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Multi-angular hyperspectral observations of Mediterranean forest with PROBA – CHRIS

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ABSTRACT

Measurements of spectro-directional radiances done with the imaging spectrometer CHRIS on-board the agile platform PROBA are being used to determine key properties of terrestrial vegetation at the appropriate spatial resolution. These data on vegetation properties can then be used to improve the accuracy and the parameterizations of models describing biosphere processes, i.e. photosynthesis and water use by irrigated crops and trees.

The vegetation properties considered are: albedo, Leaf Area Index (LAI), fractional cover, fraction of absorbed photo-synthetically active radiation (fAPAR) and canopy chlorophyll content.

The Natural Park of San Rossore (Pisa, Central Italy) is a primary test site for several national and international research projects dealing with forest ecosystem monitoring. In particular, since 1999 measurements of transpiration and ecosystem gas-exchange have been regularly taken in the park pine forest to characterize its main water and carbon fluxes. In the same period, several aerial flights have been carried out with onboard hyper-spectral sensors (MIVIS, VIRS, AISA), while a series of satellite images have been acquired using both conventional (NOAA-AVHRR, Landsat-TM/ETM+) and advanced sensors (CHRIS-PROBA).

The final objective of these activities is to calibrate and validate methodologies which integrate remotely sensed and ancillary data for monitoring forest ecosystem. More specifically, a major research effort has been focused on evaluating the additional information content provided by advanced hyper-spectral multi-angular sensors about the main parameters needed for forest characterization (species, LAI, pigment content, etc.). These activities are part of projects which are financed by the Italian and European Space Agencies (ASI and ESA, respectively) within the framework of the CHRIS-PROBA and SPECTRA missions.

During 2002 and 2003 nine complete multi-angular acquisitions were successfully performed over the San Rossore site. This paper summarizes first results of the evaluation of data acquired so far, particularly forward modeling of Top Of Canopy (TOC) reflectances. The models KUUSK, SAIL and GeoSAIL were used to simulate spectro-directional reflectance of different stands in the forest and compared with PROBA – CHRIS and airborne hyperspectral observations. Deviations of simulated from observed reflectances were significant.

Keywords: hyper-spectral; multi – angular; forest ecosystems; models

1. INTRODUCTION

The monitoring of the carbon stock in terrestrial environments, as well as the improved understanding of the surface-atmosphere interactions controlling the exchange of matter, energy and momentum, is of immediate interest for an improved assessment of the various components of the global carbon cycle. Moreover, observation and understanding of forest ecosystems is necessary to advance towards sustainable management of forest resources, taking into account impacts and variability due to climate and to anthropic disturbances. Observations from space-borne platforms have been widely used for this purpose, because of the comparability of radiometric data in the space and time domains and of the high spatial and temporal resolution. (Waring and Running, 1998). From an operational point of view there are several challenges ahead, mainly due to the complex relationship between spectro – directional radiometric data collected in space and the state variables and parameters that characterize forest ecosystem processes. The heterogeneity, both in terms of species associations and of canopy architecture, and complexity of Mediterranean forest add to this challenge.

Many vegetation properties are related to features of reflectance spectra in the 400 nm – 2500 nm. region (e.g. Verstraete et al., 1996; Menenti, 2001). Detailed observations of spectral reflectance reveal subtle features related to biochemical components of leaves such as chlorophyll and water. The architecture of vegetation canopies determines complex changes of observed reflectance spectra with view and illumination angle. Quantitative analysis of reflectance spectra requires, therefore, an accurate characterization of the anisotropy of reflected radiance. This can be achieved with nearly – simultaneous observations at different view angles. The CHRIS spectrometer has a limited spectral coverage, namely 400 nm – 1100 nm., but provides for the first time ever nearly – simultaneous observations at five different view angles between a 55^0 and a 55^0 backward view and at high spatial resolution of the same land target. On the other hand, most of the scientific and practical knowledge on the use of radiometric data to monitor forest ecosystems relies on the use of simpler multi-spectral observations.

Accordingly, we are working towards two complementary objectives:

a) Develop and validate methods to exploit simpler multi-spectral such as the ones collected by NOAA-AVHRR and Landsat-TM/ETM+ with meteorological and vegetation observations to model exchanges of energy, water and CO2 through photosynthesis and transpiration.
b) Evaluate the added value of advanced hyperspectral, multi-angular systems towards the accuracy of retrieved vegetation state variables and parameters (e.g. species association, chlorophyll content, Leaf Area Index)

Experimental work needs to be limited to land areas of limited extent because of the need to characterize forest ecosystems in great detail, including observations on the atmosphere, weather, soils and physiological processes. The research site where this investigation is being carried out is the protected area of San Rossore (Pisa), where other research organizations are active, namely the Joint Research Centre (EU), the Universities of Bologna and Florence, IBIMET-CNR and IFAC-CNR.

2. MATERIALS AND METHODS

Description of test site. The park of San Rossore, placed in the coastal plain near Pisa, is a typical Mediterranean climate with average annual temperature of 14.8°C and rainfall of 900 mm. Its pine forest is characterized by the presence of *Pinus pinaster* Ait. and *Pinus pinea* L. and has been selected as a calibration site for remotely sensed data within a Mediterranean forest in Tuscany. This choice is due to its favorable geographical position, being situated in a flat area easily reachable. In addition, ancillary data and previously collected information are already available for the area. The data available for the Natural Park are:

- 1:25.000 maps published by the Region of Tuscany.
- A digital land cover map of the study area, reporting also the boundaries of all forest stands; it was derived from the 1984-1994 Forest Management Plan of the Park.
- The Forest Management Plan of the Park. For each stand, it provides information on forest type, average diameter at breast height, average height, density of plants and basal area. In addition it contains indication of soil texture, soil depth and mineral content.
- Meteorological data recorded at two stations close to the study area: one is situated in Livorno and the other in Pisa. They are available from 1950 till 2002.
- Additional micro-meteorological and eco-physiological measurements taken by a tower placed in the pine forest near the centre of the park. The tower is measuring photosynthetic fluxes by the eddy covariance method since 1999; it also registers meteorological data at fifteen minutes intervals.
- Land cover references of 12 classes collected by ground survey near the coastline of San Rossore in June, 2000.
- Biometric measurements, including diameter at breast height, tree height and density, taken during summer 2001 within about 20 sample plots mainly placed in the pine forest. The centre of each plot was determined by the use of a grid of 400x400 meter, which is the same as for the Regional forest inventory. Circular plots were used, which are easily identified by the coordinates of the central point, with a radius of 15 m which is consistent with the resolution of Landsat TM images
- Temporal evolution of the Leaf Area Index observed during the 2001 growing season in the same plots as above; these data were collected using LAI 2000 Plant Canopy Analyser by Licor-2000.

- Additional meteorological records taken during the AISA flight campaign (16 August 2001), by a portable meteorological station measuring: Wind speed (m/sec); Wind direction (°); Global radiation (W/m2); Air temperature (°C); Soil temperature (°C); Relative humidity (%).

All these data have been used as ground reference for the calibration and analysis or the high resolution remotely sensed data considered in the project.

Ground observations of temporally stable forest state variables. During the growing seasons 2002 and 2003, 10 ground sample plots (fig. 1) were selected within the forest (the selection was driven by ecological and practical considerations). In particular, these are circular plots, with a radius of 15 m, and were identified by the coordinates of the central point. Geographical position of the centre was determined with a Geographical Positioning System (GPS). For each plot observations of the following forest state variables were collected:

- Tree and shrub species included in the plots.
- Crown-cover and understory layer cover.
- Average diameter at breast height (DBH; cm).
- Tree height (m) of some selected trees, representative of the main diameter classes.
- Basal area (m2/ha).
- Density.
- Volume (m3/ha).

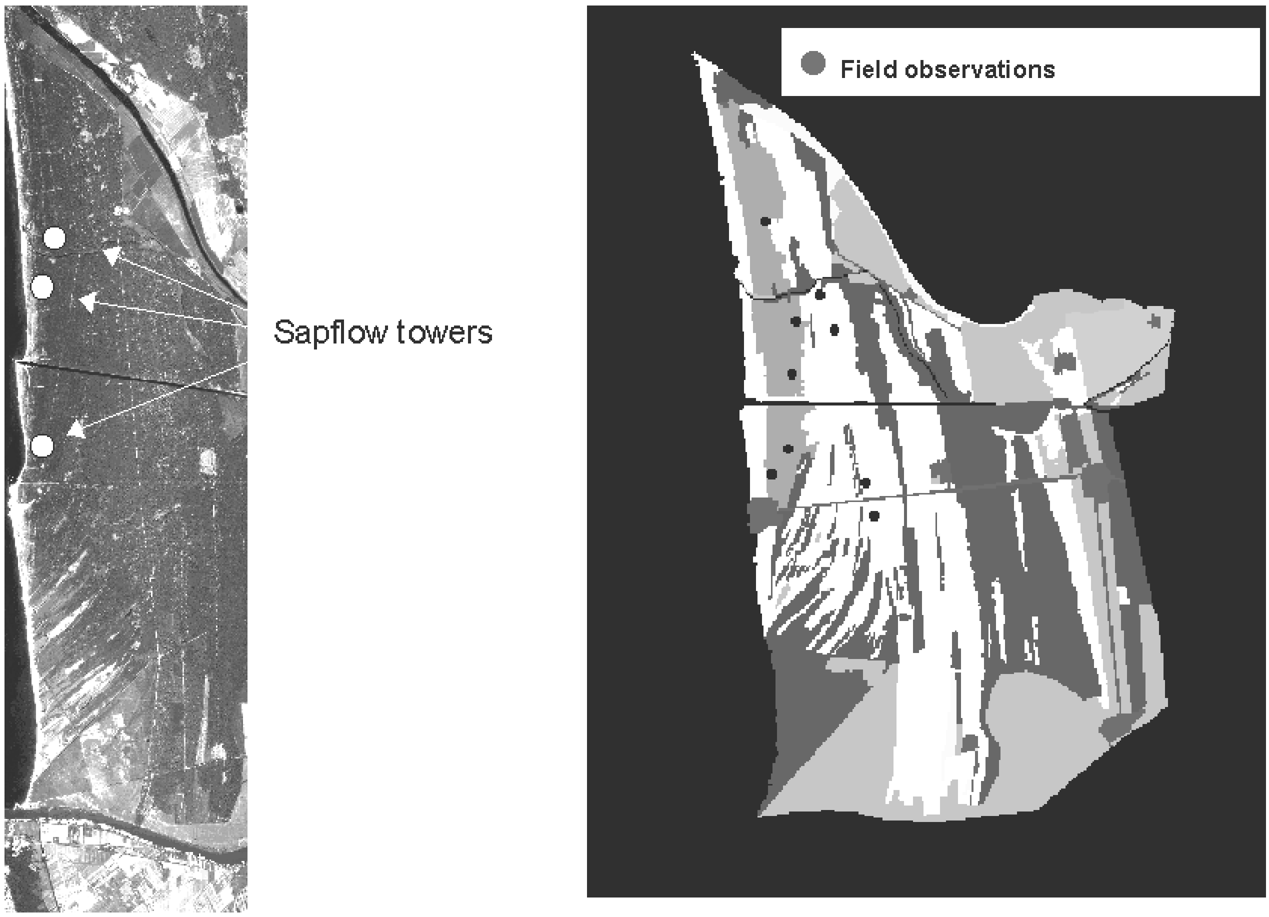

Figure 1 Location map of the San Rossore test site; location of sampling plots and of sap-flow measurements is indicated

Eco-physiological observations. During the 2002 and 2003 growing seasons, at the time of expected PROBA – CHRIS data acquisitions and good weather conditions, additional observations were performed within the same 10 stands. In particular the following measurements were done:

- LAI measurements: they were done using the LAI-2000 Plant Canopy Analyser (Li-cor, USA), an instrument which gives estimations based on light interception measurements comparing the incoming diffuse radiation to that measured under the canopy. Specifically, it measures the radiation through a fish-eye lens and uses a relationship between gap fraction and LAI to determine the real canopy cover (Eklundh *et al.*, 2001). Each sampling, collected after storing a light measurement above canopies, was carried out taking six different measurements along a linear transect of about 30 m.
- Leaf water content: it was determined on five needle samples per each plot. In particular, after collection, needle fresh weight was determined and samples, after 48 hours at 80°C in a dry oven, were weighted again.
- Leaf pigment content: it was also measured on five samples per plot by a spectro-photometric method. Both chlorophyll (*a* and *b*) and brown pigment contents were determined.

Modelling of the stand spectro – directional reflectance. The good-quality CHRIS-PROBA acquisitions over San Rossore were radiometrically and atmospherically corrected as described by Barducci et al. (2004) and co-located with the ground measurements. Re-sampling was done with a nearest-neighbor algorithm trained on ground control points, with a final co-location accuracy of approximately 1 pixel. The spectro-directional signatures of two of the ten stands were compared with simulated hyper-spectral, multi-directional signatures using the KUUSK model (Kuusk and Nilson, 2000). This radiative transfer based model accepts as input forest architectural parameters (tree height and density, crown shape and size, plant distribution, LAI etc.) and single leaf properties (chlorophyll and brown pigment content, water and dry matter content, etc.). The latter are necessary to obtain leaf reflectance and transmittance with the PROSPECT model (Jacquemoud and Baret, 1990). Stand reflectance was also simulated using the models SAIL (Verhoef, 1984) and GeoSAIL (Huemmerich, 2001). The model SAIL treats a vegetation canopy as a horizontally uniform layer of a turbid medium with arbitrarily inclined Lambertian leaves. The model GeoSAIL combines SAIL with the geometrical model of Jasinski and Eagleson (1990), which treats a vegetation canopy as being composed of randomly distributed 3D elements (individual plants). After calculating leaf reflectance, the 3D distribution of leaf radiance is calculated taking into account the distribution and shape of the 3D elements. Fractions of sun – lit and shadowed foliage and fractions of sunlit and shadowed soil are calculated taking into account sun – position, but neglecting mutual shadowing of canopy elements.

3. RESULTS

Simulated vs. observed spectro – directional reflectance. From the CHRIS images acquired on June 16th 2003, the hyper-spectral, multi-directional TOC reflectance of three stands was extracted for further analysis (figure 2). There are no evident artifacts in the reflectance spectra and anisotropy is rather significant. These observations were collected with the sun at 21^0 zenith and 157^0 azimuth. The Flyby Zenith Angle FZA = $+55^0$, i.e. D3 in Figure 2, should capture forward scattered photons, FZA = $- 55^0$, i.e. D4, backward. The PROBA – CHRIS observations agree, therefore, with the expected shape of BRDF for given illumination conditions.
Simulated spectro – directional reflectance, using the Kuusk and Nilson (2000) model, was compared with the TOC reflectance retrieved with PROBA – CHRIS data. Results shown for a stand of Pinus pinaster (figure 3) provide conflicting evidence. On the one hand, model and observations agree to some extent, namely at shorter wavelengths and at nadir and FZA = $- 55^0$. On the other hand, differences between observed and simulated reflectance are very large in the NIR region. Also, observed reflectance at FZA = $- 36^0$ is generally lower than at FZA = $+ 55^0$, the other way round for simulated reflectance.
As explained above, the SAIL and GeoSAIL models were also used to simulate the spectro – directional reflectance of the forest stands at San Rossore and the results compared with measurements done with two different hyper-spectral sensors, MIVIS and CHRIS. The airborne system MIVIS does not have the capability of observing land targets at multiple view- angles and the comparison is limited, therefore to CHRIS nadir viewing. The two sets of measurements agree rather well and are regarded, therefore, as a reliable reference. The SAIL model seems not suitable to reproduce observations, notwithstanding the use of direct measurements to characterize leaf composition, while significantly better results were obtained with GeoSAIL. Deviations were still significant, however: in the chlorophyll absorption region simulated reflectance is significantly lower than observations, which suggests that the spectral absorption coefficients may not be correct. On the other hand NIR-reflectance is much higher than observations when simulated with SAIL and significantly lower when GeoSAIL is applied. The latter suggests that the estimations of sunlit and shadowed soil and foliage may not be correct. The latter issue is evaluated in some detail in the next section.

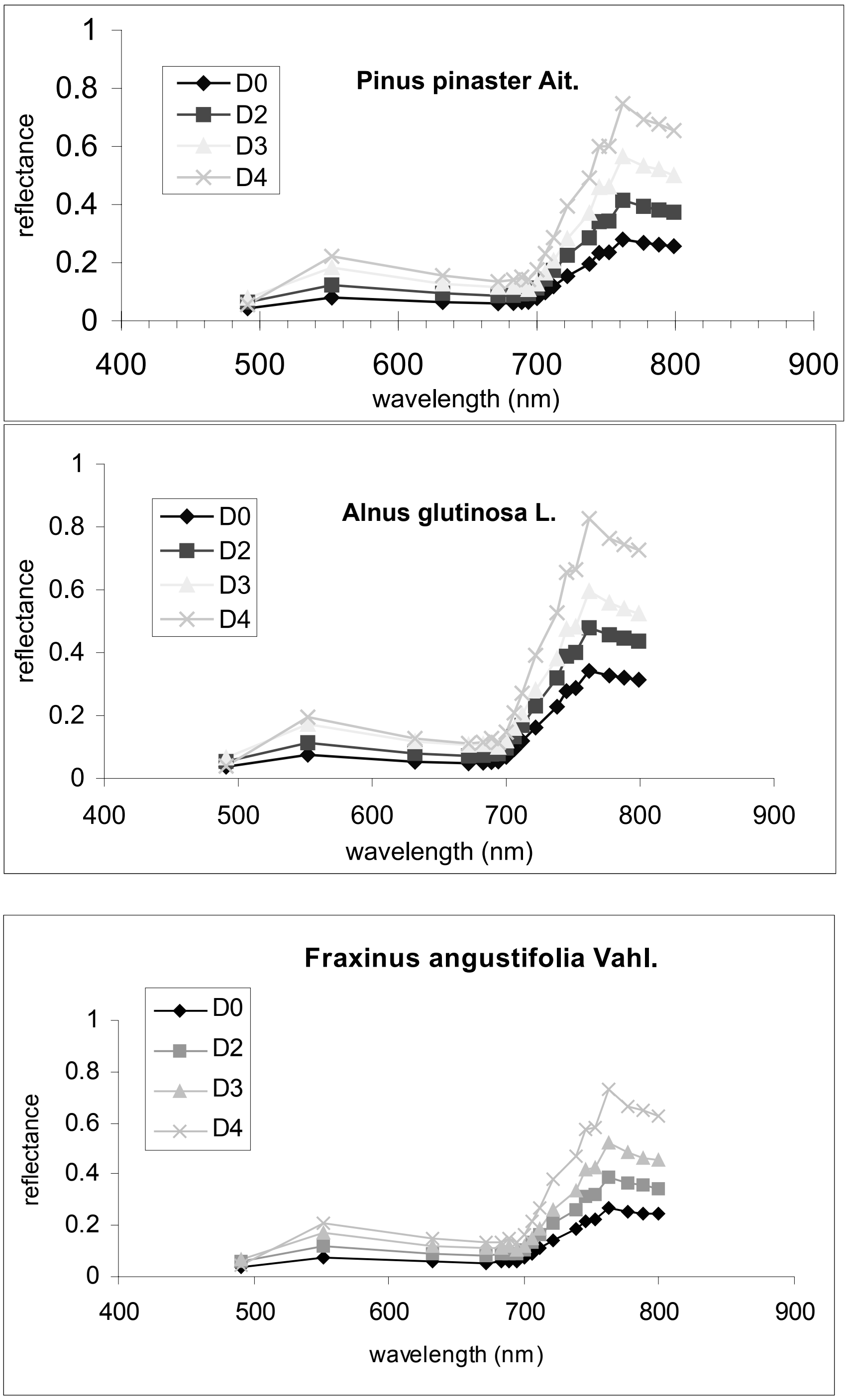

Figure 2 Spectro – directional TOC reflectance of three stands at four view angles D0=0°, D2= - 36, D3= +55° e D4=–55°: A) Pinus pinaster, B) Alnus glutinosa and C) Fraxinus angustifolia; PROBA – CHRIS June 16th , 2003; San Rossore, Italy.

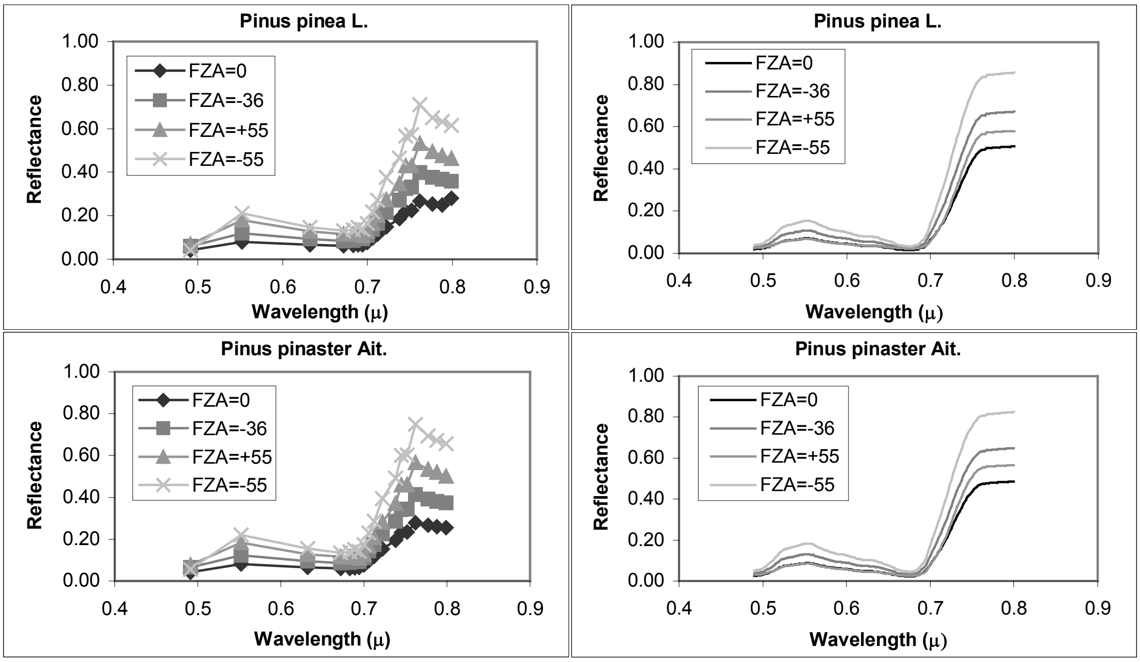

Figure 3 Spectro – directional TOC reflectance of Pinus Pinea (top) and Pinus Pinaster (bottom) stands at four view angles D0=0°, D2= - 36, D3= +55° e D4=–55°; observed (left) and simulated (right) using the RT model by Kuusk and Nilson (2000); PROBA – CHRIS June 16th, 2003; San Rossore, Italy.

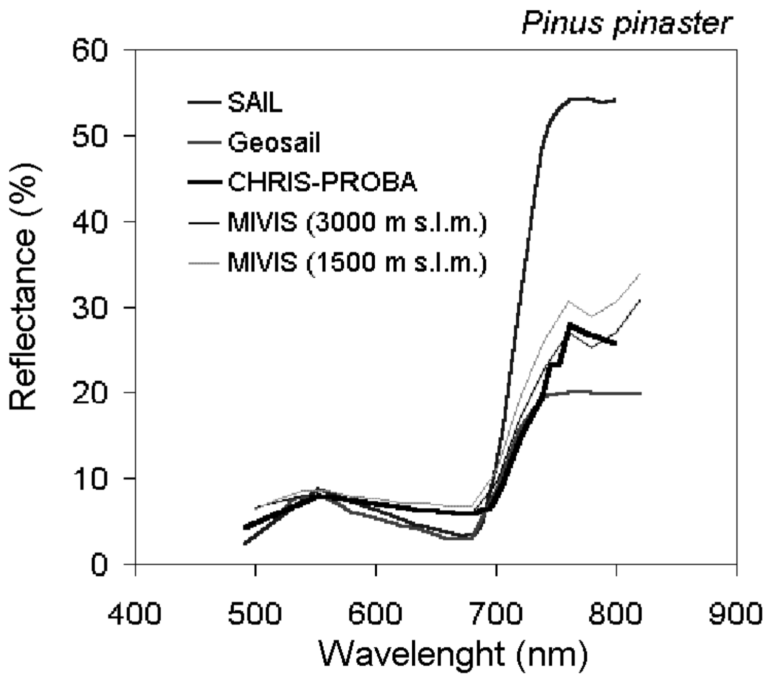

Figure 4 Spectral reflectance of Pinus Pinaster observed with two hyper-spectral systems: MIVIS from two flight altitudes and CHRIS; PROBA – CHRIS June 16th , 2003; MIVIS June 21st, 2000; San Rossore, Italy

4. DISCUSSION

The observed complex dependence of reflectance on view and illumination conditions is due to three main factors:

a) The inherent anisotropy of foliage, e.g. as described by SAIL for a layer of arbitrarily inclined leaves (turbid medium approximation);
b) The contrast between soil and foliage within a partial canopy, with soil usually brighter than foliage in the VIS region and darker in the NIR, implies that VIS reflectance is higher at nadir, while NIR reflectance is lower, than at higher view zenith angles (for given illumination conditions);
c) The CHRIS footprint is comparable with tree height and spacing: under these conditions the target observed changes (significantly) with view angle.

The effect of factor (a) is illustrated by the spectro – directional reflectance in figures 3 and 4, the effect of factor (b) is described in a simplified way by the GeoSAIL model, the effect of factor (c) is not described by any of the models used in this study. To interpret the results presented above is necessary to evaluate in some detail the deviations of simulated from observed reflectance.

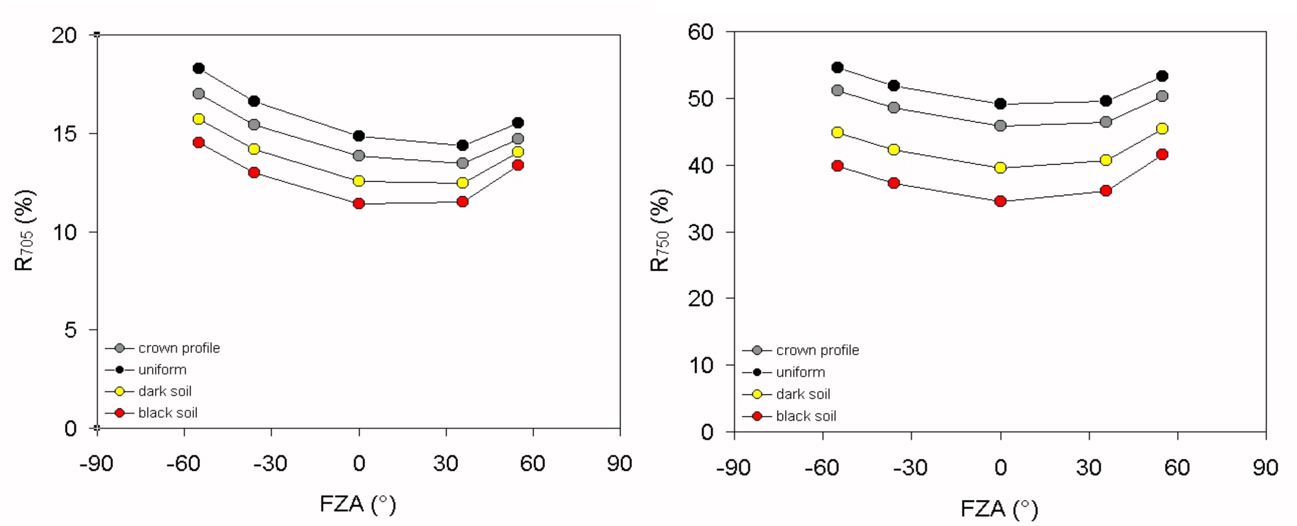

Figure 5 Simulated spectro – directional reflectance of a Pinus pinaster stand at λ = 705 nm (left) and 750 nm (right) simulated using the model SAIL; San Rossore, Italy;

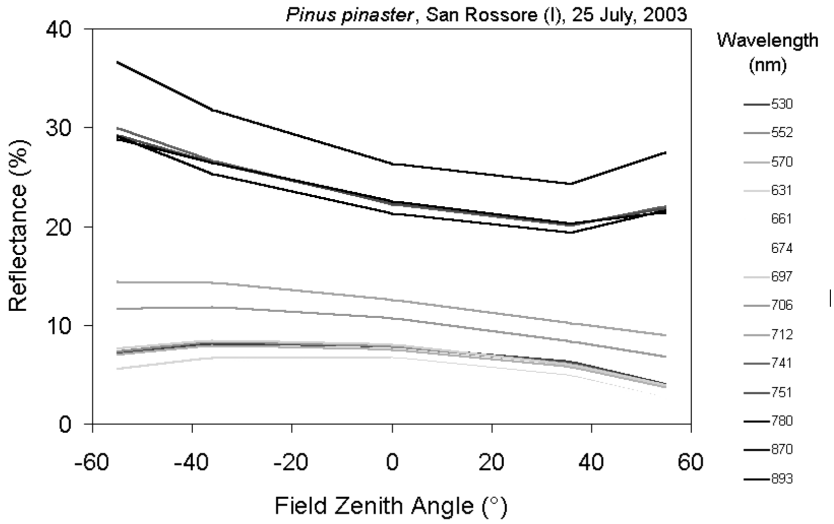

Figure 6 Observed spectro - directional of a Pinus pinaster stand; PROBA – CHRIS acquisition on July 25th, 2003; Rossore, Italy; all acquired spectral bands are shown.

Dependence of spectral Bidirectional Reflectance Factor (BRF) shown in Figure 5, simulated by SAIL, agrees with the notion that back- and forward scattering lead to higher BRF at larger view zenith angles (bowl-shaped BRDF). The model SAIL does take into account soil spectral reflectance and its BRDF, but as a background of the "cloud" of leaves. This effect is evident in the simulated BRF. On the other hand, the observed dependence of BRF on FZA is qualitatively different (Figure 6): at shorter wavelength the BRDF is bell – shaped, while it becomes increasingly bowl – shaped at longer wavelengths. Although this is easily explained by the reversal of the difference in reflectance between soil and green leaves (factor [b] above), it implies that a 3D model is necessary to describe the BRF of partial canopies. This is in agreement with the theoretical evaluation and conclusions of Pinty et al. (2002). The model GeoSAIL (Huemmerich, 2001) captures basic canopy architecture, but simplifies soil – foliage radiative interactions and deviations of simulated from observed BRF-s were still rather large (Figure 4).

The observed behavior of BRF-s (Figure 6) may also be due to factor (c) above, at least to some extent. This is less understood than factor (b) and more difficult to characterize by either observations or model, since factors (b) and (c) must be treated separately. Depending on the relative magnitudes of footprint, trees height and spacing, the fraction of canopy volume sampled at all view angles changes significantly. Synthetic 3D canopies and a 3D radiative transfer model were used by Widlowski et al. (2003) to evaluate sampled canopy volume as a function of footprint and canopy height. Taking into account CHRIS footprint at nadir (with the instrument setting used in our study) and approximate height of pine trees in San Rossore, the fraction of canopy volume sampled at all view angles is about 25% of the volume sampled at nadir. Under these conditions the combination of spectral heterogeneity and the complex architecture of partial, mixed forest canopies may easily produce significant changes of TOC BRF with view angle.

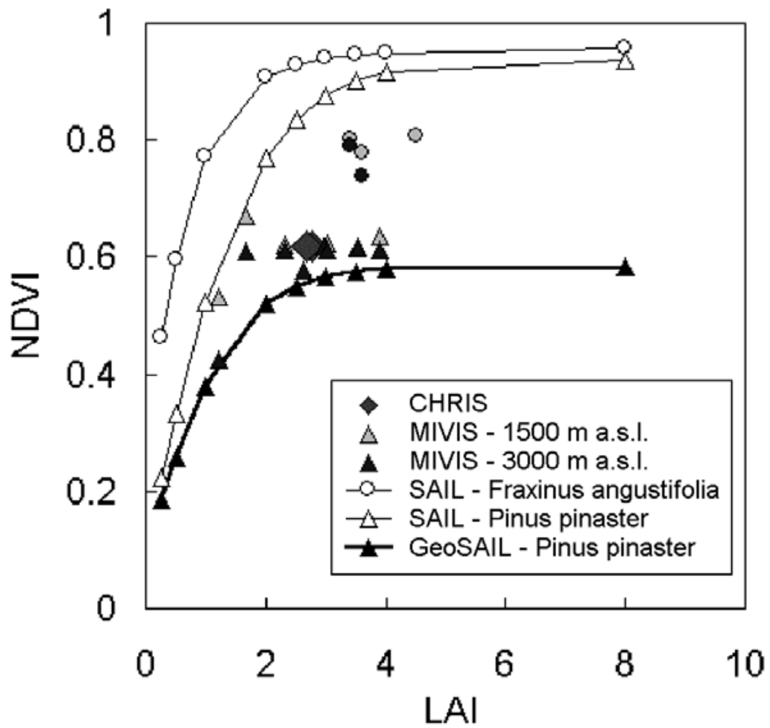

Figure 7 Simulated and observed relationships between the Normalized Difference Vegetation Index (NDVI) and the Leaf Area Index (LAI); observations done with two hyper-spectral systems: MIVIS from two flight altitudes and CHRIS; PROBA – CHRIS June 16th , 2003; MIVIS June 21st, 2000; San Rossore, Italy

The observed dependence of BRF on view and illumination conditions makes inference of canopy state variables such as Leaf Area Index by means of simple and empirical correlations rather challenging (figure 7). Observations by MIVIS and CHRIS are in good agreement, but estimates of LAI would be unreliable using any one of the relationships plotted in Figure 7. On the other hand, the large deviations between observed and simulated (KUUSK, SAIL, GeoSAIL RT models) BRF-s imply that 3D models are required to construct robust algorithms.

5. CONCLUSIONS

The observations of at-surface reflectance obtained with CHRIS agreed well with independent airborne measurements by MIVIS. This confirms the findings of Barducci et al. (2004) who used also ground measurements of reflectance as a reference. The deviations of spectro-directional reflectance, simulated with the RT models KUUSK. SAIL and GeoSAIL, from observations were rather large and suggest that the models used may not be adequate to deal with the spectral heterogeneity and complex 3D architecture of the pine stands at San Rossore. Particularly, model calculations predicted a bowl – shaped BRDF at all wavelengths, while observations gave a clear transition from bell – to bowl – shaped BRDF with increasing wavelengths when using CHRIS observations.
The combination of factors a, b and c leads to a complex dependence of BRF on view and illumination conditions. The impact of factor (a) may be evaluated using radiative transfer models of the SAIL family, while 3D models are required to evaluate the effects of factors (b) and (c). The same class of models appears necessary to construct robust algorithms to extract information on canopy state variables and parameters from spectro – directional reflectance.

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