SPECTRAL REFLECTANCE PROPERTIES OF SOILS

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ABSTRACT

The absorption of light resulting from electronic and molecular processes, taking place in clay minerals, metal oxides and hydroxides, carbonates, sulfates, organic matter, water etc... determine specific features in soil reflectance spectra that can be used for their identification and, in some cases, quantification. These possibilities, makes from spectral reflectance data obtainable in laboratory, in the field, through aircraft or spacecraft platforms, a promising tool for identification of mineral components, monitoring of organic matter and soil water contents.

The use of reflectance spectral data for soil characterization is more efficient when based on the knowledge of each component effects on the spectrum, and on the way their association promote deviations of the individual characteristics. In this paper we review some of the research works that have contributed to clarify the spectral characteristics of the reflected light from soils in the visible to medium infrared, measured by different techniques. The objective of this paper is to call attention on the possibilities offered by the spectra analysis and to show the difficulties, imposed by the complex nature of soils, in generalizing procedures applicable to all soil types.

KEY WORDS: *soils, reflectance, radiometry, remote sensing*

Soil scientists have, since the beginning of the systematic pedological studies, used reflected light in the visible spectrum as a criterion for identifying profiles and horizons. Color is the way in which the human sensors - the eyes - "measure" light reflected from objects in the visible electromagnetic spectrum. We have also learned how to correlate the existence of some soil components (organic matter and iron oxides for example) with soil color. The development of instruments which measure radiant energy in a large range of wavelengths has led several authors to study the reflectivity properties of soils and to relate them to their physical, chemical and mineralogical characteristics.

Soil reflectance is a cumulative property which derives from the inherent spectral behavior of the combination of mineral, organic and fluid matter which composes soils. Besides the composition itself, the particle size and organization of the different components also play a role in the reflectance properties of soils. This means that soil reflectance spectra can carry dual information: information relating to the soil structure, and information relating to specific components. By examining the shape of reflectance spectra one can extract valuable information on the physico-chemical characteristics of soils. Spectral variations are normally associated with specific absorption phenomena and can be quantified by using different procedures. These identification possibilities make reflectance spectroscopy an important tool for identifying soil composition in the laboratory, in the field, and through satellite imagery.

Efforts have also been made to apply the principles learned from the laboratory and field spectral studies to image analysis. Remotely-sensed satellite data has great potential for providing area estimation of soil classes, soil color, soil moisture and organic matter content. This potential relies on the existence of characteristic spectral differences in the soil scene.

When analyzing multispectral imagery to distinguish different soil types, not only radiometric data must be considered. Geological, topographical, hydrological, vegetation, etc. data must also be used to extract soil information correctly.

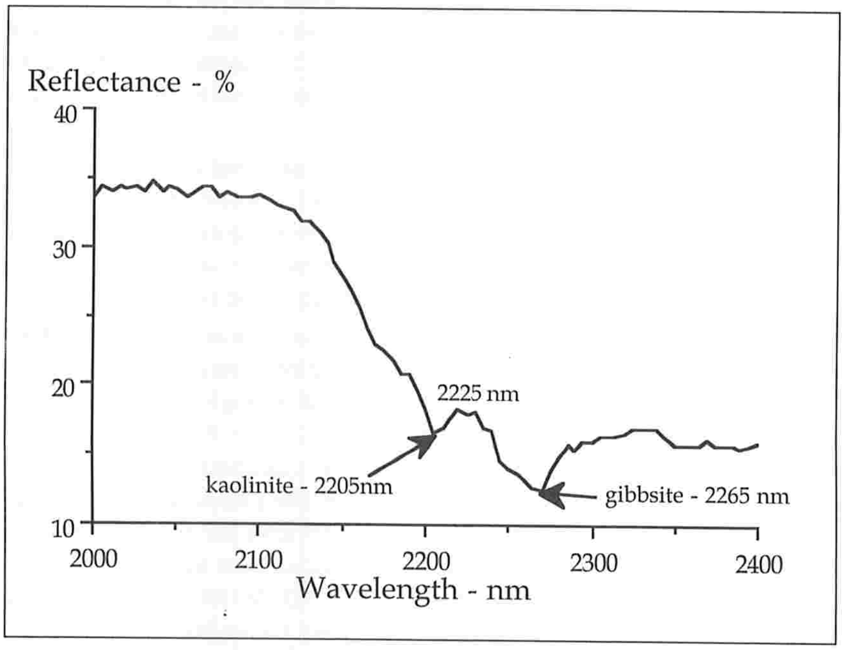
The development of soil spectrometry is relatively new and most of the literature on the subject is only about 30 years old, though some early documents were published more than 65 years ago (ÅNGSTRÖM (1925) for example). Since then some very important contributions have been made, and a few comprehensive reviews on the subject have been published. (BAUMGARDNER and STONER, 1982; BAUMGARDNER *et al*, 1985; MYERS, 1983; MULDERS 1987). In this paper we try to highlight the basic aspects of soil reflectance, and the relationships between reflectance spectrum features and soil components, texture and colors.

I - THE INFORMATION CONTENT OF SOIL SPECTRA

Authors who have studied a large number of soil spectra could define a number of characteristic curves representing the main variations of the reflectance curves. Obukhov and Orlov (1964) and Condit (1970, 1972) presented three basic curve types for the spectral region of 0.4 to 0.8 µm. Stoner and Baumgardner (1981) studying 485 soils in the 0.52 to 2.32 µm wavelength range distinguish five curve types.

Other authors have been able to reduce the dimensionality of the spectral data by applying statistical techniques. These techniques consist in defining a minimum amount of bands which, when combined with key curves (determined by multivariate analysis), reproduce the entire reflectance spectra. Price (1990) shows that just four broad bands: 0.93-1.13 µm; 2.03-2.31 µm; 0.63-0.74 µm; and 1.61-1.80 µm and four key curves account for more than 99% of the variability of the 0.55 to 2.32 µm reflectance data of 564 soils. Huete and Escadafal (1991) also show that with four key bands (410 nm, 900 nm, 610 nm and 540 nm) and four key curves, to which they could relate the biophysical properties of the soils, the spectral (400 to 900 nm) reflectance curves of 46 soils could be reproduced within ±0.17% reflectance. The components found to determine the key curves were organic matter, hematite and goethite.

***Figure 1:** Diffuse reflectance spectrum (2000 to 2400 nm) of a soil sample with 39% kaolinite and 40% gibbsite. The kaolinite and gibbsite features are shown (From Madeira Netto 1993).*



Other soil materials however also leave their marks in the reflectance spectra. Among these are the clay minerals such as kaolinite and montmorillonite; the oxides of aluminum, and titanium, calcite, gypsum etc. Extensive work has been published by Hunt and Salisbury (1970, 1971, 1971a, 1973) and Hunt *et al (*1971), describing the spectral properties of minerals and rocks, providing a valuable source of information for those interested in the reflectance properties of soils. We will restrict ourselves to the presentation of a limited number of examples of minerals in soils.

II - SPECTRAL DETECTABILITY OF SOME SOIL COMPONENTS

2 - 1 Clay minerals

The clay minerals most frequently found in soils are kaolinite and montmorillonite. Their reflectance spectra have characteristic sharp features in the reflected infrared region, centered at 1400 nm and 2200 nm and are due respectively to the overtones of fundamental OH^- stretching mode and to combinations involving OH^- stretching and Al-OH bending modes. As montmorillonite also contains bound water, a strong absorption band due to the H_2O is also present at 1400 and 1900 nm (Hunt and Salisbury, 1970).

Even though the absorption of the two minerals overlaps at 2200 nm, the shape of the bands are quite different. Hauff *et al* (1990) and Kruse *et al* (1991) discuss the identification of kaolinite and smectite in materials containing mixed layer minerals and also the possibility of estimating the proportion of kaolinite by considering the asymmetry of the absorption band at 2200 nm.

Kaolinite and gibbsite are common mineral mixtures in tropical soils. The proportions of such minerals in the soils are an important indicator of the degree of weathering, usually employed in soil mapping. Madeira Netto (1993) has shown that spectral data between 2000 and 2300 nm allows clear identification of the occurrence of those two minerals and the determination of the ratio between kaolinite and gibbsite in Brazilian latosols. The procedure applied takes into account the intensities of absorption of kaolinite and gibbsite centered respectively on 2205 nm and 2265 nm as shown in **figure 1** (MADEIRA NETTO *et al*, 1995).

STONER and BAUMGARDNER (1980) presented averaged soil spectra for four mineralogy classes: kaolinitic, montmorillonitic, gypsic and micaceous. However, the description of the curves take into account aspects that are not always directly related to the intrinsic spectral features of the minerals. Indeed, montmorillonitic soils are characterized by lower reflectance in the visible to 1000 nm wavelength because of higher organic matter content, and kaolinitic soils have a broader absorption band at 900 nm attributed to the iron oxides which are usually associated with these soils.

Landsat Thematic Mapper data has a large band in the OH absorption region, which lies between 2080 and 2350 nm (TM7). This band has been included mainly to allow for the determination of hydrothermal alteration. Successful use of this band, usually combined with TM band 5 (1550 - 1750 nm) as a ratio TM5/TM7 has been reported in the mapping of hydrothermal alterations by several authors (ABRAMS *et al,* 1977; ROWAN *et al*, 1977; ROWAN and KAHLE, 1982 PODWYSOCKI *et al* 1983).

2 - 2 Iron oxides

Goethite (FeOOH) and hematite (Fe_2O_3) are the most frequently occurring ferric iron (Fe^{3+}) minerals found in soils. They result from the oxidation of iron present as Fe^{2+} in primary minerals in the soil forming process. The predominance of one or other of these minerals has been related to pedoclimatic factors and the understanding of their occurrence is important in the study of tropical soils (SCHWERTMANN and TAYLOR, 1977; KAMPF and SCHWERTMANN, 1983; CURI and FRANZMEIER, 1984; MACEDO and BRIANT, 1987). Different management practices may also be inferred from the predominance of goethite or hematite (for example, the predominance of the former increases phosphorus absorption).

These iron oxides have different reflectance features in the ultra violet, visible, and near infrared spectra. Some of these features are responsible for their colors: red for hematite and brown-yellow for goethite. The exact position, attribution, and relative intensities of the absorption features have been presented by SHERMAN and WAITE (1985). Some of the transitions are shown in the goethite and hematite spectra in **figure 2**. One of the electronic transitions ($2(^6A_1) \longrightarrow 2(^4T_1)$) is located at 530 nm for hematite and at 480 nm for goethite. This different position is responsible for their characteristic colors (SHERMAN and WAITE, 1985, KOSMAS *et al*, 1984).

KOSMAS *et al* (1984) used the second derivative of the spectral data to define the exact location of the absorption peak of the transition $2(^6A_1) \longrightarrow 2(^4T_1)$ in goethite - hematite mixtures. They then found a good correlation between this location and the relative proportions of the two minerals.

Numerous studies have shown that it is possible to correlate color parameters extracted from soil reflectance spectra with the iron oxide content of soils. TORRENT *et al* (1980) found a high correlation between a color index determined with the Munsell color notation of hue, chrome and value and the hematite content of soils. Later, TORRENT *et al* (1983) defined another equation based on the CIE chromatic coordinates x, y, Y% which had a better correlation with hematite than the previous one. Finally, BARRON and TORRENT (1986) have optimized this relationship. MADEIRA NETTO (1993) used the color parameters: dominant wavelength, saturation and brightness to define an expression that could also be used to estimate the hematite content of soils.

Recent studies show relationships between indices derived from TM and SPOT bands and iron oxides in soils. FRASIER (1991) has shown the possibility of identifying the prevailing type of iron oxide (goethite or hematite) in arid and semiarid environments by using the TM3/TM1 ratio. This same ratio has been used by OKAMOTO *et al* (1993) to evaluate deposits of red sediments in coral reefs. The authors report a high correlation between the TM3/TM1 ratio and the free iron content in the deposited sediments. The free iron content was less than 1.5%. MADEIRA NETTO (1993) developed a new channel ratio ($TM3^2/(TM2^3*TM1)$) which is in close correlation with hematite content of lateritic soils. In the Brazilian savannas this ratio could be used to map cultivated bare soils with different hematite contents.

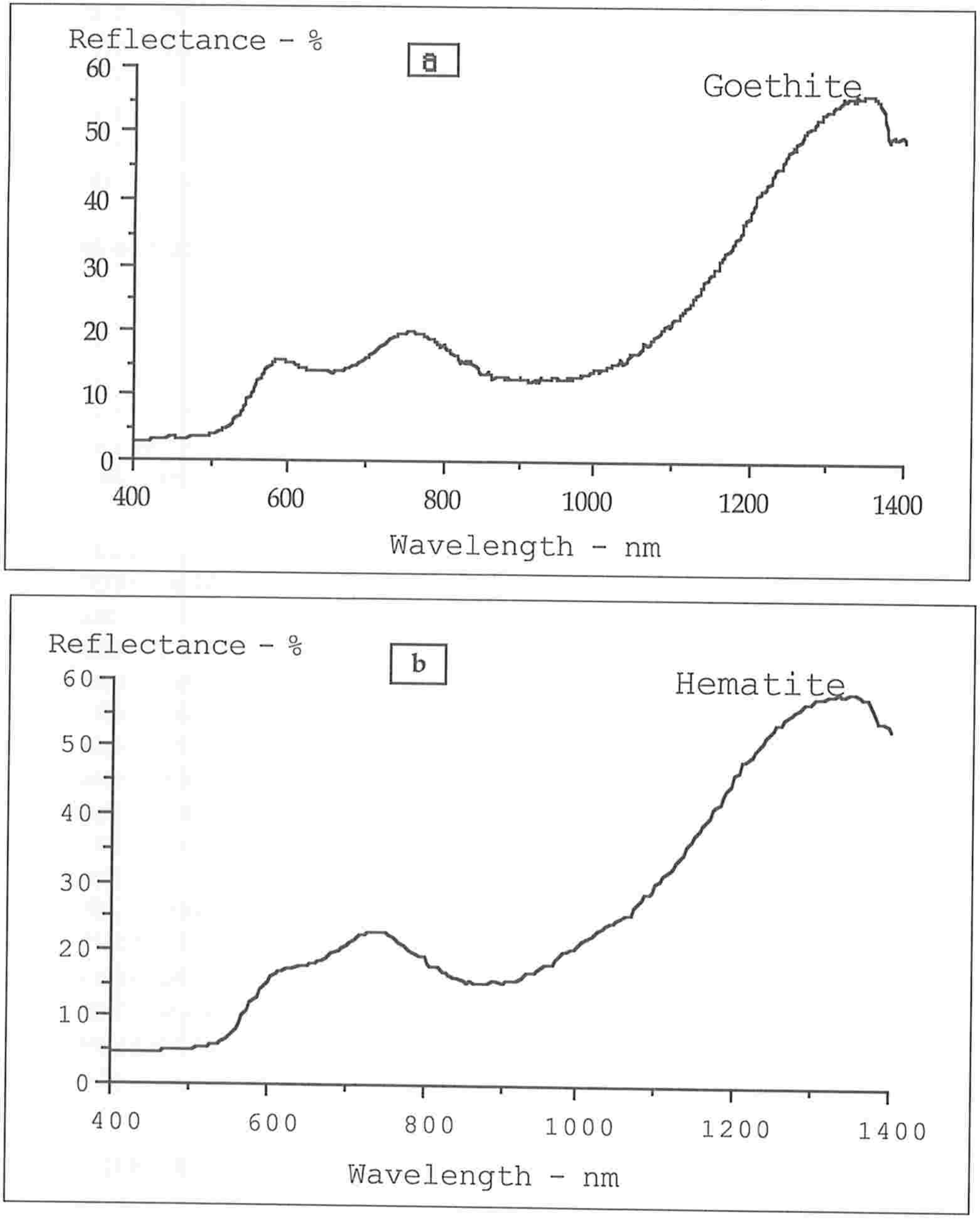
2 - 3 Gibbsite ($Al_2O_3.3H_2O$)

Soils which have been subject to pronounced alteration, like the oxisols located in the old erosion surfaces, may present a large amount of gibbsite on their compositions. In some cases it may be the most important mineral in the clay fraction.

The spectral features of gibbsite are due to OH^- vibrations. FREDERICKSON (1954) has shown the exact location of the stretching and bending mode absorption features. The near and medium infrared spectra contain the stretching harmonic (~ 1550 nm) and the combination of the stretching and bending mode (~ 2300 nm) (HUNT *et al,* 1971) as shown on **figure 3.**

The spectral resolution of LANDSAT and SPOT sensors does not allow for the individualization of clay minerals and gibbsite. However with the development of hyperspectral resolution of new sensors, which is presently available for aircraft and hopefully will shortly be available for spacecraft, this limitation should be overcome.

Figure 2 : *Diffuse reflectance spectra of a gœthite (a) and hematite (b). The assignments and position of the bands are indicated (From* MADEIRA NETTO*, 1993).*



2 - 4 Magnetite and ilmenite

Soils derived from mafic materials may have a significant amount of opaque minerals as magnetite and ilmenite. These minerals are inherited from the parent materials and are not products of alteration, and their identification is very helpful in geological and pedological mapping.

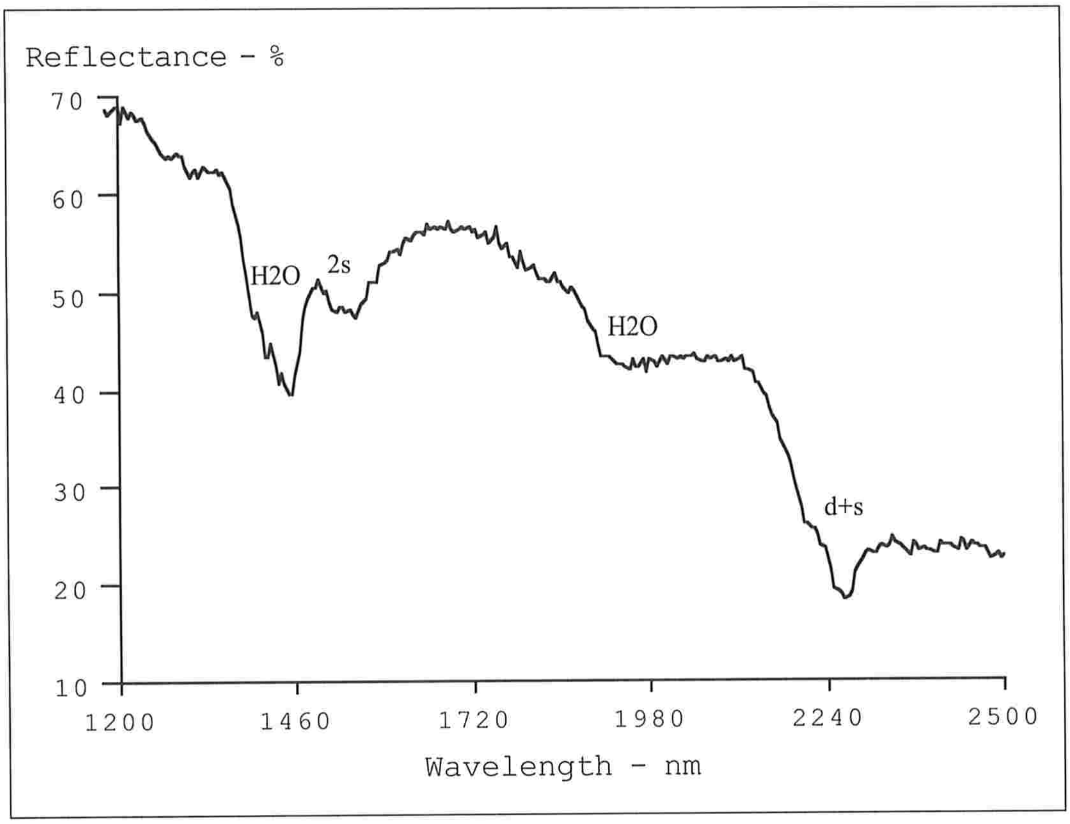
The reflectance spectra of these materials are featureless. The reflectance values of their spectra are usually less than 5% in the entire visible to mid infrared range (HUNT *et al*, 1971) The absorption responsible for this opacity has been attributed by STRENS and WOOD (1979) to the charge transfers betweeen the ions $Fe^{2+} \rightarrow Fe^{3+}$; $Fe^{3+} \rightarrow O$; $Fe^{2+} \rightarrow O$, and to the intra-ionic transitions in the Fe^{2+}, Fe^{3+} ions. For ilmenite the absorption has been attributed to the $Fe2^{2+} \rightarrow O$; $Ti^{4+} \rightarrow O$; $Fe^{2+} \rightarrow Ti^{4+}$ charge transfers and to the intra-ionic transition in the Fe^{2+} ions. The combined effect of these features is intensified by the iron and titanium metallic absorption bands that extend from the ultraviolet to the visible spectrum (HUNT *et al,* 1971)

2 - 5 Organic matter (OM)

Soil organic matter is a generic term for a complex mixture of carbon compounds with variable physical and chemical characteristics. It is usually classified into three broad categories: humins, fulvic acids (FA), and humic acids (HA). The proportion of these compounds in soils can vary greatly, depending on the formation factors such as climatic conditions, the living organisms that originated them, the composition of the inorganic soil materials etc. (FLAIG *et al*, 1975).

Laboratory spectral data has shown that reflectance characteristics of humic and fulvic acids are very different (OBUKHOV and ORLOV, 1964;

***Figure 3:** Gibbsite reflectance spectrum showing the harmonic of the stretching mode (2s) at 1550 nm and the stretching and bending mode combination (d+s) at 2265 nm. The features due to the water absorption are also indicated (From* MADEIRA NETTO, *1993).*



HENDERSON *et al*, 1992). Humic acids have an overall low reflectance due to a multitude of molecular constituents that absorb in the visible spectrum, such as phenolic compounds and their oxidation products, amino acids and their condensation products (FLAIG, *et al*, 1975).

The nature of relationships between organic matter composition and soil reflectance is not well understood. The first direct investigation of organic fraction reflectance was conducted by OBUKHOV and ORLOV (1964), using visible data (400 - 750 nm). Humic acid had extremely low reflectance (< 2%) throughout the entire range, and fulvic acid reflectance reached a maximum of 20% at 750 nm. Since this study, several researchers have attributed reflectance differences among soils with similar organic carbon contents to differences in organic matter composition (SHIELDS *et al*, 1968; KARMONOV and ROZHKOV, 1972; VINOGRADOV, 1981). However this assumption has not been experimentally determined. HENDERSON *et al* (1992) have fractionated organic matter from soils and obtained reflectance data (400 nm to 2500 nm) from four different soils, but they could not clearly identify the effects of organic matter composition.

A strong relationship between soil color - or visible reflectance - and organic carbon content has long been recognized, with darker soils containing more organic matter than lighter ones (ALEXANDER, 1969; STEINHARDT and FRANZMEIER, 1979). Oxidation of organic matter in soils with H_2O_2 has shown that the effects of organic matter on soil spectra may be wavelength-dependent and vary according to soil type. BOWERS and HANKS (1965), OBUBHOV and ORLOV (1964) and COURAULT and GIRARD (1988) showed that elimination of OM resulted in an increase in reflectance from # 400 to # 2 500 nm, although beyond 1300 nm the differences become very small. MATHEWS *et al* (1973) destroyed the OM in a soil with a 12.8 % OM content. The reflectance increased in the range of 400 to 1300 nm but decreased slightly in the region from 1500 to 2400 nm. MADEIRA NETTO (1993) shows for three oxisols with different iron oxide contents that the effect of extracting organic matter of reflectance was very different. When the iron content was close to zero, reflectance increased for the entire 400 to 2500 nm spectral range **(figure 4a)**. For soils with a high content of iron oxides and no opaque minerals, elimination of organic matter increased the reflectance in the wavelength range below 600 nm and decreased for the rest of the spectra **(figure 4b)**. For soils rich in opaque substances (magnetite and ilmenite) the reflectance actually decreased in almost the entire wavelength range after elimination of the organic matter **(figure 4c).**

Numerous laboratory studies have attempted to quantify organic matter from measured soil reflectance data (BOWERS and HANKS, 1965; ORLOV, 1966; STONER and BAUMGARDNER, 1981).

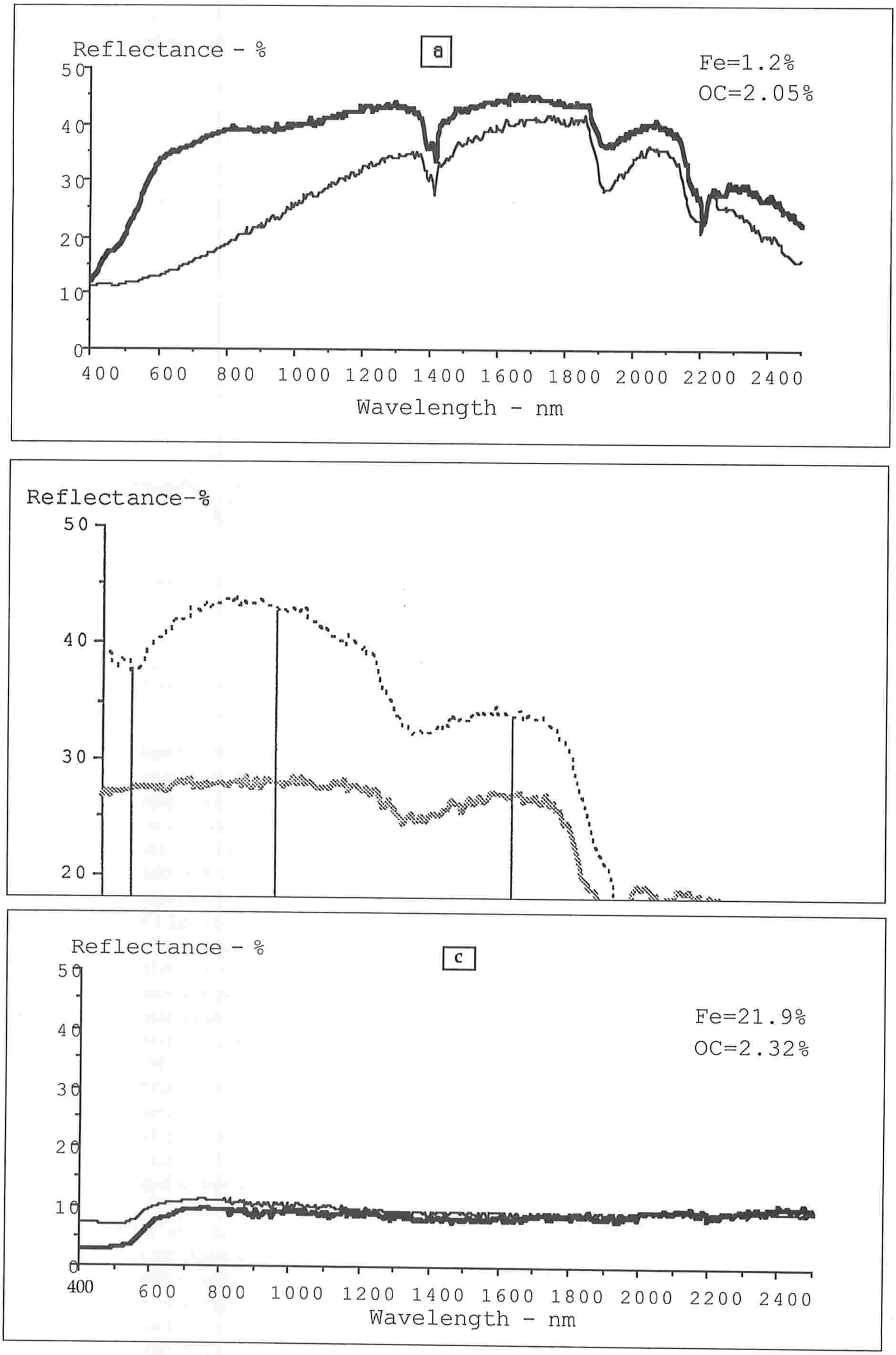


Figure 4: *Effect of eliminating OM on reflectance spectra of three oxisols. Bold lines represent spectra of samples with organic matter; plain lines represent spectra of samples after elimination of organic matter. a - Soil sample with very low (Fe_2O_3 = 1.2%) iron oxide content. OC = 2.05%; b - soil sample rich in iron oxides (Fe_2O_3 = 10.1%) and without opaque minerals. OC = 1.84%; c - soil sample rich in iron oxides (Fe_2O_3 = 21.9%) and magnetite. OC = 2.32% (OC : organic carbon content).*

FERNANDEZ *et al* (1988) found a high correlation between the soil Munsell value calculated from visible reflectance data and the organic carbon content within a landscape. Other researchers, using soils collected from large geographic areas, had much poorer results (RICKMAN *et al.* 1981; PITTS *et al.*, 1983). Low correlation between reflectance and organic carbon content has been attributed to the complicating effects of texture, moisture and mineralogy. CURRAN *et al* (1990) showed that for OM contents over 3%, an index based on the chromatic coefficients (X, Y, Z) was highly correlated to the OM content, regardless of the composition of the soil mineral fraction. However, for low OM contents the inorganic composition was the most important factor explaining these variations.

HENDERSON *et al* (1992) has shown the potential of high dimensional reflectance data in specific visible, near-infrared, and middle-infrared bands to provide information about soil organic matter content. Reflectance in the visible range (425 to 695 nm) has the highest correlation ($r = 0.991$ or better) with organic carbon content (OC) for soils having the same parent material. However this wavelength range also responds significantly to Fe content which may mask the organic matter response. For soils formed on different parent materials, five middle-infrared bands (1955-1965, 2215, 2265, 2295-2295, and 2315-2495 nm) gave the best correlation ($r= 0.964$ or better) with OC.

A strong negative logarithmic relationship was found between OM content and reflectance in the red wavelength region (FUKUHARA *et al*, 1979). This fact was exploited by HATANAKA *et al* (1989, 1990) and OKAMOTO *et al* (1990) to map organic matter content in different regions of Japan. This same relationship was used by SHINGYOJI *et al* (1990) to map organic matter depletion of cultivated fields in a region with volcanic ash soils. WILCOX *et al* (1994) also relate the surface organic carbon levels of soils to a selected transformation of TM band ratios. Significant regressions (with r_2 of the order of 0.88 to 0.71) were observed between these parameters for four different locations in USA.

2 - 6 Soil moisture

Soil moisture affects soil reflectance due to the water absorption bands at 760, 970, 1190, 1450 and 1940 nm (CURCIO and PETTY, 1951) and decreases the reflectance values throughout the entire spectra. The absorption bands are overtones and combinations of the three fundamental vibration frequencies of the water molecule.

Already in 1925, ÅNGSTRÖM (1925), explained the reduction of the reflected light with moisture due to total internal reflections in the water film covering the soil particles, which cause a portion of the energy to be reflected not to space but to the soil itself.

The effect of moisture on soil reflectance has been the subject of many studies (BOWERS and HANKS, 1965; SHIELDS *et al*, 1968; CIERNIEWSKI, 1985; CELIS-CEUSTER 1980; BEDIDI *et al*, 1992). BOWERS and HANKS (1965) show examples of almost constant overall reflectance decreasing with increasing soil moisture content. However, for soils presenting strong absorption bands like the lateritic soils, BEDIDI *et al* (1992) have shown that the moisture effects depend on wavelength and on the position and intensity of the solid component absorption bands.

Predictions of soil moisture based on the analysis of spectral data has been studied by several authors. The 1940 nm absorption band is the most sensitive to soil water content. BOWERS and SMITH, (1972) report a linear relationship between the intensity of this absorption band and soil water content. Based on near infrared (1100 to 2500 nm) data measured in laboratory for samples from different types of soils, DALAL and HENRY (1986) made predictions of soil moisture by using a multiple correlation (three wavelengths) with absorbencies ($\log(1/R)$, where R = reflectance). They found the three best wavelengths: 1926, 1954 and 2150 nm. The standard error of prediction was only of 0.58%.

YAMAMOTO *et al* (1991) studied the quantitative relations between soil moisture and the visible to near infrared spectra (400 to 1100 nm) of four different types of soils. They found a good correlation (coefficient of determination greater than 0.95) between water content (Vol %) and reflectance. The equations that best fitted the data were of the exponential type. However the wavelength with the best coefficient of determination was dependent on the soil type.

Satellite data have also been used to estimate soil moisture content as reported by Hatanaka *et al* (1995). The differences between the CCT counts of TM band 5 (1550 - 1750 nm) on two dates were proportional to the available water in an area of different soils in northern Japan.

III - PARTICLE SIZE EFFECTS

A general explanation of the effect of the particle size on reflectance has been given by SIMMONS (1972). He presents an equation that shows an inverse relationship between particle size and reflectance. The explanation for this behavior is that finer particle materials have a more even surface with fewer pores to trap incoming light.

Experimental work confirms this theory. BOWERS and HANKS (1965) studying kaolinite and bentonite reflectance and ORLOV (1966) studying soil aggregates have found similar results. There was an exponential relationship between particle size and reflectance. For particles greater than 2 mm in diameter there is practically no variation in reflectance. ORLOV (1966) proposed the following equation below to explain his results:

$$R = k*10^{-nd} + R,$$

Where R is the reflectance ; d is the aggregate diameter, R is the reflectance for the aggregates above which there is no further effect due to particle size, k and n are constants that depend on soil type.

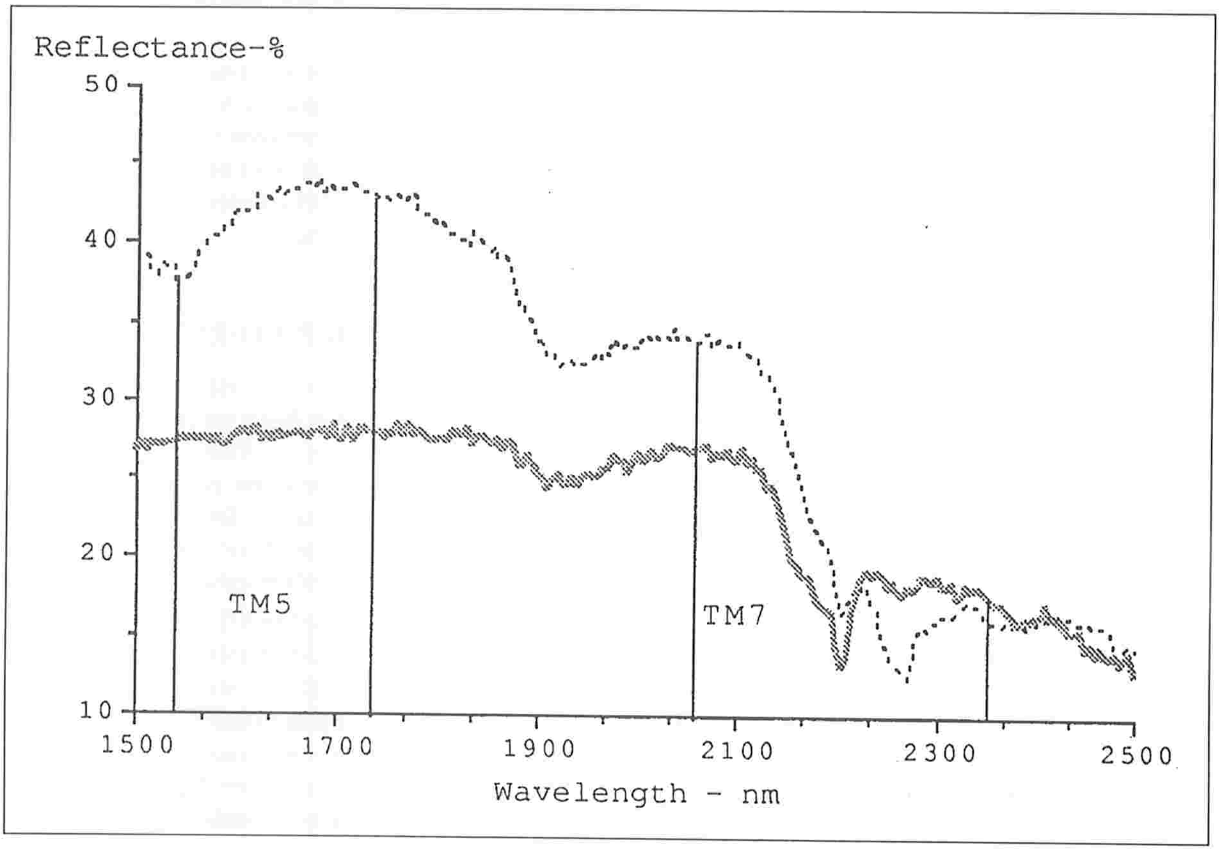
The reflectance of undisturbed soils measured in the field tends to show opposite results to those obtained in the laboratory, i.e. the reflectance for the clay soils is usually lower than for sandy soils. The structure of fine textured soils, in undisturbed conditions, generally presents aggregates of size coarser than sand (MYERS and ALLEN, 1968). ORLOV (1966) studying a Sod- Podzolic soil also concluded that the effect of structure was dominant over that of texture.

For disturbed soil surfaces (by tillage for example), the surface roughness decreases soil reflectance (STONER and HORVATH, 1971, EPIPHANIO and VITORELLO, 1984). This is due to the shadowing effect created by clods. The measured reflectance depends then not only on the clods characteristics but also on the illumination and viewing geometry. Successful attempts have been made to model roughness effects taking this geometric measurement configuration into consideration (CIERNIEWSKI, 1984, 1987; ESCADAFAL, 1989; COURAULT *et al*, 1993).

Attempts have been made to find quantitative relationships between reflectance intensities and particle size. LEU (1977) found that reflectance intensities in the spectral ranges of 430 - 470 nm and 510 - 530 nm are correlated to the grain size of beach sands. However, GERBERMAN and NEHER (1979) studying reflectance in the 460 - 860 nm spectral range for clay soil and sand mixtures reported a logarithmic relationship between reflectance intensities and the amount of sand in the mixture.

A different approach was used by MADEIRA NETTO (1993) to determine the texture for latosols. Kaolinite and gibbsite are the main components of the clay-size particles of these soils, and so there is a good correlation between the sum of these components and the clay-size particle content. As kaolinite and gibbsite have spectral features in the TM7 wave range, and in the TM5 band there are no specific features related to the minerals occurring most frequently in latosols, it was possible to use the ratio (TM5 - TM7/TM5 + TM7) to estimate the sum of kaolinite and gibbsite content. This same ratio is also well correlated to the clay particle content. **Figure 5,** shows the reflectance spectra (1500 - 2500 nm) of two soils where kaolinite + gibbsite totals and band ratio are 0.82 and 0.33 res-

Figure 5: *Examples of diffuse reflectance spectrum (1550 - 2500 nm) for two soils presenting different kaolinite + gibbsite totals, and the ratio of simulated TM bands 5 and 7 (TM5 - TM7)/(TM5 + TM7). Kaolinite + gibbsite totals and band ratio are respectively 0.82 and 0.33 for the sample with darker reflectance curve and 0.12 and 0.015 for the grayish colored reflectance curve.*



pectively for the sample with the darker reflectance curve. For the grayish colored reflectance curve the values were 0.12 and 0.015 respectively. A regression analysis of 52 samples showed a significant correlation between the ratio (TM5 - TM7/TM5 + TM7) and clay content with an error of less than 5% and a correlation coefficient r = 0.80. When applied to a Landsat TM image this ratio was effective in discriminating four soil surface texture classes.

IV - CONCLUSIONS

This paper reviews some of the research results concerning the relationships between soil composition and its spectral properties. An analysis of these results brings some very general conclusions which may be useful for extracting information from soil spectral data:

- Spectral data may be a valuable aid in the study of soil components. Radiometers can be used to collect data in the laboratory, in the field, in aircraft, or in spacecraft. These data are affected by certain soil components which are important for soil classification, cartography, degradation, and management studies.
- Depending on the way the data is acquired (laboratory or satellite, for example), it may contain "undesirable" information about factors other than the one we may want to determine. Surface roughness, moisture, etc. can introduce important modifications in an index sensitive to organic matter determinations, for example. The understanding of such effects is important when defining the accuracy of predictions.
- A universal formula for analyzing the spectral data of all types of soils has yet to be found. The relationships defined between some soil components and spectral characteristics are usually valid for a set of conditions which must be experimentally defined. Much work is still necessary to study the effects of the interactions of different soil components.
- Radiometric data in the visible - mid infrared range refers to the interaction between light and matter of a very narrow soil layer (only a few millimeters). Soil scientists using radiometric data - mainly from satellites - need to understand how the properties of this thin layer relates to entire soil cover to derive valuable pedological information.

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PROPRIÉTÉS DE LA RÉFLECTANCE SPECTRALE DES SOLS

José da Silva MADEIRA NETTO

La réflectance des sols est une propriété cumulative qui résulte de la combinaison des caractéristiques spectrales propres de leurs composants minéraux, organiques et liquides. En plus de la composition chimique elle-même, la dimension des particules et l'organisation des composants jouent également un rôle important dans la réflectance des sols. Les spectres de réflectance des sols peuvent ainsi apporter une double information : l'une relative au processus de formation des sols et l'autre relative à leurs composants spécifiques. En analysant les formes des spectres de réflectance, on peut ainsi extraire des informations pertinentes sur les caractéristiques physisco-chimiques des sols. Les variations spectrales sont généralement associées à des bandes spécifiques d'absorption et peuvent être quantifiées en utilisant différentes procédures. Ces possibilités d'identification, font de la spectroscopie de la réflectance, un outil important pour étudier la composition des sols au laboratoire, sur le terrain et à partir d'images satellitaires.

La diversité des courbes de réflectance des sols peut se résumer par quelques courbes caractéristiques de leurs principaux constituants. La dimension des données spectrales peut également être réduite en appliquant des techniques statistiques. Cela revient à définir le nombre minimum de bandes spectrales nécessaires pour reproduire le spectre complet de réflectance lorsqu'elles sont utilisées conjointement avec des courbes-clés (déterminé à l'aide d'une analyse multi-variables). Ces courbes-clés sont influencées par un certain nombre de composants tels que la matière organique, l'hématite et la goethite.

Les argiles rencontrées le plus fréquemment dans les sols - kaolinite et montmorillonite - possèdent d'étroites bandes d'absorption caractéristiques dans le domaine de l'infrarouge réfléchi, centrées sur 1400 nm et 2200 nm. Comme la montmorillonite possède également de l'eau liée, elle présente également une intense bande d'absorption due à H_2O à 1900 nm. Bien que les spectres d'absorption de ces deux minéraux se recouvrent à 2200 nm, la forme des bandes d'absorption est relativement différente. C'est pourquoi, Landsat Thematic Mapper possède une bande large dans le domaine correspondant à l'absorption de l'ion OH^- entre 2080 et 2350 nm (TM7) qui a été installée principalement pour détecter les altérations hydrothermales.

La goethite (FeOOH) et l'hematite (Fe_2O_3) sont les minéraux ferriques (Fe^{3+}) rencontrés le plus fréquemment dans les sols. La prédominance de l'un ou l'autre de ces minéraux a été mise en relation avec des facteurs pédoclimatiques et joue un rôle important dans les systèmes de classification. Ces oxydes de fer ont des formes de spectres de réflectance différentes dans l'ultraviolet, le visible et le proche-infrarouge. Certaines des transitions électroniques responsables de ces différences, sont montrées sur les spectres de réflectance de la goethite et de l'hématite présentés sur la **figure 2**. La transition située à 530 nm pour l'hématite et à 480 nm pour la goethite est responsable de leurs couleurs caractéristiques : rouge pour l'hématite et brun-jaune pour la goethite. Un certain nombre d'études a ainsi permis de montrer la possibilité de corréler les paramètres de couleur, extraits des spectres de réflectance, avec la teneur en fer des sols.

Des indices dérivés des bandes de TM de Landsat et de SPOT ont été corrélés à la teneur en oxydes de fer des sols. Le type dominant d'oxydes de fer (goethite ou hématite) peut ainsi être estimé dans les environnements aride et semi-aride en utilisant le rapport des bandes de Thematic Mapper (TM3/TM1). Un rapport inter-canaux ($TM3^2/(TM2^3*TM1)$) est étroitement corrélé à la teneur en hématite des sols latéritiques. Dans les savanes brésiliennes, ce rapport a été utilisé pour cartographier les sols nus cultivés avec différentes teneurs en hématite.

La gibbsite ($Al_2O_3.3H_2O$) est souvent un composant important des sols tropicaux fortement altérés, et sa proportion dans la fraction argileuse est un moyen utile pour discriminer les classes de sols. Les bandes d'absorption de la gibbsiste sont dues aux vibrations de l'ion OH^-. Dans le proche et le moyen infrarouge, se trouvent les harmoniques correspondant aux mouvements d'étirement (~ 550 nm) et à la combinaison des modes d'étirement et de rotation (~ 2300 nm) comme cela est montré sur la **figure 3.** L'intensité de cette dernière bande d'absorption a été montrée comme étant proportionnelle à la concentration en gibbsite dans les latosols.

Les sols dérivés des matériaux mafiques peuvent contenir une quantité significative de matériaux opaques tels que la magnétite et l'ilmenite. L'absorption responsable de cette opacité a été attribuée aux transferts de charges entre les ions $Fe^{2+} \longrightarrow Fe^{3+}$; $Fe^{3+} \longrightarrow O$; $Fe^{2+} \longrightarrow O$, et aux transitions intra-ioniques dans les ions Fe^{2+}, Fe^{3+}. Pour l'ilmenite l'absorption a été attribuée aux transferts de charge $Fe^{2+} \longrightarrow O$; $Ti^{4+} \longrightarrow O$; $Fe^{2+} \longrightarrow Ti^{4+}$ et aux transitions intra-ioniques dans les ions Fe^{2+}. Les sols avec de fortes quantités de ces minéraux possèdent un "applatissement" caractéristique des courbes de réflectance.

La matière organique (OM) des sols, terme général désignant un mélange complexe de composés carbonés avec des caractéristiques physico-chimiques très variables, est généralement classée en trois grandes catégories : humines, acides fulviques (FA) et acides humiques (HA). Les acides humiques ont une réflectance très faible (< 2 %) dans le visible, tandis que les acides fulviques peuvent avoir une réflectance maximum qui atteint 20 % à 750 nm. L'oxydation de la matière organique du sol par un traitement par H_2O_2 a montré que l'effet de la matière organique sur les spectres des sols, dépend de la longueur d'onde et varie d'un sol à l'autre, comme le montre la **figure 4**. Pour des teneurs en fer proches de zéro, la réflectance augmente sur l'ensemble du domaine spectral de 400 à 2500 nm **(figure 4a)**. Pour les sols avec une teneur élevée en oxydes de fer mais sans minéraux opaques, l'élimination de la matière organique diminue la réflectance pour les longueurs d'ondes inférieures à 600 nm et l'accroît pour les plus grandes longueurs d'ondes **(figure 4b)**. Pour les sols riches en substances opaques (magnétite et ilmenite), la réflectance décroît pratiquement dans l'ensemble du domaine de longueurs d'ondes après l'élimination de la matière organique **(figure 4c)**. Une relation étroite entre la couleur du sol ou sa réflectance dans le visible et la teneur en carbone organique est connue depuis longtemps avec les sols foncés qui contiennent plus de matière organique que les sols clairs.

Une étroite relation logarithmique négative a été trouvée entre la teneur en matière organique et la réflectance dans le domaine du rouge. Cette relation a été exploitée pour cartographier la teneur en matière organique du sol et l'épuisement des sols en matière organique dans les zones cultivées à partir d'images satellitaires.

L'humidité affecte la réflectance du sol en raison des bandes d'absorption à : 760, 970, 1190, 1450 et 1940 nm. Elle a pour effet une diminution des valeurs de la réflectance sur l'ensemble du spectre. Des courbes de réflectance pratiquement homothétiques peuvent être observées pour des sols qui ne présentent pas de bandes d'absorption prononcées, elles montrent une décroissance de la réflectance avec l'accroissement de l'humidité. Pour les sols qui présentent de fortes bandes d'absorption comme les sols latéritiques, l'effet de l'humidité dépend de la longueur d'onde. Dans ce cas, la position et l'intensité des bandes d'absorption de la phase solide, sont les facteurs dominants. Il est ainsi possible d'estimer l'humidité du sol à partir de données spectrales. La bande d'absorption à 1940 nm est la plus sensible à la teneur en eau du sol. Cependant, des données satellitaires ont également été utilisées pour estimer l'humidité du sol en dehors de cette bande spectrale.

La taille des particules et la réflectance sont liées par une relation logarithmique inverse parce que les particules les plus fines tendent à présenter une surface plus uniforme avec moins de pores pour piéger le rayonnement incident. Cependant, la réflectance de sols non perturbés, mesurée sur le terrain, tend à présenter un résultat inverse car la taille des agrégats des sols argileux est généralement plus grossière que celle des particules sableuses.

Des relations quantitatives entre l'intensité de la réflectance et la taille des particules ont été recherchées à travers différentes approches. Ainsi, pour certains types de sols latéritiques, le rapport (TM5 - TM7/TM5 + TM7) montre une bonne corrélation avec la somme des teneurs en gibbsite et en kaolinite **(figure 5)**. Ces deux minéraux constituent la quasi totalité des particules de la fraction argileuse des sols latéritiques.

Pour les sols travaillés (labour par exemple) la rugosité de la surface induit une importante réduction de la réflectance. Cela est dû à l'effet d'ombre des mottes qui dépend non seulement des caractéristiques des mottes mais aussi de la géométrie de l'éclairement et de la visée. Des modélisations ont permis de rendre compte avec succès des effets de la rugosité de surface.

RÉFÉRENCES

Voir texte en anglais.

LISTE DES FIGURES

Figure 1 : *Spectre de reflectance diffuse (2000 à 2400 nm) d'un échantillon de sol contenant 39% de kaolinite et 40% de gibbsite. Les zones de kaolinite et de gibbsite sont représentées (d'après* M*ADEIRA* N*ETTO 1993).*

Figure 2 : *Spectre de reflectance diffuse de a) gœthite et b) hématite. Les attributions et positions des bandes sont indiquées. (D'après* M*ADEIRA* N*ETTO, 1993).*

Figure 3 : *Spectre de reflectance de gibbsite montrant l'harmonique du mode d'élongation (2s) à 1550 nm et la combinaison des modes d'élongation et de flexion (d+s) à 2265 nm. Les particularités*

résultant de l'absorption par l'eau sont également indiquées (D'après MADEIRA NETTO, *1993).*

Figure 4 : *L'effet de l'élimination de la matière organique sur les spectres de reflectance de trois oxysols. Les traits gras représentent les spectres des échantillons contenant de la matière organique alors que les traits normaux représentent les spectres des échantillons après élimination de la matière organique. (a) échantillon de sol avec très faible teneur en oxides de fer (Fe_2O_3 = 1.2 %), teneur en carbone organique (C0) = 2.05 % ; (b) échantillon de sol avec forte teneur en oxides de fer (Fe_2O_3 = 10.1%) et sans minéraux opaques, CO = 1.84 % ; (c) échantillon de sol avec forte teneur en oxides de fer (Fe_2O_3 = 21.9 %) et magnétite, CO = 2.32 %). (D'apres* MADEIRA NETTO, *1993).*

Figure 5 : *Exemples de spectres de reflectance diffuse (1550 - 2500 nm) pour deux sols présentant différents taux de kaolinite + gibbsite, ainsi que le rapport entre bandes TM 5 et 7 simulées (TM5 - TM7)/(TM5 + TM7). Les taux de kaolinite + gibbsite et le rapport de bande pour l'échantillon avec la courbe de reflectance plus sombre sont respectivement de 0,82 et 0,33, tandis que pour la courbe de reflectance grisâtre, ceux-ci sont respectivement de 0,12 et 0,015 (D'après* MADEIRA NETTO, *1993).*

PROPRIEDADES DE LA REFLECTANCIA ESPECTRAL DE LOS SUELOS

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La reflectancia de los suelos es una propiedad acumulativa que deriva del comportamiento espectral del conjunto de los constituyentes minerales, orgánicos y líquidos que componen los suelos. Además de la composición misma, el tamaño de las partículas y la organización de los constituyentes representan influyen también en las propiedades de reflectancia de los suelos. Así, a través de los espectros de reflectancia se puede tener una doble información : una en relación con los procesos de formación y otra en relación con los constituyentes específicos de los suelos. El análisis de los distintos modelos observados en los espectros de reflectancia permite tener una información pertinente de las características físico-químicas de los suelos. Las variaciones espectrales, generalmente ligadas a fenómenos de absorción específica, pueden ser cuantificadas utilizando diferentes procedimientos. Estas posibilidades de identificación hacen de la espectroscopía de reflectancia una importante herramienta para el estudio de la composición de los suelos, en el laboratorio, en el terreno y a través de las imágenes satelitales.

La diversidad de las curvas de reflectancia puede resumirse en algunas curvas características de los principales constituyentes del suelo. La simplificación de los datos espectrales se obtiene también aplicando técnicas estadísticas. Esto consiste en definir el número mínimo de bandas tal que, utilizadas conjuntamente con las curvas-patrones determinadas por análisis multivariable, puedan reproducir el conjunto del espectro de reflectancia. Estas curvas-patrones son influenciadas por algunos componentes del suelo tales como la materia orgánica, la hematita o la goetita.

Los espectros de los minerales arcillosos más frecuentemente encontrados en los suelos - caolinita y montmorillonita - tienen formas características en el infrarrojo, entre 1400 y 2200 nm. En cuanto a la montmorillonita, la presencia de agua ligada, determina a 1900 nm una banda de absorpción fuerte, que se debe al H_2O. A pesar de la superposición de las curvas a 2200 nm, la forma de dichas curvas es totalmente distinta. El sensor Thematic Mapper tiene una amplia banda en la zona de absorpción de los OH^- (entre 2080 y 2350 nm). Se retuvo esta banda para permitir la determinación de las alteraciones hidrotermales.

La goetita (FeOOH) y la hematita (Fe_2O_3) son los minerales férricos (Fe^{3+}) más frecuentes en los suelos. El predominio de uno u otro de estos minerales se relaciona con los factores pedoclimáticos y representa un papel importante en los sistemas de clasificación. Estos óxidos de hierro tienen distintas espectros de reflectancia en el ultravioleta, el visible y el infrarrojo cercano. Algunas de las transiciones electrónicas responsables de las diferencias espectrales entre hematita y goetita se presentan en la **figura 2**. La transición, ubicada a 530 nm para la hematita y a 480 para la goetita, es responsable de sus colores característicos: rojo para la hematita y pardo-amarillo para la goetita. A través de numerosos estudios, se ha mostrado que es posible establecer correlaciones entre los parámetros color, extraídos de los espectros de reflectancia, y del contenido en óxidos de hierro de los suelos.

Los índices derivados de las bandas TM y SPOT se correlacionan a los óxidos de hierro presentes en los suelos. El tipo de óxido de hierro dominante (goetita y hematita) se puede estimar en los medios áridos y semi-áridos utilizando la relación entre las bandas Thematic Mapper (TM3/TM1). Una relación que combina los tres canales TM del visible ($TM3^2/TM1*TM2^3$) está estrechamente relacionada con el tenor en hematita de los suelos lateríticos. En las sabanas brasileñas, se utilizó esta relación para cartografiar los suelos desnudos con diferentes tenores en hematita.

A menudo, la gibbsita ($Al_2O_3\ 3H_2O$) es un constituyente importante de los suelos tropicales fuertemente meteorizados y su proporcion en la fracción arcillosa contribuye a la discriminación de las clases de suelo. Las características espectrales de la gibbsita se deben a las vibraciones del ion hidróxilo (OH^-). **La figura 3** muestra la ubicación, en el infra-rojo cercano y medio, del armónico de estiramiento (~1550 nm) y de la combinación estiramiento-rotación (~2300 nm). Se mostró que la intensidad de esta última absorción es proporcional a la concentración en gibbsita en los latosuelos.

Los suelos derivados de materiales máficos pueden tener una cantidad significativa de minerales opacos como la magnetita y la ilmenita. La absorción responsable de esta opacidad se atribuye a las transferencias de cargas entre los iones

$Fe^{2+} \rightarrow Fe^{3+}$; $Fe^{3+} \rightarrow O$; $Fe^{2+} \rightarrow O$, y a las transiciones intra-iónicas en los iones Fe^{2+}, Fe^{3+}. Para la ilmenita, la absorción se atribuye a las transferencias de carga entre $Fe^{2+} \rightarrow O$; $Ti^{4+} \rightarrow O$; $Fe^{2+} \rightarrow Ti^{4+}$ y a las transiciones intra-iónicas en los iones Fe^{2+}. Los suelos que contienen una cantidad importante de estos minerales presentan un aplanamiento característico de las curvas de reflectancia.

La materia orgánica de los suelos (OM), término general para designar una mezcla compleja de compuestos carbónicos con características físicoquímicas muy variables, se clasifica generalmente en tres grandes categorías: las huminas, los ácidos fúlvicos (FA) y los ácidos húmicos (HA). Los ácidos húmicos tienen reflectancias muy débiles (<2%) en la parte visible del espectro, mientras que los ácidos fúlvicos pueden alcanzar un máximo de 20% de reflectancia a 750 nm. La oxidación de la materia orgánica por los tratamientos con agua oxigenada H_2O_2, muestra que los efectos de esta materia orgánica sobre el espectro de los suelos puede depender de la longitud de onda y varía de un suelo a otro, como lo muestra la **figura 4.** Para los contenidos en hierro próximos a cero, la reflectancia aumenta sobre el conjunto del espectro, de 400 a 2500 nm **(figura 4a)**. Para los suelos con contenidos elevados en óxidos de hierro pero sin minerales opacos, la eliminación de la materia orgánica provoca una disminución de la reflectancia para las longitudes de onda inferiores a 600nm y un aumento de esta reflectancia para el resto del espectro **(figura 4b)**. Para los suelos ricos en sustancias opacas (magnetita e ilmenita), la reflectancia decrece efectivamente en casi la totalidad del espectro después de la eliminación de la materia orgánica **(figura 4c)**. Una estrecha relación entre el color del suelo, es decir la reflectancia en el visible, y el contenido de carbono orgánico se ha puesto de manifiesto desde hace largo tiempo con los suelos oscuros que contienen más materia orgánica que los suelos más claros.

Se ha encontrado una estrecha relación logarítmica negativa entre el contenido en materia orgánica y la reflectancia en las longitudes de onda del rojo. Este hecho ha sido aprovechado para cartografiar el contenido en materia orgánica de los suelos y el agotamiento en materia orgánica utilizando imágenes satelitales.

La humedad afecta la reflectancia de los suelos debido a las bandas de absorción a 760, 970, 1190, 1450 y 1940 nm. Esto tiene por efecto una disminución de los valores de reflectancia sobre el conjunto del espectro. Las curvas son sensiblemente homotéticas, sin bandas de absorcián particularmente marcadas, y decrecen cuando la humedad de los suelos aumenta. En cuanto a los suelos que presentan importantes bandas de absorción, como es el caso de los suelos lateríticos, los efectos de la humedad dependen de la longitud de onda. Los factores determinantes son, entonces, la posición y la intensidad de las bandas de absorción de la fase sólida.

Es posible estimar la humedad de los suelos a partir de datos espectrales. La banda de absorción a 1940 nm es la más sensible a la cantidad de agua contenida en los suelos. Igualmente, los datos satelitales han sido utilizados para la estimación de la humedad de los suelos.

El tamaño de las partículas y la reflectancia presentan una relación de tipo logarítmico inversa, y a que las partículas más finas presentan una superficie más uniforme con menos poros para captar la luz incidente. Sin embargo, la reflectancia de los suelos no perturbados medida en el terreno, tiende a mostrar resultados inversos, pues el tamaño de los conglomerados en los suelos arcillosos es generalmente más grosero que el de las partículas arenosas.

Las relaciones cuantitativas entre la intensidad de la reflectancia y el tamaño de las partículas han sido investigadas a través de enfoques diferentes. Así, para ciertos tipos de suelos lateríticos, la relación (TM5 - TM7/TM5 + TM7) presenta una buena correlación con la suma gibbsita + caolinita **(figura 5).** Estos dos minerales constituyen la casi totalidad de la fracción arcillosa de los suelos lateríticos.

Para los suelos perturbados, por ejemplo por la labranza, la rugosidad de la superficie da lugar a una disminución de la reflectancia. Esto se debe a los efectos de sombra creados por los terrones; la reflectancia depende no sólo de los terrones, sino también de la geometría de la iluminación y del ángulo de mira. Se han desarrollado modelos que han permitido mostrar con éxito los efectos de la rugosidad de superficie.

REFERENCIAS

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Figura 2: *Espectro de reflectancia difusa de (a) goetita y (b) hematita. Se han indicado las atribuciones y las posiciones de las bandas (según* MADEIRA NETTO*, 1993).*

Figura 3: *Espectro de reflectancia de gibbsita en el que aparece el armónico de estiramiento (2s) en 1.550 nm y la combinación estiramiento-rotación* *(d + s) en 2.265 nm. Se han indicado asimismo las características resultantes de la absorción por el agua (según* Madeira Netto, *1993).*

Figura 4: *Efecto de la eliminación de la materia orgánica en los espectros de reflectancia de tres suelos con materia orgánica oxidada. Las líneas reforzadas representan los espectros de las muestras que contienen materia orgánica mientras que las líneas normales representan los espectros de las muestras una vez eliminada la materia orgánica. (a) Muestra de suelo con un contenido muy bajo de óxidos de hierro (Fe_2O_3 = 1,2 %) y un contenido de carbono orgánico (CO) = 2,05 %. (b) Muestra de suelo con contenidos elevados de óxidos de hierro (Fe_2O_3 = 10,1 %) y sin minerales opacos; CO = 1,84 %. (c) Muestra de suelo con alto contenido de óxidos de hierro (Fe_2O_3 = 21,9 %) y magnetita; CO = 2,32 % (según* Madeira Netto, *1993).*

Figura 5: *Ejemplos de espectros de reflectancia difusa (1.550 - 2.500 nm) para dos suelos que presentan distintos porcentajes de la suma caolinita + gibbsita, y de la relación entre las bandas TM5 y TM7 simuladas (TM5 - TM7) / (TM5 + TM7). En la curva de reflectancia más oscura, el porcentaje de caolinita + gibbsita y la relación entre bandas, para la muestra considerada, son del 0,82 y 0,33 respectivamente, mientras que en la curva de reflectancia grisácea, las cifras son del 0,12 y 0,015 respectivamente (según* Madeira Netto, *1993).*