IMAGING SPECTROSCOPY FOR VEGETATION STUDIES

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ABSTRACT. High spectral resolution enables to characterize spectral shift of the red edge for a plant canopy. The mechanisms that are involved, are 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 of leaf reflectance, and with the SAIL canopy reflectance model. The results of model simulations are compared with experimental data corresponding to laboratory measurements on isolated leaves and to ground level and airborne measurements on plant canopies. The first results obtained with airborne imaging spectrometers are in good agreement with experimental and simulated data.

The results obtained show that the information contained in the spectral shifts can be compared, in a first step, to the information provided by broad red and near-infrared bands. At the canopy level the spectral shifts depend on 3 main factors : leaf chlorophyll content, leaf area index (and related factors : leaf overlap index, percent soil cover) and leaf inclination angle. The soil reflectance and sun position has a limited effect.

Introduction

Imaging spectroscopy enables to have detailed spectral information on plant canopies. The use of narrow (1 to 10 nm) instead of broad (50 to 200 nm) spectral bands could offer new potentials for remote sensing applied to vegetation. The goal of this synthesis is to determine what is the new information obtained with spectral imaging systems, compared with that given by the actual earth observation satellite data.

The radiometric response of a plant canopy in broad spectral bands has been studied for many years. Numerous authors have established relations between crop status and combinations of reflectance measurements in different spectral bands (Ahlrichs and Bauer, 1983). The combinations of red and near-infrared bands (ratio or normalized difference ND) are the most frequently used (Rouse et al., 1974; Pearson and Miller, 1972; Tucker, 1977, 1979) because the contrast between soil and vegetation is maximum in these bands. Moreover statistical analyses performed, in order to determine the best combinations of broad spectral bands, characterizing the vegetation, show that more than 90% of the spectral information on a plant canopy are contained in red and near-infrared bands (Baret et al., 1986, 1988a; Sheffield, 1985).

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Detailed spectral analyses performed on leaves and plant canopies (Gausman et al., 1970; Gausman and Allen, 1973; Baret et al., 1987) show that not any narrow spectral band, characteristic of a particular chemical component, can be observed. For this reason, high spectral resolution is essentially used to analyse the spectral distortions which cannot be detected with the broad spectral bands. In a first step the studies have been centred on the transition of the vegetation reflectance between red and near-infrared. In this domain the reflectance presents a sharp increase, between 670 and 760 nm, which is called the "red edge". This red edge presents an inflection point, the wavelength of which λ_i depends on the plant status (Baret et al, 1987; Collins, 1978; Ferns et al, 1984; Horler et al., 1980, 1983).

In order to interpret high spectral resolution data, it is necessary to analyse the phenomena at different scales: the leaf and the plant canopy viewed at ground level and from space. To reach this goal we shall try to examine the mechanisms affecting the spectral distortions at leaf and canopy level by comparing model simulation with experimental data. But, for interpreting data of spectral imaging systems, it is necessary to introduce the atmospheric effects. This problem will be discussed in the last paragraph.

1. High spectral resolution at leaf level

The optical properties of a plant canopy mainly depend on optical properties of leaves and underlying soil. Therefore it is necessary to analyse the factors affecting leaf optical properties during the growth cycle and to quantify the introduced spectral distortions.

1.1. THE LEAF OPTICAL PROPERTIES

The incident radiation on a leaf surface can be reflected, transmitted or absorbed. The absorption mainly depends on different phenomena according to the wavelength :

- visible : changes in the spin and angular momentum of electrons and transitions between orbital states of electrons in particular atoms (absorption by the pigments : chlorophylls a and b, carotenoids, brown pigments and other accessory pigments).
- near and middle infrared : vibrational-rotational modes within the polyatomic molecules (water) (Hodanova, 1985).

The diffuse character of reflectance is only due to leaf internal structure which determines the leaf optical properties in the near-infrared (Grant, 1987). As it has been shown by Gaussman et al. (1970) a good relationship exists between the leaf reflectance and the number of air spaces in the tissues.

The Willstater and Stoll's theory (1928) has been used for a long time to explain light diffusion by plant leaves. According to this theory, light diffusion is mainly due to total reflections, which occur on air-cell interfaces, when the incidence angle is equal or greater than the total reflection angle. As the refraction index of hydrated cell walls is around 1.4 (at 1 µm) the total reflection angle is around 45°. Therefore the diffusion of the light is mainly due to the spongy mesophyll (figure 1), where the orientation of cell walls are randomly distributed and where there is a large number of air-cell interfaces (Gausman and Allen, 1973). The role of palisade parenchyma is of little importance. For this reason the leaves of dicotyledones reflect more than monocotyledones because their spongy mesophyll is less compact and has a larger number of air cavities.

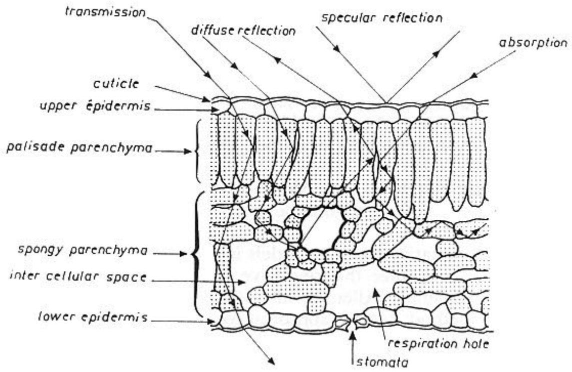

Figure 1 : Schematic representation of the interaction of incoming radiation with leaf tissues. The cross-section corresponds to a dicotyledonous leaf (*Eleborus niger*). (adapted from Lichtenthaler and Pfister, 1978)

In fact, the real mechanism of light diffusion is more complex as it has been shown by Kumar and Silva (1973) and Sinclair et al. (1973). Light is also reflected on cell walls when the incidence angle is inferior to the total reflection angle but it is less reflected. Moreover, light is also scattered by the heterogeneousness of cell content.

In order to give a more accurate and exhaustive description of leaf optical properties, physical models are developed for introducing specific optical properties of different leaf tissues.

1.2. MODELING OF LEAF OPTICAL PROPERTIES

1.2.1. Review of models representing the leaf optical properties. Allen et al. (1969) explain the diffuse reflectance and transmittance of a compact leaf with the "plate model" specified by two optical constants: the effective refraction index n and the effective absorption coefficient k. This model only applies to a compact leaf. Allen et al. (1970) and Gausman et al. (1970) have later extended this model for N layers, introducing the concept of Void Area Index (VAI) given by : $VAI = N - 1$

They show that the leaves of monocotyledones have a VAI equal to zero and they can be considered as a unique compact plate. On the contrary, for dicotyledones, VAI increases from zero to a maximum value depending on the species and on the leaf development.

Beside the discrete approach of the generalized "plate model", a continuous theory is proposed by Allen and Richardson (1968). Their leaf reflectance and transmittance model is based on the theory of Kubelka and Munk (1931). This theory describes the transfer of radiation in a diffuse scattering media with two parameters: the scattering and the absorption coefficients. Baret et al. (1988a) have developed a simplified semi-empirical model based on this approach and have successfully described the optical properties of single wheat leaves.

Yamada and Fujimura (1988, 1990) have proposed a mathematical model which applies for different leaves. They consider four layers (two cuticles, a palisade parenchyma and a spongy mesophyll) described by the Kubelka-Munk's theory. In the same way Tucker and Garrat (1977) have represented the interactions between and within the leaf compartments by using a Markhov's chain approach. But the solution of this problem requires to have a very good description of the leaf internal structure with many input variables.

The advantage of radiative transfer models is that they need only a limited number of input parameters. Some other theories have been developed to describe the leaf optical properties. for example Allen et al. (1973), Brakke and Smith (1987) have proposed a ray tracing method; but this approach requires a long computation time.

All of the presented works are adapted to specific conditions and restricted to a limited number of kinds of plants. Relatively little work has been done which tries to generalize the results obtained on particular plant species. Recently, Jacquemoud et al. (Jacquemoud, 1989 ; Jacquemoud et al., 1989 ; Jacquemoud and Baret, 1990) have developed a model that represents the leaf optical properties from 400 to 2500 nm with only 3 input variables. It is a first attempt for a generalized and easily invertible model.

However in this Paper, the analysis of factors affecting the leaf optical properties is based on the results of the semi-empirical model developed by Baret et al. (1988).

1.2.2. The semi-empirical model. This model takes into account two factors which determine the optical properties of leaves in visible and near-infrared :

- The absorption by chlorophyll pigments (C and K parameters). In the model, only concentration of chlorophyll a and b is considered because a very close relationship is observed between the concentration of chlorophyll a and b and carotenoids for wheat leaves on which the model is based (Baret et al., 1988a).
- The diffusion of light by the structure of the leaf. It corresponds to the reflectance of a leaf deprived of chlorophyll. This formula assumes that the spectra of senescent leaves are homothetic and can be deduced from one another by using a simple scaling coefficient. It also assumes that the appearance of the brown pigments, that are solely responsible for the absorption of green and red radiations by dead leaves, is stablely tied to the disappearance of chlorophyll.

This model can be written :

$$\rho(\lambda) = \rho\infty(\lambda) + \left[\frac{\rho\,(IR)}{\rho\,s(IR)} \rho_s(\lambda) - \rho\infty(\lambda) \right] e^{-K(\lambda).C}$$

with :

$\rho(\lambda)$: leaf reflectance for the wavelength λ,
$\rho_\infty(\lambda)$: asymptotic reflectance of a green leaf, reached when the chlorophyll content tends towards infinity,
$\rho_s(\lambda)$: mean reflectance of senescent leaves,
$\rho(IR)$: mean reflectance of the considered leaf between 760 and 800 nm,
$\rho_s(IR)$: mean reflectance of senescent leaves between 760 and 800 nm,
$K(\lambda)$: extinction coefficient of the reflectance due to the chlorophyll,
C : leaf chlorophyll content per surface unit.

This model is based on wheat leaf reflectance measurements performed between 450 and 850 nm with 10 nm steps and a spectral resolution better than 5 nm. The measured reflectance and that estimated by the model are in very good agreement (Baret et al., 1988). This model can also be successfully applied to leaf transmittance. It allows the effects of chlorophyll concentration and leaf structure to be conjugated with leaf reflectance. Figures 2 and 3 show the spectral dependency of the parameters K, ρ_∞ and ρ_S adjusted for this model on wheat leaves.

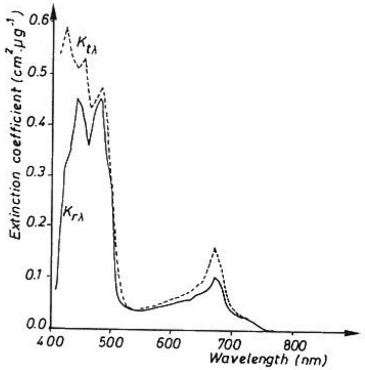

Figure 2 : Extinction coefficient of reflectance $K_r(\lambda)$ and transmittance $K_t(\lambda)$. (after Baret et al., 1988).

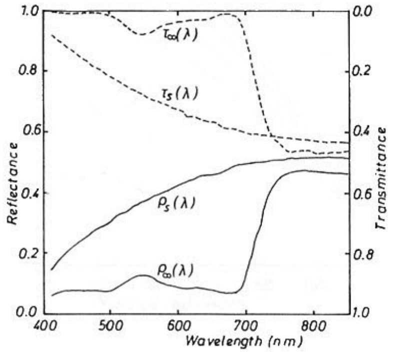

Figure 3 : Parameters ρ_∞ (λ) and $\rho_S(\lambda)$ for reflectance (and $\tau_\infty(\lambda)$ and $\tau_S(\lambda)$ for transmittance). (after Baret et al., 1988).

Throughout this simulation study the spectral shift is characterized by the shift of the wavelength λ_i at the point in the spectrum where reflectance is equal to the mean of the red (670 nm) and the near-infrared (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 narrower than 10 nm. The results of Baret et al. (1987) have shown, in effect, that the centre of symmetry is very close to the inflection point for canopies with LAI not too small.

1.3. RED SHIFT STUDY FROM MODEL SIMULATIONS

The objective of these simulations is to determine the parameters which have a significant effect on the shift of the red edge. The semi-empirical model is used to determine the factors affecting the wavelength λ_i of the inflection point of the red edge for wheat leaves (Guyot and Baret, 1989, Baret et al., 1988).

1.3.1. Effect of chlorophyll concentration. Figure 4 presents the simulation results for 4 leaves that have different structures (NIR reflectance). These results are in good agreement with the experimental results of Horler et al. (1983) (Figure 5). It is apparent that in both cases there is a red shift (displacement of λ_i towards larger wavelengths) as chlorophyll concentration increases.

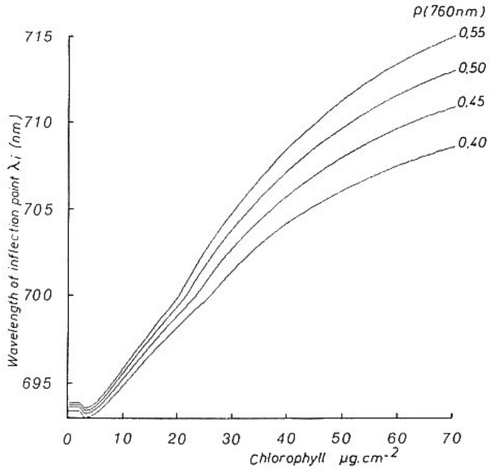

Figure 4 : Variation of λ_i as a function of chlorophyll content for four leaves with different NIR reflectances. (after Guyot and Baret, 1989)

Schematically, the value of λ_i depends on the level of red and near-infrared (NIR) reflectances. Every factor, that produces a relative variation of the reflectance in one or in these two domains, induces a variation in λ_i. When reflectance increases in the red, λ_i shifts towards the shorter wavelengths; when it decreases in the NIR, λ_i also shifts equally towards the short wavelengths if the point of half amplitude is considered.

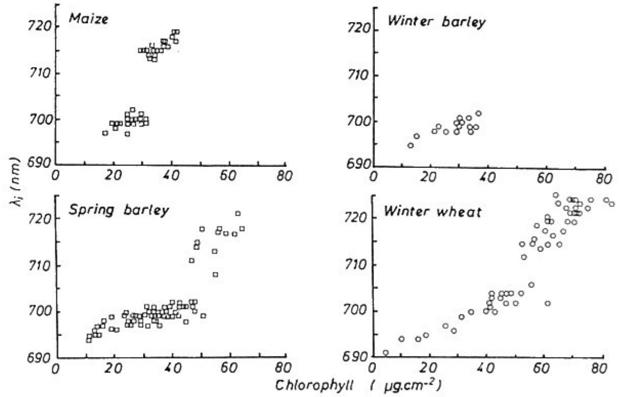

Figure 5 : Variation of λ_i as a function of chlorophyll content for four crops. (after Horler et al., 1983)

The chlorophyll concentration used in the model, corresponds to chlorophylls a and b but it implicitly takes into account carotenoids. This global measurement is justified by the experimental data of Horler et al. (1983). They show that the value of λ_i is not correlated to the chlorophyll a/b ratio, whose range of variation is limited under natural conditions. Andrieu et al. (1988) have confirmed these results on wheat.

The comparison of the experimental results of Horler et al. (1983) (Figure 5) with ours (Figure 4) shows, however, that the curves are different for the relationship between λ_i 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_i.

1.3.2. Effect of leaf anatomy. Figure 4 shows that λ_i shifts towards the larger wavelengths when 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 in the number of cell layers causes a reduction in the NIR reflectance.

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 cuticular waxy layer (Vanderbilt and Grant, 1985). This component is additive and does not depend greatly on the wavelength in the red or infrared. Thus the surface effects act by the translation of the value of the reflectance and would not therefore affect the position of λ_i.

2. High spectral resolution at the canopy level

The variation of λ_i, 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 relative 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 Baret 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 :

$$\rho(\lambda) = a\,\rho_{670} + b$$

2.1. EFFECT OF CANOPY PARAMETERS

2.1.1. Effect of leaf area index and 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_i is different.

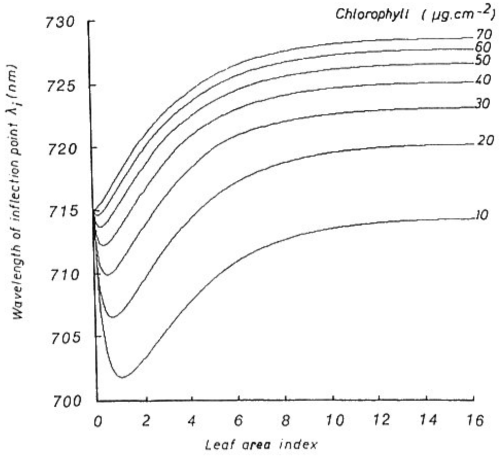

Figure 6 :. Effect of leaf chlorophyll content on λ_i. The calculations are made using the principal soil line $\rho_{ir} = 1.16\,\rho_r + 0.067$ with ρ_r set at 0.15 for the soil. For the leaves $\rho(760) = 0.52$ and $\tau(760) = 0.44$. The view angle is vertical, the solar zenith angle is 40° and the leaf angle distribution is spherical with a mean angle of 60°. (after Guyot and Baret, 1989)

The leaf area index (LAI) is the primary factor controlling the optical properties of the canopy (Leamer et al., 1978; Hinzman, 1986) so all of the model simulations were carried out as a function of this variable.

Figure 6 shows that, for green leaves with a high chlorophyll concentration, λ_i 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_i increases with ND (normalized difference) vegetation index which itself increases with LAI.

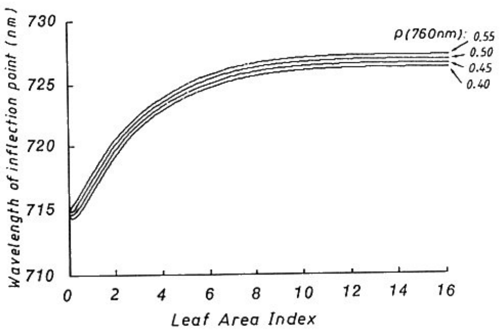

Figure 7 : Effect of leaf reflectance in the NIR (relative to their thickness) on λ_i. The calculations are made with the same parameters as in Figure 6 and using a leaf chlorophyll content of 60 g.cm^{-2}. (after Guyot and Baret, 1989)

For small LAI λ_i shifts towards the shorter wavelengths (Fig. 6). This shift corresponds to the change in the curvature of the spectrum between red and NIR. For a bare soil, the curvature of the spectrum between red and NIR is very small and λ_i 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_i is shifted 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 LAI increases. When the reflectance reaches its saturation level (for LAI>8) λ_i is essentially constant. Similarly, for the large LAI values, λ_i is very insensitive to the internal leaf structure characterized by their NIR reflectance and transmittance (Fig. 7).

2.1.2. The effect of canopy geometry. Figure 8 shows that the canopy geometry has a quite large effect on λ_i. It shifts towards longer wavelengths when the leaf angle (with the horizontal plane) increases. This effect also increases with LAI.

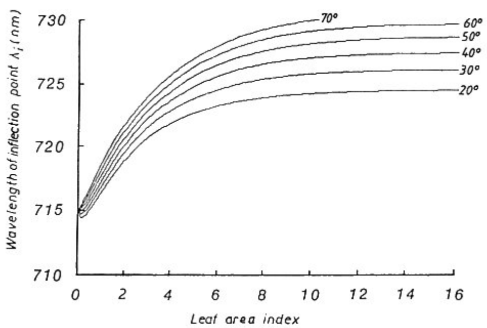

Figure 8 : Effect of mean leaf inclination angle, θ_l, on λ_i (θ_l = 90°: erect leaves). The other parameters are the same as in Figure 6. (after Guyot and Baret, 1989)

In fact, 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 Leaf Overlap Index (LOI). The level of these two factors depends, for a given LAI, on the canopy geometry. Simulations performed by Leprieur (1989) are in good agreement with these results (Fig. 9).

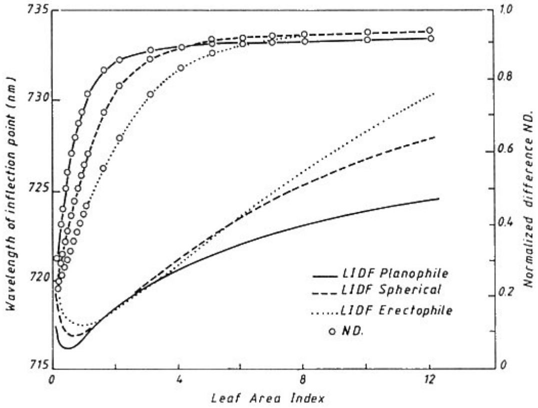

Figure 9 : Variation of λ_i and ND as a function of LAI for maize canopies with different LIDF. (after Leprieur, 1989)

For low LAI the variation of λ_i is not strongly affected by the canopy geometry. For high LAI values the effect of canopy geometry is large, as it is also shown on figure 8. A saturation level does not appear like on the Normalized Difference (ND). These results of model simulations are confirmed by field measurements performed by Ferns et al., (1984) on cucumber. These authors have shown that an increase of LOI from 1 to 5 when leaves are stacked, produced a red shift.

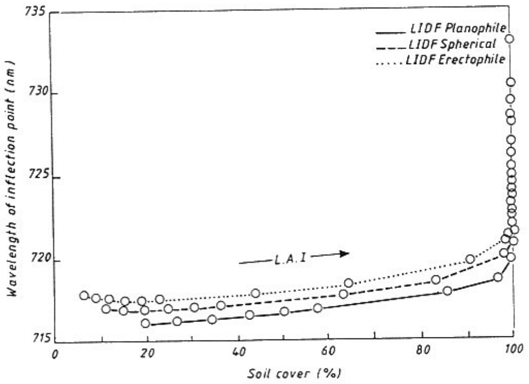

Figure 10 : Variation of λ_i as a function of the percent soil cover for maize canopies with different LIDF. (after Leprieur, 1989)

Figure 10 presents the effect of the percent soil cover on λ_i (Leprieur, 1989). It shows that the soil cover does not practically affect the wavelength of the inflection point of the red edge. These simulation results are in good agreement with the experimental data of Horler et al. (1983). These authors have shown, in the laboratory, that the position of the red edge was not affected when the soil cover with maize leaves varied between 20 and 80%.

2.1.3. The effect of soil optical properties. Figure 11 shows that, under the condition of our simulations, the shift in λ_i is not very sensitive to the optical properties of the soil. The effect does not exceed 3 or 4 nm and is most pronounced for intermediate LAI. An increase in soil brightness translates into a shift of λ_i 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_i of the different factors which modify the soil optical properties.

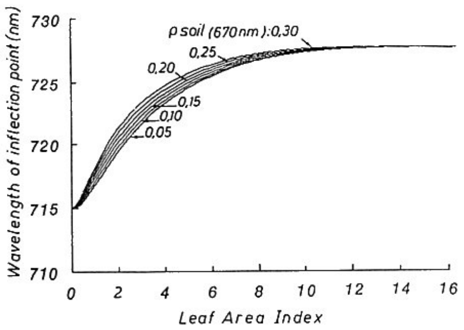

Figure 11 : Effect of soil reflectance on λ_i. The indicated values correspond to the red reflectance. The other parameters are the same as in Figure 6. (after Guyot and Baret, 1989)

2.2. THE EFFECT OF SUN POSITION

Figure 12 shows the effect of the solar zenith angle on λ_i. This effect is limited and the shift of λ_i does not exceed 3 or 4 nm. The largest shift is observed for intermediate LAI and large sun zenith angles.

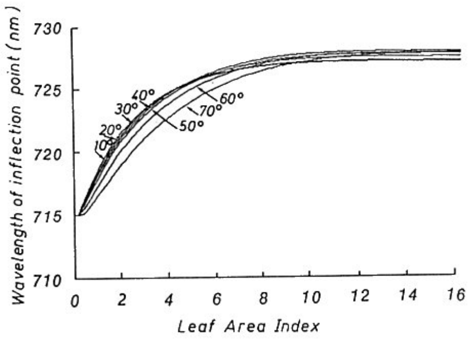

Figure 12 : Effect of solar zenith angle on λ_i. The other parameters are the same as in Figure 6. (after Guyot and Baret, 1989)

The results of the simulation of the effects of canopy properties and external factors on the spectral shift between red and NIR show the complexity of the phenomena involved. The principal factors are the leaf chlorophyll concentration, the LAI and the leaf inclination. One can therefore visualize that the information provided by the parameter λ_i is very close to that contained in the classical wide spectral bands. However, the relative independence of λ_i *vis a vis* the sun zenith angle and the optical properties of the soil make them a useful tool. But this initial analysis has to be compared 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.

3. 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 outside the atmosphere.

3.1. MODEL SIMULATION

In order to determine the importance of these perturbations and their effect on the value of λ_i, we considered the reflectance spectra of two wheat leaves : one leaf, green and in good health (chlorophyll a + b content = 69.7 g.cm^{-2}) and one senescent leaf in which the chlorophyll content was very low (chlorophyll a + b = 4.6 g.cm^{-2}). To these reflectances we applied the model "5S" (Tanré 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 outside the atmosphere, for a nadir view angle, are presented in Figure 13 without taking into account the absorption by atmospheric gases.

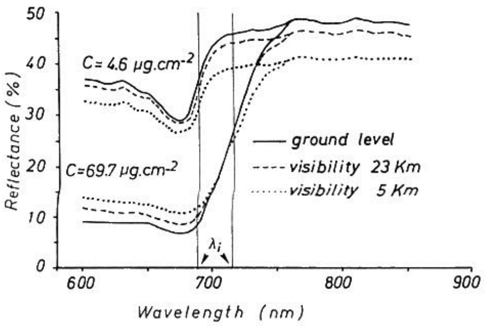

Figure 13 : Reflectance spectra of two wheat leaves with a high and low chlorophyll concentration and for measurements at ground level and at the limit of the atmosphere. (after Guyot and Baret, 1989)

On this 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_i 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_i determined by the method described by Baret et al. (1987) is practically unaffected by the atmosphere. By contrast 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_i furnishes more stable information about vegetation than does ND considering that atmospheric visibility varies.

3.2. AIRBORNE MEASUREMENT ON PLANT CANOPIES

These measurements where performed with the AVIRIS airborne spectral imaging spectrometer developed at JPL (Vane and Goetz, 1988). It consists in 4 spectrometers giving a 614 pixel wide image with 224 spectral bands between 400 and 2400 nm. The sampling interval varies from 9.6 to 10 nm. After resampling the number of bands is reduced to 210, each of them being 9.6 nm wide.

Leprieur (1989) has analyzed AVIRIS data acquired over 8 different vegetated sites near Moffet Field in San Francisco area. The airborne data have been corrected for atmospheric diffusion and gaseous absorption with 5S model (Tanré et al., 1986). As it is shown on figure 14, the observed shifts of the red edge, on the different sites, are in very good agreement with the results of the model simulations.

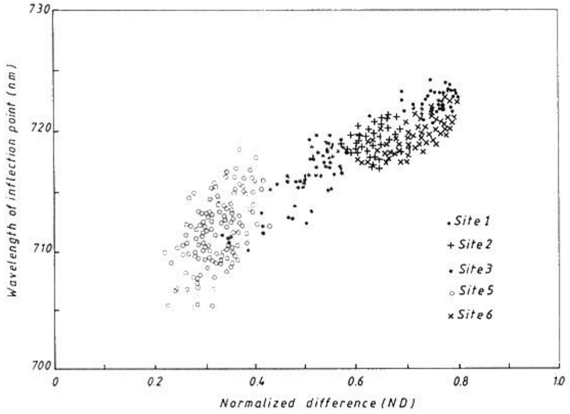

Figure 14 : Plot of λ_i as a function of ND for five vegetated sites (AVIRIS data). (after Leprieur, 1989)

On large forested areas the spectral imaging systems can be used to determine the variation of leaf chlorophyll content due to air pollutants or to the presence in the soil of ions of heavy metals. Experimental data obtained in Germany and in North America (Rock et al., 1985, 1986a, 1986b, 1988; Hermann et al., 1988) have shown the existence of a very good correlation between the shift of the red edge towards shorter wavelengths (blue shift) and the severity of damages, as it is shown on figure 15.

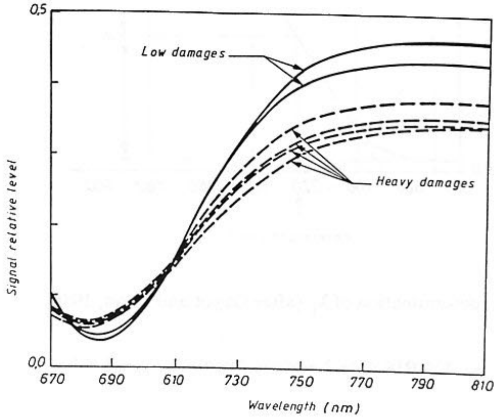

Figure 15 : Comparison of red edge for forests with low and heavy damages. These spectra are adjusted with a model to the data of the Canadian spectral imager FLI. (after Rock et al., 1988)

3.3. PRACTICAL USE OF HIGH SPECTRAL RESOLUTION DATA

As it has been shown by Guyot and Baret (1988), it is possible to use a limited number of narrow spectral bands to determine the wavelength of the inflection point of the red edge. In this case the inflection point is assimilated to the symmetry centre of the red edge (Baret et al., 1987) (Fig. 16).

The reflectance, corresponding to the symmetry centre λ_i, is equal to the mean value of the reflectances measured in the red (670 nm) (1) and in the near-infrared (780 nm) (4). To determine λ_i it is necessary to know the shape of the reflectance curve in the proximity of the inflection point. The different data presented in this study show that λ_i can vary between 700 (2) and 740 nm (3). Two narrow spectral bands can be centred on these two wavelengths and if the reflectance curve is assimilated to a straight line, in this interval, it is then possible to determine λ_i.

$$\rho_i = [\rho(1) + \rho(2)] / 2$$

and $$\lambda_i = \lambda(2) + [\lambda(4) - \lambda(1)] \frac{\rho_i - \rho(2)}{\rho(3) - \rho(2)}$$

with : $\lambda(1)$: 670 nm; $\lambda(2)$: 700 nm; $\lambda(3)$: 740 nm; $\lambda(4)$: 780nm

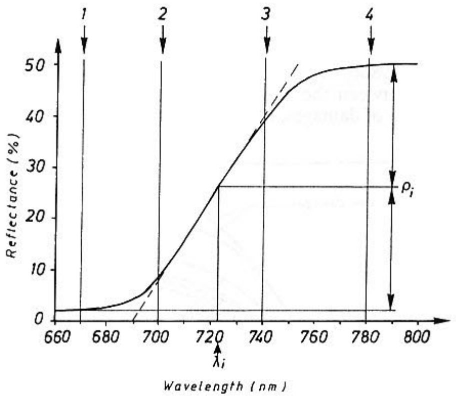

Figure 16 : Practical determination of λ_i. (after Guyot and Baret, 1988)

For interpreting AVIRIS data Leprieur (1989) has used this approach. Bands 29 (674.4) and 40 (782.2) were selected to determine the reflectance corresponding to the symmetry centre. Bands 31 (694 nm) and 36 (743 nm) were used to approximate the reflectance curve.

3.4. FUTURE DEVELOPMENTS

This study is exclusively focussed on the analysis of the red edge shift. However a recent experimental work has shown the possibility of characterizing, in the laboratory, the leaf content in nitrogen (proteins), lignin and starch with reflectance measurements in the 1200-2400 nm domain (Peterson et al., 1988). Airborne measurements performed with the AIS spectral imaging system (Vane and Goetz, 1988) did not permit to characterize the nitrogen content of forest leaves but interesting informations have been obtained on lignin and starch content from reflectance measurements around 1550 nm.

Conclusion

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 affect the wavelength λ_i of 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 canopy geometry 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 strictly equivalent and this provides a supplementary advantage for high spectral resolution.

Our simulation studies of atmospheric effects and airborne experimental data also show that the position of λ_i is less affected by atmospheric conditions. This parameter therefore appears to be very interesting for monitoring the evolution of plant canopies. However, before initiating operational applications, 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.

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