

HIGH SPECTRAL RESOLUTION : DETERMINATION OF SPECTRAL SHIFTS BETWEEN THE RED AND NEAR INFRARED

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ABSTRACT

High spectral resolution permits characterization of the spectral shift of the red edge for a plant canopy. The mechanisms that are involved in these spectral shifts were analyzed at two different scales : the leaf and the canopy.

This study is based on a review of the literature and on model simulations with an empirical model for leaf reflectance and with the SAIL canopy reflectance model.

The results obtained show that the information contained in the spectral shifts can be compared to the information provided by wide red and near-infrared bands. However, simulation of the atmospheric effects performed with the "5S" model shows that the spectral shifts are independant of atmospheric conditions.

I. INTRODUCTION

One of the principal goals in remote sensing of agricultural crops is to use the spectral information to estimate biological parameters that are related to the canopy condition and that can be used as input into growth models to predict yield. The spectral measurements that have been used for these estimations have been either broad (50–200 nm) or narrow spectral bands (1.5 nm)

The objective of this study was to analyze the mechanisms which determine these spectral shifts. This analysis was conducted at the level of a single leaf and progressed to that of the canopy. We compared the results from simulation models to experimental results of various authors. Finally, we approached the problems which would appear when results obtained at ground level are extended to space based measurements.

II. ANALYSIS OF SINGLE LEAF REFLECTANCE MECHANISMS

We used the reflectance and transmittance model described by ANDRIEU et al (1988). This model takes into account two factors which determine the optical properties of leaves in the visible and the near-infrared :

- The absorption by chlorophyll pigments. In the model, only concentration of chlorophyll a and b is taken into account. It therefore reveals the very close relationship that has been observed between the concentration of chlorophyll a and b and carotenoids for wheat leaves on which the model was based.

- The diffusion of light by the structure of the leaf. It corresponds to the reflectance of a leaf lacking chlorophyll. This formula assumes that the spectra of senesced leaves can be deduced from one another by simple rotation. It also assumes that the appearance of the brown pigments that are solely responsible for the absorption of green and red of dead leaves is tied to the disappearance of chlorophyll.

This model was based on wheat leaf reflectance between 450 and 850 nm in 10 nm steps with a spectral resolution better than 5 nm. The measured reflectance and that estimated by the model were in very good agreement (with slope of 0.996, intercept of 0.002 and $R^2 = 0.998$). The model applies equally well to leaf transmittance. It allows the effects of chlorophyll concentration and leaf structure to be conjugated with leaf reflectance. Throughout this simulation study we characterize the position of the spectral shift by the position of the wavelength at the point in the spectrum where reflectance is equal to the mean of the red (670 nm) and the NIR (760 nm) reflectances. This description of the spectral shift is preferable to using the inflection point of the increase from red to NIR, because its determination is less precise and requires measurement at intervals of less than 10nm. The results of BARET et al. (1987) have shown, in effect, that λ_1 was the centre of symmetry and was very close to the inflection point.

2.1 Effect of Chlorophyll Concentration

Figure 1 presents the simulation results for 3 leaves that have different structures (NIR reflectance). These results are in good agreement with the experimental results of HORLER et al. (1983) (Figure 2). It is apparent that in both cases there is a displacement of λ_1 towards larger wavelengths as chlorophyll concentration increases.

In a schematic sense, the value of λ_1 depends on the level of reflectance in the red and NIR and every factor that produces a variation relative to the reflectance in one or the other domain results in a similar variation in λ_1 . When reflectance increases in the red, λ_1 shifts towards the shorter wavelengths; when it decreases in the NIR, λ_1 shifts equally towards the short wavelengths if one considers the point of half amplitude.

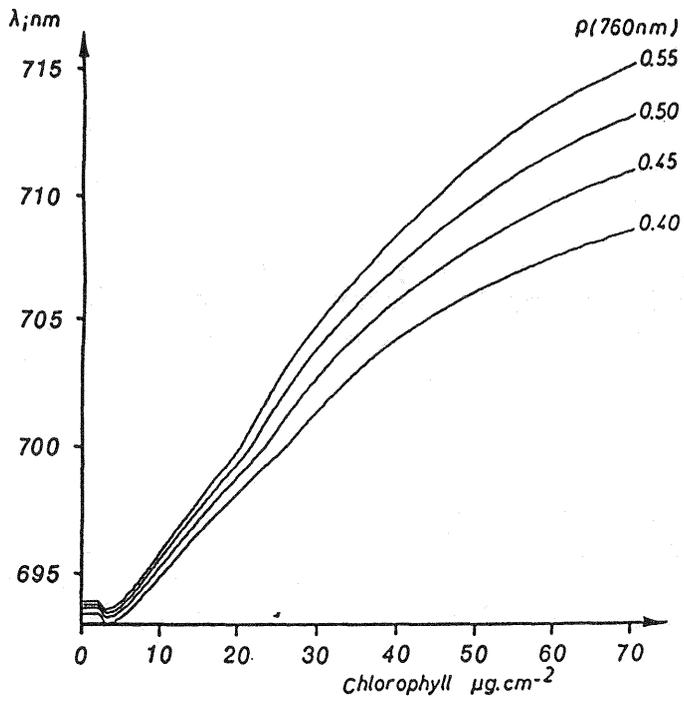


Figure 1 : Variation of λ_i as a function of chlorophyll content of three leaves with different NIR reflectance.

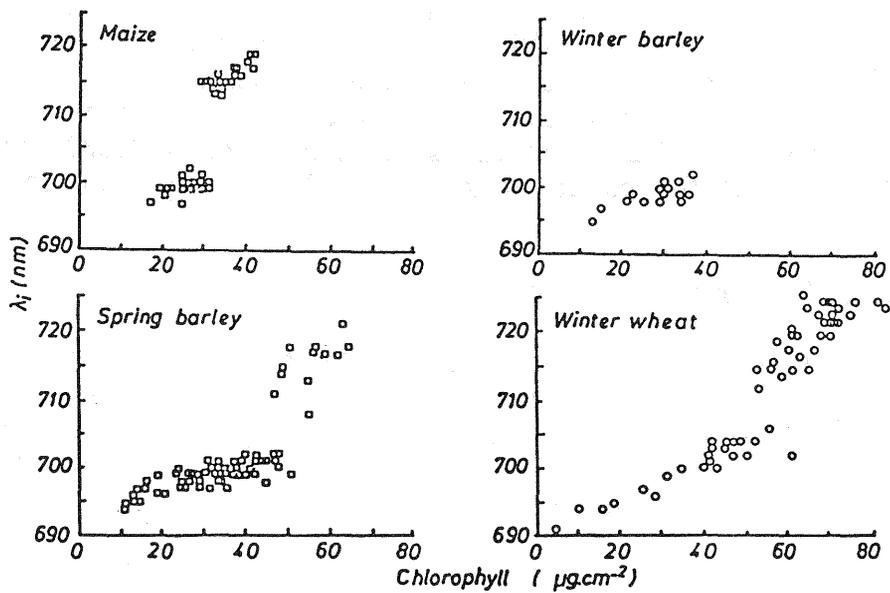


Figure 2 : Variation of λ_i as a function of chlorophyll content for four crops (HORLER et al., 1983).

It must be noted that the relationship between chlorophyll a and b can change during leaf growth and vary depending on the species (BOARDMAN, 1977). Since the absorption spectrum of the two pigments differs, a change in their relative proportions would result in a shift in λ_1 , even if the concentration did not change. This possibility is not taken into account in our model. The work of HORLER et al. (1983) shows that the value of λ_1 does not appear to be correlated to the chlorophyll a/b ratio whose range of variation is limited under natural conditions. ANDRIEU et al. (1988) have confirmed these results in wheat.

The comparison of HORLER et al.'s experimental results (Figure 2) and ours (Figure 1) shows, however, that the curves are different for the relationship between λ_1 versus chlorophyll concentration. This can be explained by the fact that HORLER et al. defined spectral shifts by the inflection point in contrast to the method we used. It can also be explained by the simultaneous variations in leaf structure and chlorophyll concentrations. We therefore studied the effect of leaf structure on λ_1 .

2.2 Effect of Leaf Anatomy

Figure 1 shows that λ_1 shifts towards the larger wavelengths when the NIR reflectance increases. The NIR reflectance is related to the internal structure of the leaf (GAUSMAN and ALLEN, 1973 ; GAUSMAN, 1974). Thus a reduction in leaf thickness or the number of cells causes a reduction in the NIR reflectance. This effect is evidently much more pronounced when the chlorophyll concentration is low.

Beyond the internal structure of the leaves, the effects of the leaf surface are not explicitly taken into account by the model. The surface effects are due to the diffusion of light or to the specular reflection by the cuticle. It essentially depends on the condition of the wax (VANDERBILT and GRANT, 1985). This composition is additive and does not depend greatly on the wavelength in the red or infrared. Thus the surface effects act by their translation of the value of the reflectance and would not therefore affect the position of λ_1 .

III. ANALYSIS OF MECHANISMS AT THE CANOPY LEVEL

The variation of λ_1 which is observed for vegetation canopies under natural conditions (BARET et al., 1987 ; COLLINS, 1978) is perhaps due to either the canopy factors proper (LAI, leaf and soil optical properties) (VERHOEF 1984, 1985) or to external factors (solar elevation).

In order to analyze the importance of each of the factors we have used the SAIL model of canopy reflectance (VERHOEF 1984, 1985) in which single leaf reflectance and transmittance spectra produced by ANDRIEU et al.'s (1988) model is used. The reflectance spectrum of the soil was estimated from its reflectance in the red (670 nm) and the principal soil line (RICHARDSON and WIEGAND, 1977). The linear relationship was developed for the bare soil between reflectance at each wavelength and the reflectance at 670 nm as follows :

$$\rho_1 = a \cdot \rho_{670} + b$$

3.1 Effect of Canopy Parameters

The leaf area index (LAI) is the primary factor controlling the optical properties of the canopy (HINZMAN, 1986) so all of the model simulations were carried out as a function of this variable.

Figure 3 shows that for green leaves with a high chlorophyll concentration, λ_1 shifts progressively towards the longer wavelengths in proportion to the increase in LAI. These results are in complete agreement with those of BARET et al. (1987) : λ_1 increases with the ND (normalized difference) vegetation index which itself increases with the LAI.

3.1.1 The Role Played by Leaf Optical Properties

The spectral shifts that are observed at the single leaf level are equally apparent at the canopy level (FERNS et al., 1984 ; CURRAN and MILTON, 1983). However, because of soil interactions the amplitude of the variation of λ_1 is different.

For small LAI there is a displacement of λ_1 towards the short wavelengths (Figure 4). This displacement corresponds with the change in the curvature of the spectrum between the red and the NIR. For a bare soil, the curvature of the spectrum between the red and the NIR is very small and λ_1 is normally situated midway between 670 and 760 nm (715 nm). After vegetation appears the reflectance spectra take the form of an S with dis-symmetry to the left for the very small LAI and therefore λ_1 is displaced in the direction of the shorter wavelengths. It then passes a minimum for LAI less than one and beyond that it moves towards the longer wavelengths when the LAI increases. When the saturation level of the reflectance is reached, for LAI in the order of 8, λ_1 is essentially constant. Similarly, for the elevated LAI, λ_1 is very insensitive to the internal leaf structure (NIR reflectance and transmittance).

In reality, as noted by HORLER et al. (1983), the spectral shifts depend on two factors which are bound to the LAI : the percentage ground cover and the amount of mutual shading by leaves. The size of these two factors depends, for a given LAI, on the canopy geometry.

3.1.2 The Effect of Canopy Geometry

Figure 5 shows the effect of leaf inclination angle on λ_1 . It is particularly sensitive to the erectophile type of leaf distribution (mean leaf angle greater than 50°) and for the intermediate LAI (of the order of four). But this effect is relatively unimportant because modification of the leaf angle distribution does not cause a shift of λ_1 of more than 3 or 4 nm. But this effect can be dependent on other factors.

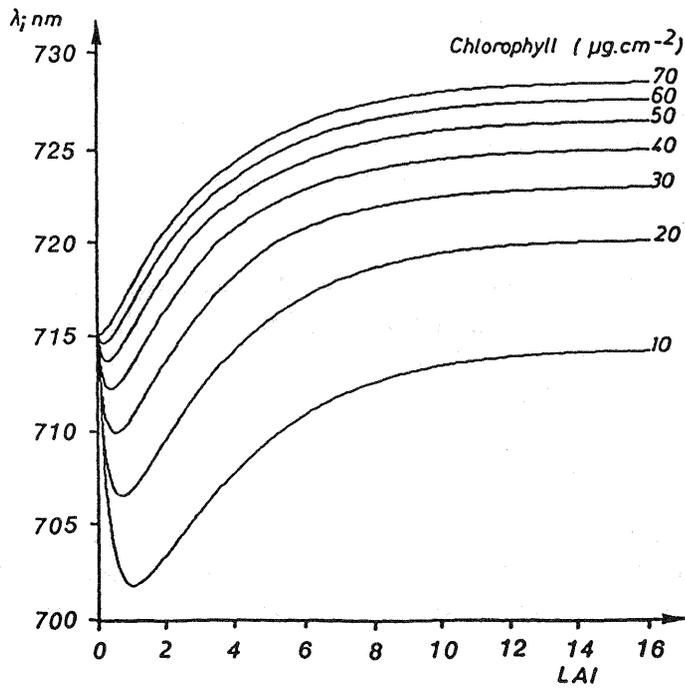


Figure 3 : Effect of leaf chlorophyll content on λ_i . The calculations were made using the principal soil line $\rho_{i,r} = 1.16 \rho_r + 0.067$ with ρ_r set at 0.15 for the soil. For the leaves $\rho(760) = 0.52$ and $\rho(760) = 0.44$. The view angle is vertical, the solar zenith angle is 40° and the leaf angle distribution is spherical with a mean angle of 60° .

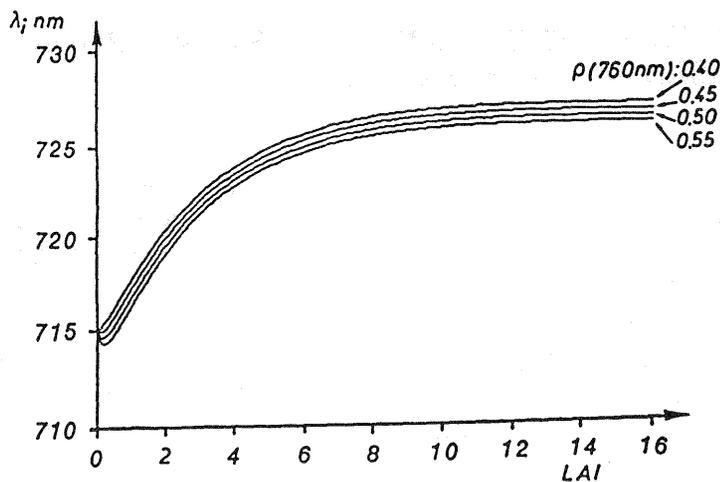


Figure 4 : Effect of leaf reflectance in the NIR (relative to their thickness) on λ_i . The calculations were made with the same parameters as in Figure 3 and using a leaf chlorophyll content of $60 \mu\text{g}\cdot\text{cm}^{-2}$.

3.1.3 The Effect of Soil Optical Properties

Figure 6 shows that under the condition of our simulations the shift in λ_1 is not very sensitive to the optical properties of the soil. Here, also, the effect does not exceed 3 or 4 nm and is most pronounced for the intermediate LAI. An increase in soil brightness translates into a displacement of λ_1 towards the longer wavelengths.

The simulations do not take account of the variation of the soil optical properties for different moisture contents, roughness or illumination. It would therefore be necessary to test the effect on λ_1 of the different factors which modify the canopy optical properties.

3.2 The Effect of Sun Position

Figure 7 shows how the solar zenith angle has a large influence on the position of λ_1 . This effect increases until an LAI for which saturation in the NIR is reached. When the solar zenith angle increases, λ_1 shifts towards the short wavelengths.

The results of the simulation on the effects of canopy properties and external factors on the spectral shift between red and NIR show the complexity of the phenomena put into play. The principal factors involved are the leaf chlorophyll concentration, the LAI and solar zenith angle. One can therefore visualize that the information provided by the parameter λ_1 is very close to that contained in the classical wide spectral bands. However, the relative independence of λ_1 vis a vis the angular distribution of leaves and the optical properties of the soil make them a useful tool. But this initial analysis has to be subjected to experimental data to be fully validated. Likewise it is also necessary to address the problem raised in the transition from ground based measurements to space based measurements.

IV. PROBLEMS POSED BY THE TRANSITION FROM GROUND-BASED TO SPACE-BASED MEASUREMENTS

The radiance measured by a satellite in any spectral band corresponds to the radiance of the target viewed, adjusted for attenuation by absorption and diffusion through the atmosphere and to which must be added the atmospheric path radiance. Thus the spectral response of an object will be different to that which would be determined at the soil level or at the surface of the atmosphere. In order to determine the importance of these perturbations and their effect on the value of λ_1 , we considered the reflectance spectra of two wheat leaves : one leaf, green and in good health (chlorophyll content of $a + b = 69.7 \mu\text{g}\cdot\text{cm}^{-2}$ and one senescent leaf in which the chlorophyll content was very low (chlorophyll $a + b = 4.6 \mu\text{g}\cdot\text{cm}^{-2}$). To these reflectances we applied the model "5S" (TANRE et al., 1986) to a very clear atmosphere (visibility 23 km) and an atmosphere charged with aerosols (visibility 5 km) using a solar zenith angle of 40° . The reflectance spectra measured at ground level and simulated at the surface of the atmosphere, for a nadir view angle, are presented in Figure 8 without taking into account the absorption by atmospheric gases.

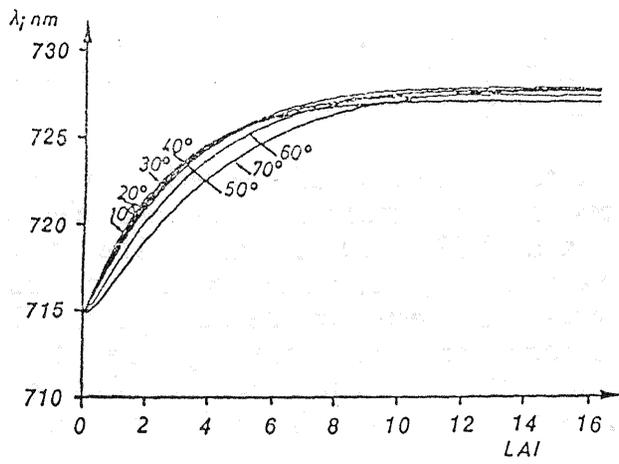


Figure 5 : Effect of mean leaf inclination angle, θ_1 , on λ_i ($\theta_1 = 90^\circ$: erect leaves). The other parameters are the same as in Figure 3.

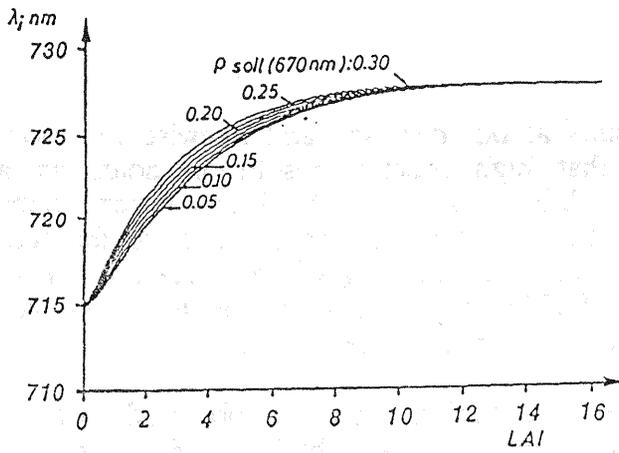


Figure 6 : Effect of soil reflectance on λ_i . The values indicated are for reflectance in the red. The other parameters are the same as in Figure 3.

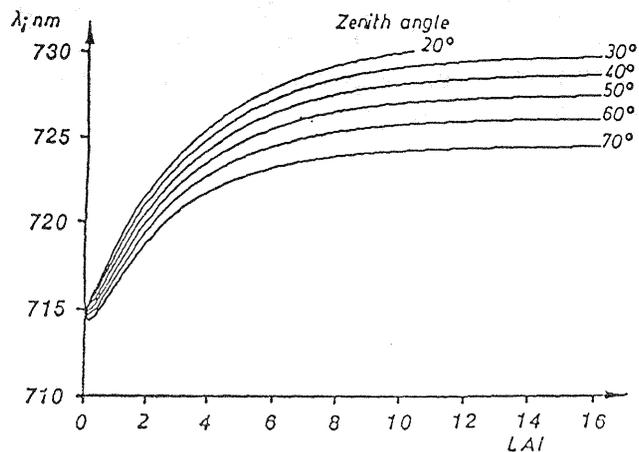


Figure 7 : Effect of solar zenith angle on λ_i . The other parameters are the same as in Figure 3.

On the figure it can be seen that when the reflectance is low, the radiance of the optical path has a dominant effect, and when the reflectance is high the atmospheric absorption becomes more important.

From the simulation data we determined the value of λ_1 and the ND using the mean reflectances for the spectral bands equivalent to those of SPOT XS2 (620–680 nm) and XS3 (790–890 nm). The results of these calculations show that the value of λ_1 determined by the method described by BARET et al. (1987) is practically unaffected by the atmosphere. By contrast the ND depends on the atmospheric conditions, especially when the vegetation is healthy. ND decreases from 0.71 at ground level to 0.64 outside of the atmosphere with visibility of 23 km and 0.54 with visibility of 5 km.

It would appear that the location of the position of λ furnishes more stable information about vegetation than does the ND considering that atmospheric visibility varies.

V. CONCLUSIONS

The experimental results at our disposal, and likewise the model simulations that we performed, show that high spectral resolution holds an advantage for determining vegetation condition. The mechanisms which depend on the wavelength of λ_1 , the inflection point of the transition from the red to NIR were analyzed and provided a better understanding of their relative weights. The most important factors are the leaf chlorophyll concentration and the LAI but the role played by the solar zenith angle cannot be neglected.

At first glance, the information that is obtained with high spectral resolution seems to be the same as that obtained with wide spectral bands. However, our simulation results lead us to believe that they are not at all equivalent and this provides a supplementary advantage for high spectral resolution.

Our simulation studies of atmospheric effects also show that the position of λ_1 is unaffected by atmospheric conditions. This parameter therefore appears to be very interesting for following the evolution of plant canopies. Before initiating operational applications however, it will be necessary to refine the model simulations and to pursue additional field experiments. This is what we are doing in the research currently in progress at Avignon.

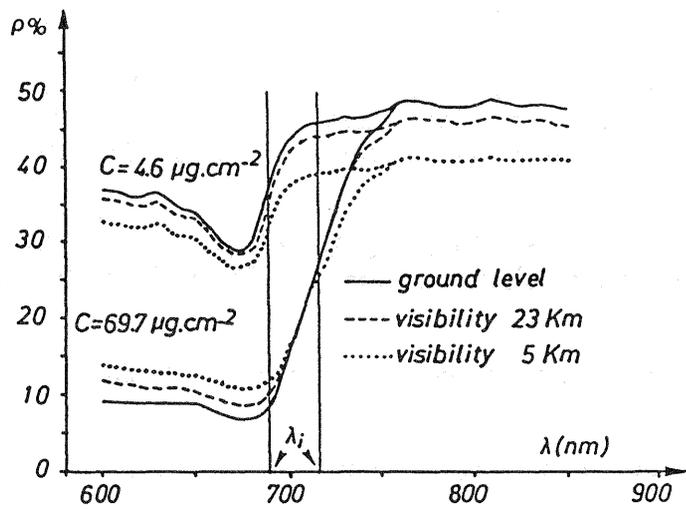


Figure 8 : Reflectance spectra of two wheat leaves with a high and low chlorophyll concentration and for measurements at ground level and at the surface of the atmosphere (after GUYOT and BARET, 1988)

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