ESTIMATING FOLIAR CHEMICAL CONCENTRATIONS WITH THE AIRBORNE VISIBLE/INFRARED IMAGING SPECTROMETER (AVIRIS)

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ABSTRACT

The reflectance spectra of a vegetation canopy contains information on the chemicals within that canopy. This paper reviews the underlying theory and the use of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) to estimate foliar chemical concentrations. There are several problems associated with the use of AVIRIS data in this way. *Sampling* of forest canopies, *wet laboratory analysis* of foliar chemicals and *visualization* of AVIRIS data are discussed with reference to AVIRIS data collected for a flat site in Florida and a hilly site in Wales.

KEY WORDS: AVIRIS, foliar chemical concentrations, forest ground data collection.

1. INTRODUCTION AND REVIEW

Measures of foliar chemical concentration provide indicators of plant productivity (e.g., levels of chlorophyll), rate of litter decomposition (e.g., levels of lignin) and availability of nutrients (e.g., nitrogen). By making such estimates remotely we have the potential of studying the quality of the vegetation and a portion of several nutrient cycles on a local to a global scale (Janetos *et al.*, 1992). A number of agencies have stated that their research goals for the 1990s include the study of global biochemical cycling and that remote sensing is a tool needed to achieve this goal (Curran, 1989). For example, the US Committee on Earth Sciences was very specific about the role that remotely sensed information on foliar chemical concentrations could play. *"New, high spectral resolution remote sensing techniques show promise of estimating canopy chemical composition parameters that can be used to elucidate ecosystem properties. Basic understanding and wider validation of this approach are needed"* (Committee on Earth Sciences, 1989, p.58).

The reflectance spectra of all types of vegetation in the 400-2400 nm spectral region are, in general, similar (Figure 1). In near-infrared wavelengths there is high reflectance as a result of leaf scattering and at approximately equal distances throughout the spectrum there are 5 major absorption features. These absorption features are the result of electron transitions in chlorophyll (400-700 nm) and of the bending and stretching of the O-H bond in water and other chemicals (970, 1200, 1400, 1940 nm) (Osborne and Fearn, 1986; Williams and Norris, 1987). In addition, spectroscopic measurements of dried and ground leaves, made by researchers with the U.S. Department of Agriculture (USDA), have revealed over 40 minor absorption features (Curran, 1989). These minor absorption features have been correlated with the concentration of organic compounds (e.g., cellulose, lignin, protein, oil, sugar, starch) in dried and ground leaves. These organic compounds absorb radiation strongly in the ultraviolet (<400 nm) and middle-infrared (>2400 nm) spectral regions as a result of stretching and bending vibrations of the strong molecular bonds between hydrogen atoms and the atoms of carbon, nitrogen, and oxygen (Banwell, 1983; Osborne and Fearn, 1986). The minor absorption features we see in the 400-2400 nm spectral region are relatively weak and broad, with a 30-40 nm half-depth bandwidth. They are the result of harmonics and overtones of the stronger absorptions and combination bands at longer and shorter wavelengths (Peterson and Running, 1989; Barton *et al.*, 1992). For some years now researchers at the USDA have been using regression relationships between reflectance derivatives (Dixit and Ram, 1985) in several narrow wavebands and chemical concentrations to estimate accurately the chemical composition of dried and ground vegetation (Williams and Norris, 1987). Today reflectance spectroscopy is a routine procedure, where the accuracy and repeatability of reflectance estimates of protein, lignin and starch concentrations in dried and ground plant materials are at least comparable to those obtained by wet laboratory methods (McLellan *et al.*, 1991b). As a result, the technique has been certified by the Association of Official Analytical Chemists (AOAC, 1990) and is used throughout the American agricultural industry (Weyer, 1985; Marten *et al.*, 1989; Williams and Norris, 1987; Barton and Windham, 1988). The procedures developed by the USDA have been extended most successfully to the analysis of dried and ground tree leaves in the laboratory (Wessman *et al.*, 1988a; Card *et al.*, 1988; Peterson *et al.*, 1988; McLellan, 1991a, 1991b), a forest canopy in the field (Peterson *et al.*, 1988; Wessman *et al.*, 1988b; 1989; Johnson and Peterson, 1991) and fresh leaves in the laboratory (Curran *et al.*, 1992). In recent years the techniques of spectral matching (Goetz *et al.*, 1990) and spectral decomposition (Card and Peterson, 1992) have also been used as a way of avoiding some of the pitfalls associated with the standard regression-based methodology that uses reflectance derivatives and a wet laboratory analysis (Curran, 1989; Clark, 1991; Janetos *et al.*, 1991). This is just an interim step, as in the future we will need to develop a physically-based modelling approach to the remote sensing of foliar chemical concentrations (Wessman, 1990; Peterson, 1991; Janetos *et al.*, 1992; Baret *et al.*, 1992).

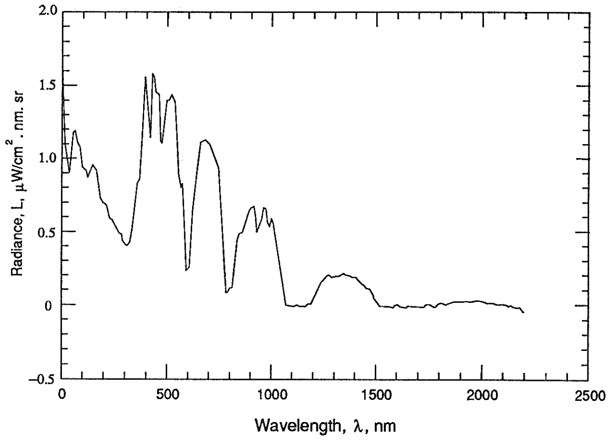

Figure 1. A radiance spectrum of one forested pixel recorded by AVIRIS.

There is a wide range of laboratory sensors that are capable of recording the spectrum of a leaf or a sample of dried and ground foliage. In addition, high-quality field and airborne sensors have been developed which can record vegetation canopy spectra (Goetz, 1991). Three sensors in particular have encouraged the remote-sensing community to use reflectance spectra to estimate foliar chemical concentration. These sensors are the Airborne Imaging Spectrometers I and II (AIS) (Vane and Goetz, 1988), the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Vane, 1987) and the satellite-borne High Resolution Imaging Spectrometer (HIRIS) (Goetz and Herring, 1989) that is scheduled for launch early in the 21st century (Dozier, 1991). While an ideal sensor for estimating foliar chemical concentrations does not exist (Peterson and Hubbard, 1992), an acceptable sensor would record a spectrum between 400-2400 nm with a spectral resolution of 10 nm or less and a level of noise about an order of magnitude smaller than the depth of the absorption feature of interest (Goetz and Calvin, 1987). A fine spectral resolution is achievable through the use of linear arrays and long dwell times. A high signal-to-noise ratio (SNR) is more difficult to achieve as the spectrometers are further developed from their use in the field to their use on aircraft and satellites. The SNR of the AIS was marginal for the study of canopy chemistry; however, chemically ascribable absorption features were seen in the spectra (Peterson *et al.*, 1988). The SNRs for AVIRIS were also low (Curran and Dungan 1989), but again, chemically ascribable features were seen in the spectra (Elvidge, 1988; 1990; Elvidge and Portigal, 1990). Today the SNR of the AVIRIS is much larger than those achieved for the AIS and the early AVIRIS flights (Curran and Dungan, 1990; Curran *et al.* 1991) with >100:1 at wavelengths less than 1000 nm and >50:1 at wavelengths above 2000 nm being possible. If these SNRs can be attained for vegetated surfaces then the absorption features located between the two water absorption wavelengths of 1400 nm and 1940 nm should be larger than the noise and therefore observable in the foliar spectra recorded by these sensors (Dozier, 1989).

Research on the use of AVIRIS data to estimate foliar chemical concentrations is still in its early stages (Wessman, 1990; Peterson and Dungan, 1990). The many problems to be overcome are detailed in the reports of two recent workshops on the remote sensing of foliar chemical concentrations (Peterson, 1991; Janetos *et al.,* 1992). The research reported here concentrates on 3 of these problems: sampling of forest canopies, wet laboratory analysis of foliar chemicals and the visualization of AVIRIS data.

2. STUDY SITES

Two study sites were used in the research discussed here. The first is north east of Gainesville, Florida, it is funded by the U.S. National Science Foundation (NSF) and is maintained by the University of Florida. This site is covered by a slash pine (*Pinus elliottii*) plantation in which 8 fertilised and 8 control plots, each 50 m x 50 m in size were established. These were overflown by AVIRIS in March and September 1990, with multiple overpasses on each date (Curran *et al.*, 1991). The second site is around Llyn Brianne in Wales, UK. This upland site is covered mainly by a Sitka spruce (*Picea sitchensis*) plantation with small areas of other plantation species (japanese larch, *Larix kaempferi*; lodgepole pine, *Pinus contorta var. latifolia*). At this site 51, 50 m x 50 m plots were established. These were overflown twice by AVIRIS in July 1991 as part of the NASA MAC Europe (Curran and Plummer, 1992).

3. RESEARCH PROBLEMS

3.1. Sampling of forest canopies

The four main stages were: choosing the site and plots, locating the plots, collecting forest mensuration data and finally sampling the foliage. These will be discussed in turn.

The two sites have a history of environmental research. The site in Florida has a homogeneous canopy in a flat area and the site in Wales has a heterogeneous canopy in a hilly area. The Florida site contained established experimental plots. While at the Welsh site the establishment of plots was made difficult by windthrow/drains and in addition, flat areas were seasonally waterlogged and suffered from large variations in tree growth over small distances. Collecting ground data in such areas would mean sampling virtually every tree within the plot. Therefore, the plots at the Welsh site were chosen to represent relative levels of tree vigour were all on drained, slightly sloping land where neighbouring trees were of similar size.

It was proposed to use a Global Positioning System (GPS) to locate the plots at both sites. Unfortunately, the trees shielded the signals from the GPS transmitters. Therefore, classical surveying techniques were used to locate the plots.

Forest mensuration data (diameter at breast height, leaf area index, tree height) were collected by researchers from the University of Florida at the Florida site (Gholz *et al.,* 1991) and a team of researchers from 11 different Universities and research institutes at the Welsh site (Curran and Plummer, 1992).

The open canopy and lack of low-level branches at the Florida site meant the canopy could be sampled by shooting small branches from the upper part of the canopy, which then fell to the ground. The Sitka spruce at the Welsh site had a very dense canopy and retains its dead branches on lower whorls preventing sample branches from reaching the ground. Two methods were used to sample this canopy. At some points within the plots the lower dead branches from the tree were cleared until the live canopy was reached. A ladder and pruning pole were then used to remove the selected live branches from the canopy. At other points within the plots a tree was felled and then hand pruners were used to remove the required parts of the canopy. In total 539 foliage samples were collected; 384 for the site in Florida and 155 for the site in Wales. The sampled foliage was bagged by age class and frozen for return to the University College of Swansea for chemical analysis.

3.2. Wet laboratory analysis of foliar chemicals

The foliar samples from the sites in Florida and Wales were analysed with replication using standard wet laboratory techniques for chlorophyll, moisture, lignin, cellulose, nitrogen and carbon. So far the chlorophyll, moisture and lignin analyses have been completed. The chlorophyll and moisture analysis shows statistically significant differences between the fertilized and control plots at the Florida site and the relative level of tree vigour at the Welsh site. The lignin analysis shows a constant (around 10% by weight) concentration of foliar lignin regardless of treatment or location. Wet laboratory analysis is less accurate than laboratory-based reflectance spectroscopy (McLellan *et al.*, 1991b). Therefore, in future research laboratory-based reflectance spectroscopy calibrated against wet laboratory analysis will be used for the chemical analysis of foliar samples.

3.3. Visualization of AVIRIS data

Conventional image analysis is oriented towards broadband remotely sensed data and so initial analysis of AVIRIS data was slow and relatively unproductive. This early processing was divided into two sections: spatial analysis and spectral analysis. The original data remained on a VAX 8820 and the required data were displayed spatially on a GEMS image processing system and spectrally on a 386PC running in-house software. This separation of the data made it difficult to link images and spectra together. Effective processing was achieved using SUN SPARC stations running 'PV-Wave' software which is designed for the visualization of multi-dimensional data sets. A set of routines has been developed in the PV-Wave command language to perform the necessary processing associated with AVIRIS data (Smith and Curran, 1992).

4. A LOOK TO THE FUTURE

Remotely sensed data recorded in broad optical wavebands are being used increasingly to drive and validate environmental simulation models for the study of net primary productivity at scales from the local to the global (Running *et al.*, 1989). Later in the decade the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) will launch their Polar Platform satellites. These satellites will carry sensors that will provide multi-wavelength/multi-polarization synthetic aperture radar data and imaging spectrometry data for use in such environmental modelling. In anticipation of these developments, airborne sensors (e.g., AVIRIS) typical of planned satellite sensors (e.g., HIRIS) have been flown over the sites in Florida and Wales (Curran and Plummer, 1992). The aim of future research is to estimate the key variables of above ground biomass, leaf area index and foliar chemical concentration in order to drive and validate an ecosystem simulation model for forested terrain. This area of resesarch is likely to be a major driver for the development of terrestrial imaging spectrometry.

5. SUMMARY

The remote sensing of foliar chemical concentrations is an important development in remote sensing, not least because of the input it can provide to ecosystem models at regional to global scales. Field campaigns are vital if it is to be demonstrated that AVIRIS can provide such information. This paper has focussed on some of the key issues involved in the remote sensing of foliar chemistry and has emphasised the complexity of field campaigns; in particular the need for meticulous site preparation and a large number of foliar samples, backed up by the facilities necessary for wet laboratory analysis and the visualization of AVIRIS data.

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