Remote Sensing of Environment*, 65:280-291.

How to use PROSPECT+SAILin inverse mode?

iterative algorithms, look-up-tables

calibrated data

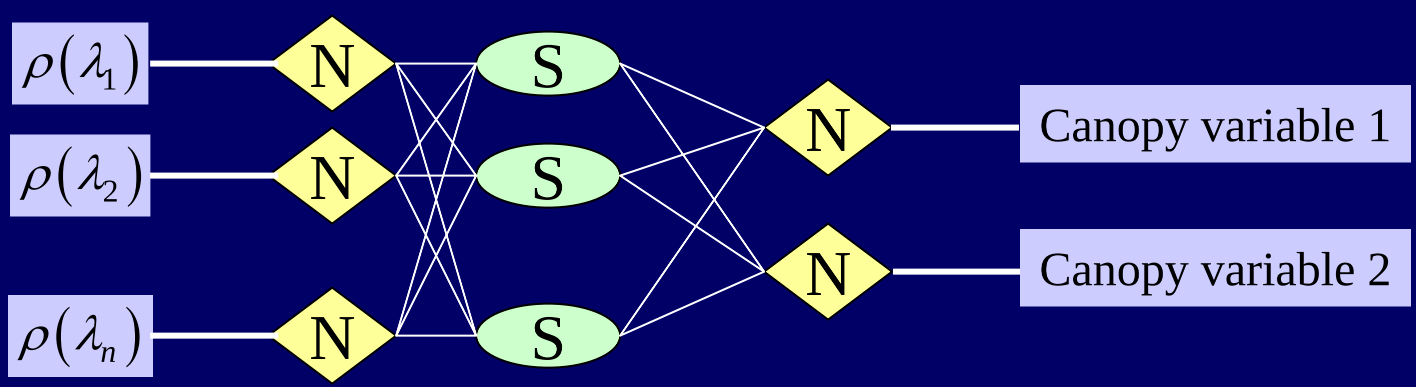
model

minimum distance criterion

$$\chi^2 = \sum_{i=1}^{n} \left[\rho_i - \mathrm{M}(\Theta, X_i) \right]^2$$

artificial neural networks

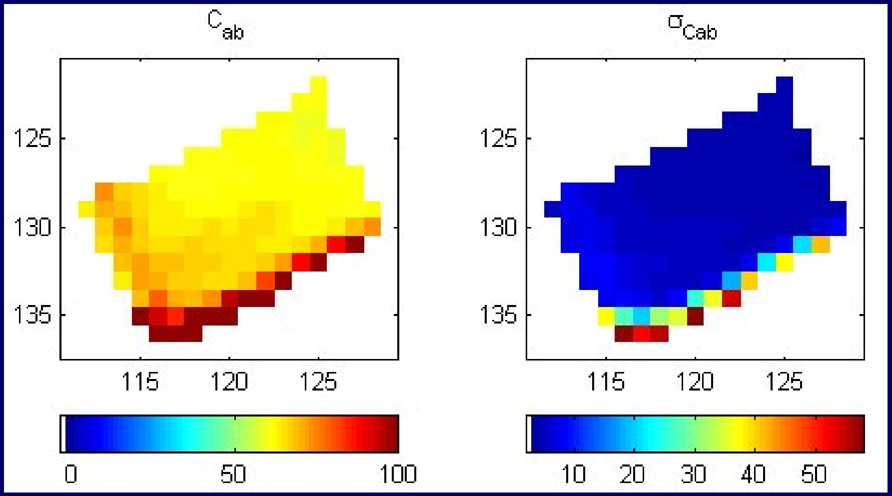
input layer hidden layer output layer



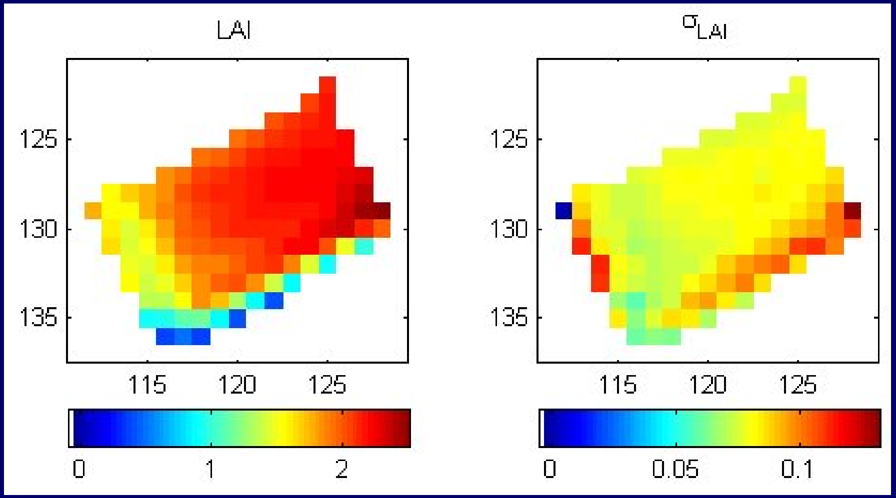
PROSPECT+SAILH inversion performed using iterative methods

Ex Airborne POLDER image (ReSeDA 1997 field experiment)
4 wavebands in the VIS-NIR + about 50 viewing angles

Chlorophyll content (µg cm^{-2})



Leaf Area Index

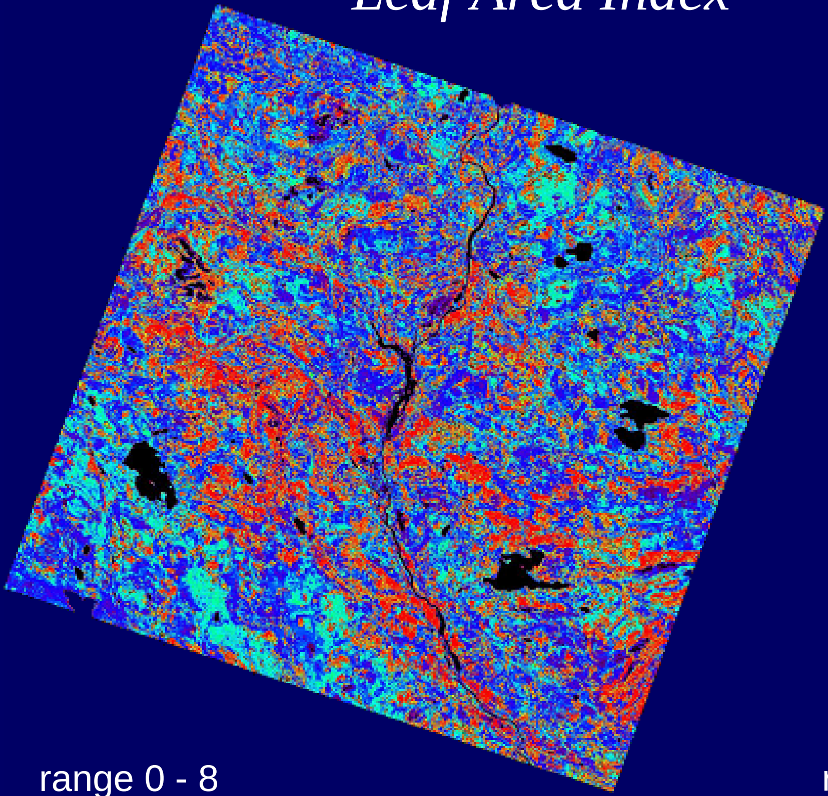


C. Bacour, S. Jacquemoud, M. Leroy, O. Hautecoeur, M. Weiss, L. Prévot, N. Bruguier & H. Chauki, 2002, Reliability of the estimation of vegetation characteristics by inversion of three canopy reflectance models on airborne POLDER data, *Agronomie*, 22:555-565.

PROSPECT+GeoSAIL inversion performed using look-up-tables

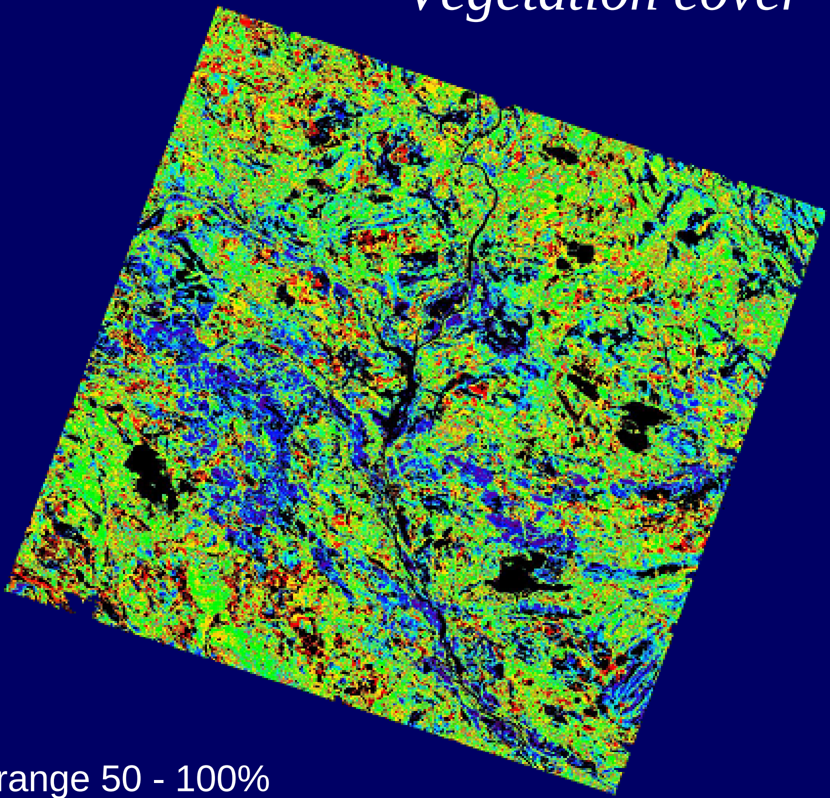
Ex Landsat image (13 August 2002)
3 wavebands in the VIS-NIR + 1 viewing angle

Leaf Area Index



range 0 - 8

Vegetation cover



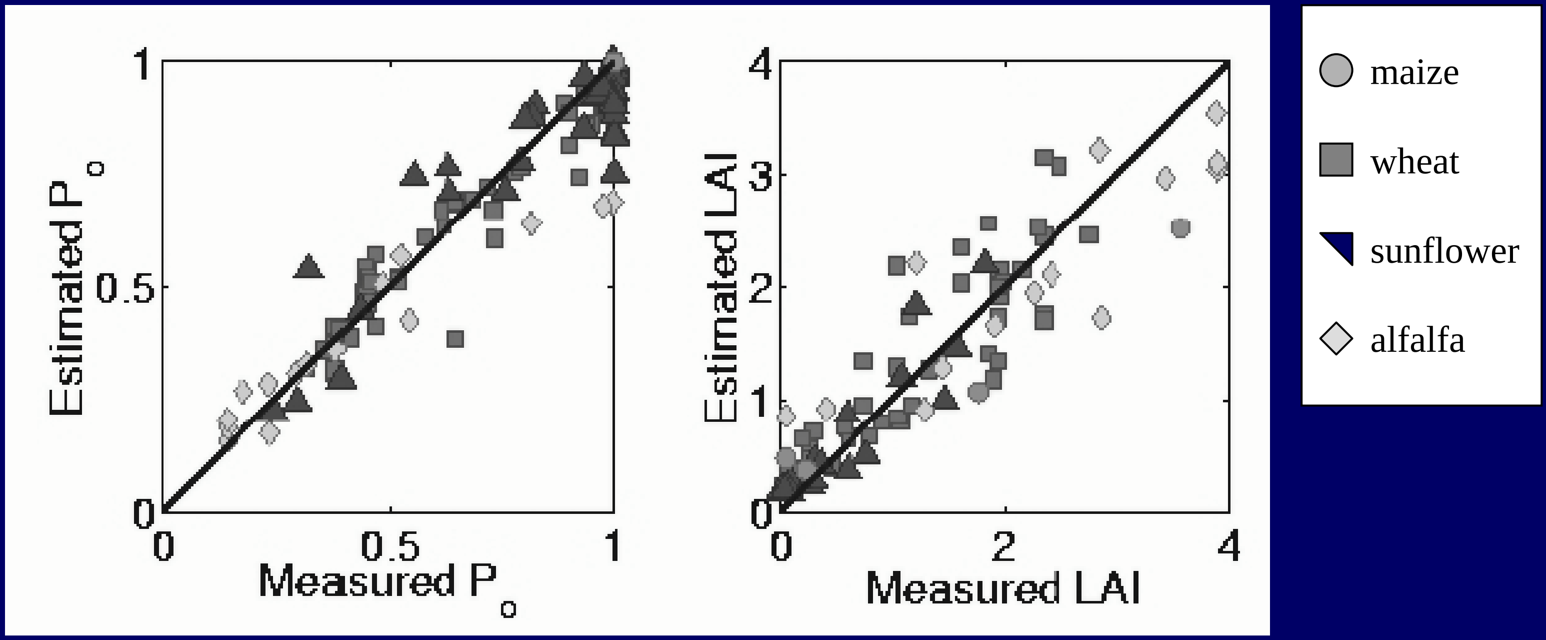
range 50 - 100%

W. Verhoef & H. Bach, 2003, Simulation of hyperspectral and directional radiance images using coupled biophysical and atmospheric radiative transfer models, *Remote Sensing of Environment*, 87:23-41.

PROSPECT+SAILH inversion performed using artificial neural networks

Ex Airborne POLDER image (ReSeDA 1997 field experiment)
4 wavebands in the VIS-NIR + about 50 viewing angles

Gap fraction *Leaf Area Index*



M. Weiss, F. Baret, M. Leroy, O. Hautecoeur, C. Bacour, L. Prevot & N. Bruguier, 2002, Validation of neural net techniques to estimate canopy biophysical variables from remote sensing data, *Agronomie*, 22:547-553.

Conclusion

- PROSPECT+SAIL is now a widely used RT code which has been validated on various natural or agricultural vegetation canopies over the years.

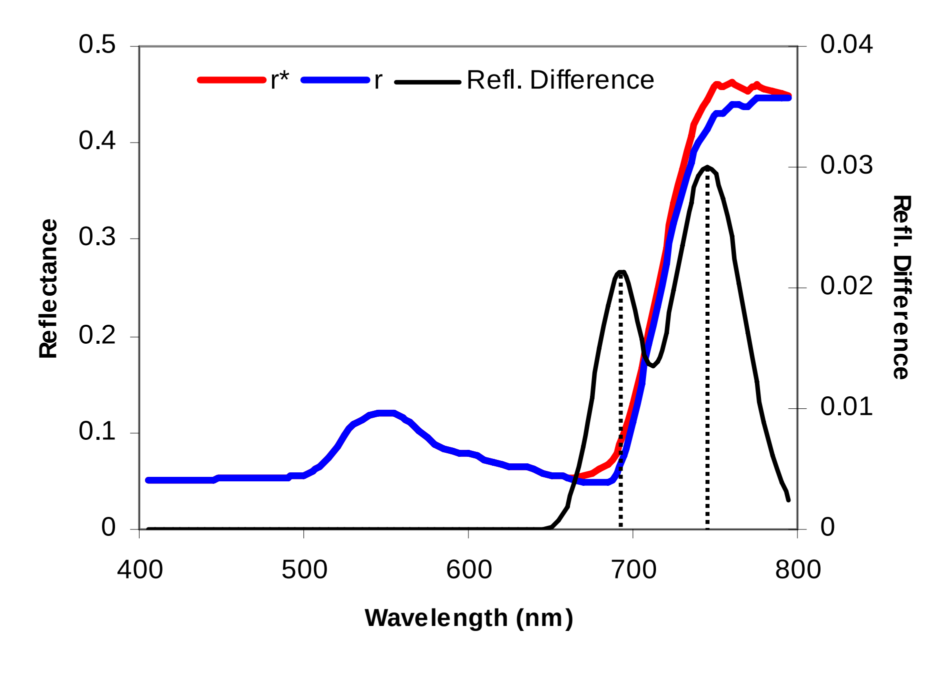
- It is simple, fast, accurate, and accessible to the scientific community.

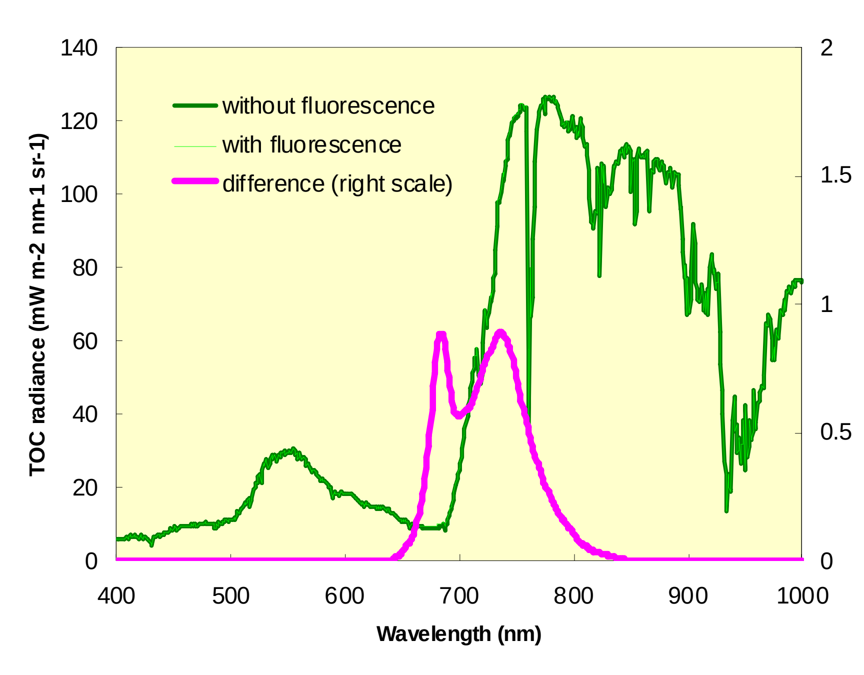
- It links the canopy variables describing the plant biochemistry to the ones describing their architecture and it allows to reduce the dimensionality of the inverse problem when using multispectral or hyperspectral data.

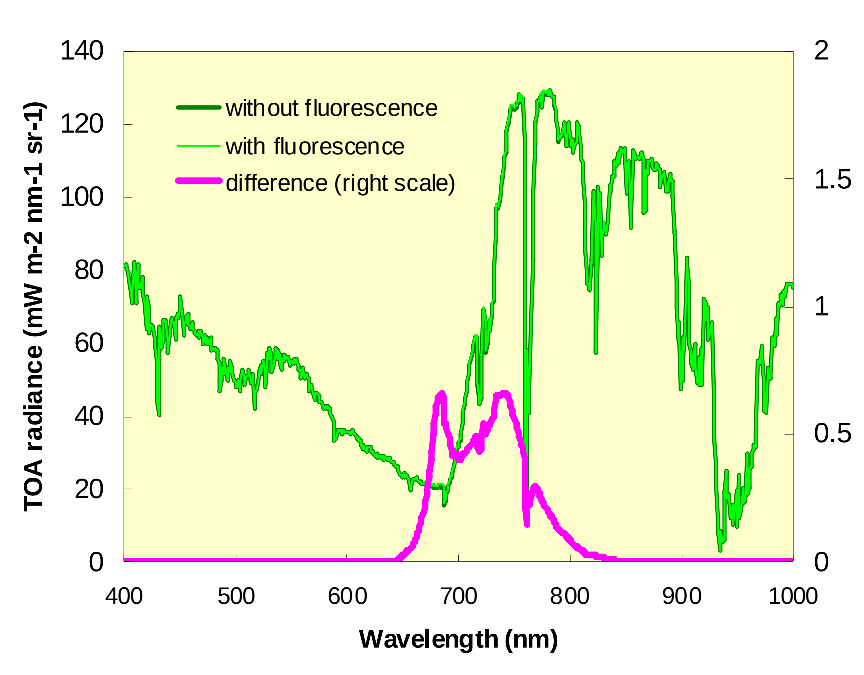
- It is still evolving: the introduction of new leaf pigments, of leaf specular reflectance, of solar induced chlorophyll fluorescence, the consideration of plant heterogeneities (crown clumping effect) will open up new vistas in the monitoring of terrestrial ecosystems.

Latest development: FluoSAIL

PS2 @ 690 nm and PS1 @ 730 nm



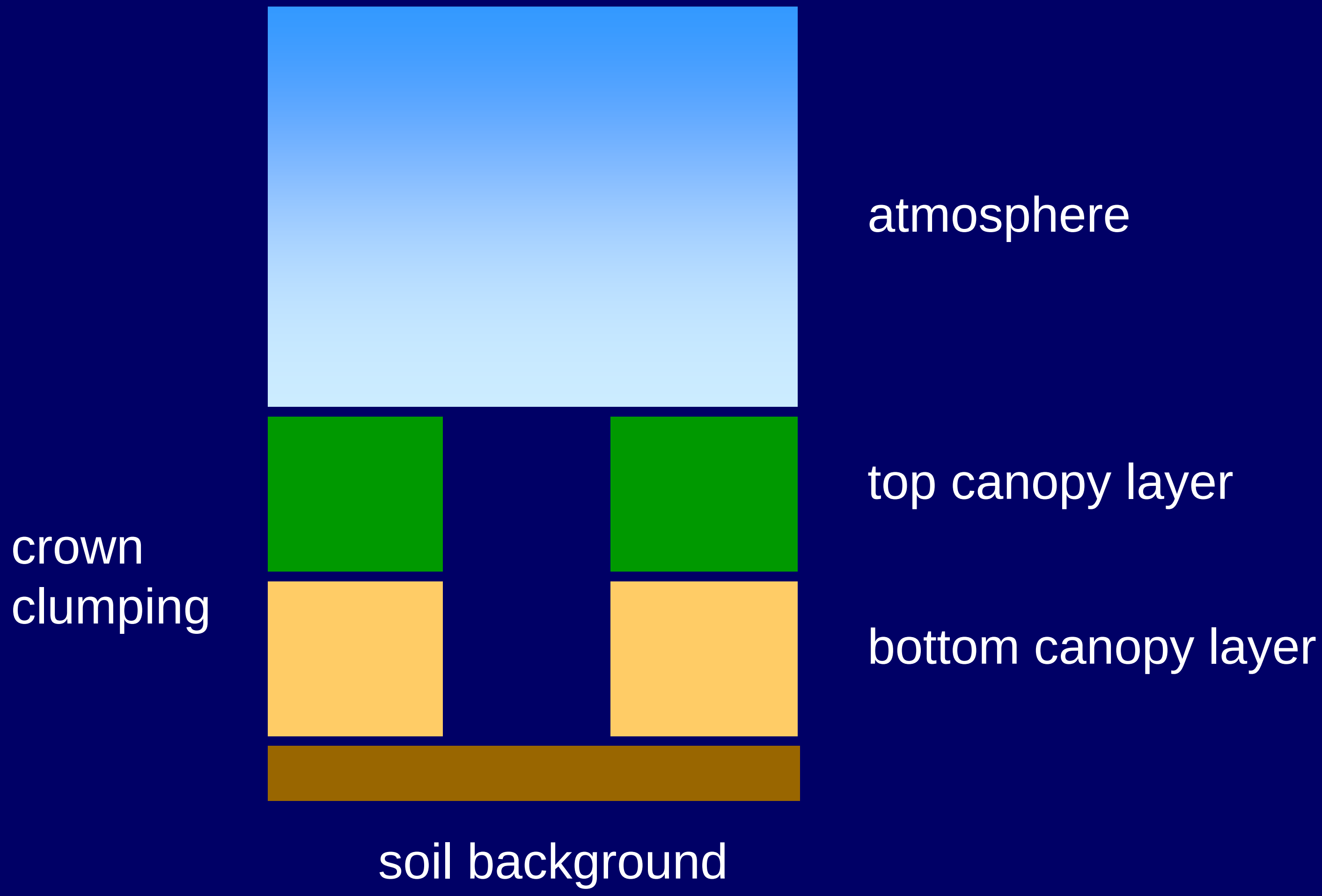




P.J. Zarco-Tejada, J.R. Miller, G.H. Mohammed & T.L. Noland, 2000, Chlorophyll fluorescence effects on vegetation apparent reflectance: I. Leaf-level measurements and model simulation, *Remote Sensing of Environment*, 74:582-595.

J. Miller, M. Berger, Y. Goulas, S. Jacquemoud, J. Louis, G. Mohammed, N. Moise, J. Moreno, I. Moya, R. Pedrós, W. Verhoef & P. Zarco-Tejada, 2005, Development of a Vegetation Fluorescence Canopy Model, ESTEC Contract No. 16365/02/NL/FF, 138 pp.

Latest development: 4SAIL



W. Verhoef, 2005, Earth observation model sensitivity analysis to assess mission performances in terms of geo-biophysical variable retrieval accuracies, in *Proc. 9th International Symposium on Physical Measurements & Signatures in Remote Sensing*, Beijing (China), 17-19 October 2005, pp. 324-327.

Thank you for your attention

Variability of plant canopy reflectance