FIELD SPECTROSCOPY

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Summary

Field spectroscopy is the technique used to measure the reflectance properties of vegetation, soils, rocks, and water bodies in the natural environment, generally under solar illumination. Many disciplines are interested in the measurement of light reflected off objects in the natural environment. Natural targets are usually illuminated by the whole hemisphere of the sky, and thus receive direct solar flux and scattered sky light. Interactions at the surface result in a proportion of this incident radiation being reflected, either directly from the surface or after multiple interactions within the surface if the material is translucent to the incoming radiation. Natural targets are generally not perfectly diffuse (Lambertian) reflectors and, thus, the intensity of the reflected flux varies with the angle with which it leaves the surface. Consequently, the

radiation environment comprises two hemispherical distributions of electromagnetic radiation, one incoming and one outgoing, and it is the interaction between these two, represented by the bidirectional reflectance distribution function (BRDF), that constitutes the focus of interest in field spectroscopy. Various techniques have been developed to visualise the BRDF of natural surfaces, including (i) the 2-D polar plot, (ii) the solar principal plane plot, (iii) the anistropy plot, and (iv) the 3-D polar plot.

Field spectroscopy finds application as a remote sensing technique in its own right; as a tool in education and training; in the calibration of airborne and spaceborne sensors; and, as a source of data for quantitative models and spectral libraries.

1. Introduction

Spectroscopy is the study of the interaction between electromagnetic radiation (EMR) and matter. In remote sensing, we are primarily concerned with EMR that has interacted with the object of interest and therefore carries information about the composition of the object or the nature of processes occurring within it. This information is generally contained in the EMR transmitted through the object or reflected from it, and is revealed in the spectrally selective nature of the wavelengths absorbed or emitted by the object. Quantitative reflectance spectroscopy requires:

- A source of illumination of sufficient intensity across the range of wavelengths of interest
- A means of measuring the intensity and spectral composition of the illumination, or of maintaining it constant
- A method of directing the illumination on to the sample in a controlled way
- A means of analysing the intensity and spectral composition of the light after it has interacted with the sample

Field spectroscopy is the term used to describe spectroscopy undertaken in the natural environment, particularly where the reflectance properties of vegetation, soils, rocks, and water bodies are measured under solar illumination. Some people have argued that the correct term for such measurements is "field spectrometry" as the aim is to make measurements rather than observe or visualise spectra.

However, the term "spectroscopy" is well established for such measurements in physics and analytical chemistry, so its use will be adopted in this article. "Spectroscopy" describes the branch of science involved in laboratory and field investigations of energy–matter interactions, whereas the actual instruments used to measure spectra are referred to as "spectrometers" or "spectroscopes," depending upon whether they make quantitative measurements or form an image. We may also note in passing that field spectroscopy has been referred to by many other terms, including "hand-held radiometry," "ground radiometry," "field radiometry," "reflectance spectrometry," and "field spectroradiometry."

Spectroscopy is a subject that has grown considerably since the beginning of the twentieth century, and now encompasses a wide range of techniques and applications, from infra-red spectroscopy for foodstuffs analysis to nuclear magnetic resonance

spectroscopy for medical applications. In essence, all these applications are made possible because when EMR interacts with matter it is altered in very specific ways that are characteristic of the molecules making up the material. We see this with our eyes when we observe that white light from the sun is changed to green light when it is reflected off a healthy green leaf **(see *Physical Basis of Remote Sensing*)**. In this case, the reflected energy that we perceive is what remains after the blue and red wavelengths have been absorbed by pigments within the green leaves. However, our eyes are sensitive over only a small range of wavelengths, roughly from 400 to 700 nanometers (nm). A spectrometer measuring the same scene over the range 400 nm–2.4 micrometers (μm) would detect many more features in the reflected spectrum, such as the large increase in reflectance at the "red-edge," the broad absorption features caused by liquid water in the leaf, and maybe much finer absorption features caused by biochemicals within the leaf (Figure 1).
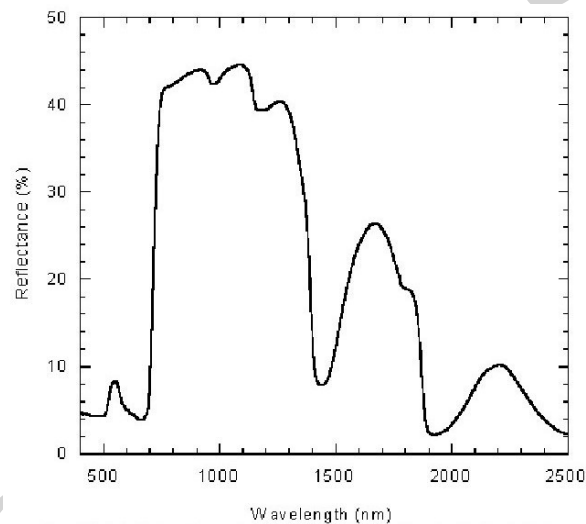

Figure 1. Spectral reflectance of a green leaf measured in the laboratory using an Analytical Spectral Devices Inc. FieldSpec Pro™ spectroradiometer with contact probe attachment
(*Source*: Data from the NERC EPFS)

In this example, the spectrometer recorded the intensity of the reflected light at different wavelengths as a proportion of that reflected from a perfectly reflecting white reference panel (Spectralon). Illumination was provided by an intense, highly stable light source held close to the leaf. In the field, the source of illumination is normally the sun, and the light falling on the target is much more variable as it is affected by short-term variations in atmospheric clarity. The quality of spectra measured under field conditions are also affected by the spectral distribution of the source of the light. Figure 2 shows the spectral distribution of sunlight at the earth's surface compared with the spectral irradiance of a 100W quartz halogen lamp of the type often used for active field spectroscopy (see section 6). It is clear from this figure that the amount and spectral distribution of energy from the artificial source is very different from that from the sun. The peak intensity of the lamp is less and is shifted to longer wavelengths, and the lamp

has significant output energy in those regions of the spectrum around 1.4 μm and 1.9 μm where the solar spectrum is close to zero.
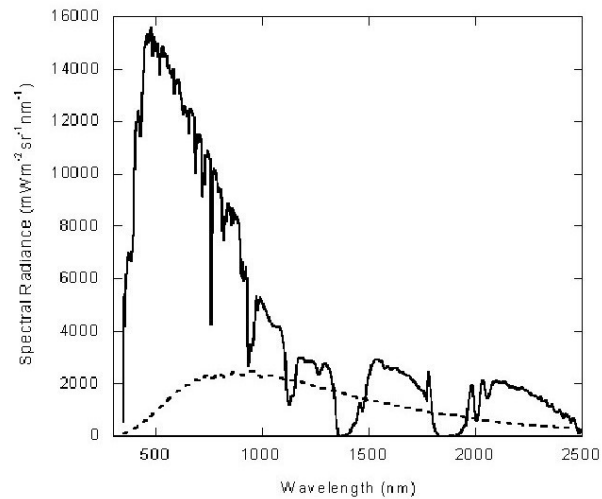

Figure 2. Spectral radiance of a white reflectance panel measured under solar illumination (solid line) compared with its radiance under when illuminated by a 100W quartz halogen lamp in the laboratory (broken line)
(*Source*: Data from the NERC-EPFS)
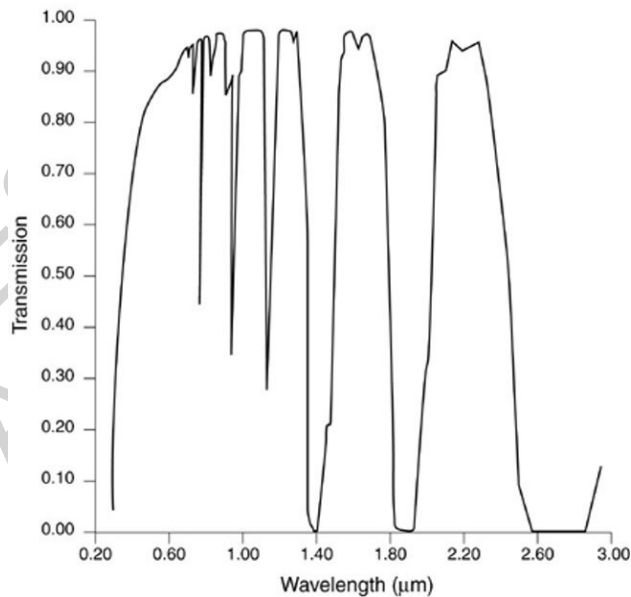

Figure 3. Atmospheric transmission showing the combined effects of attenuation due to absorption by water vapour, atmospheric gases (mainly CO_2, O_2, O_3), and molecular scattering
(*Source*: Y. Kaufman, The atmospheric effect on remote sensing and its corrections, *Theory and Applications of Optical Remote Sensing* (ed. G. Asrar) (New York: John Wiley, 1989))

Absorption and scattering processes in the atmosphere are fundamental to field spectroscopy because they determine what proportion of the sun's energy reaches the surface in each of the wavelengths. However, this fact can easily be overlooked because the results of field spectroscopy are normally presented as reflectance spectra in which the amount of reflected EMR from the surface is expressed as a proportion of that which fell on the surface, thereby compensating for the intensity and spectral distribution of the light source.

The enduring legacy of atmospheric processes in such spectra is a reduced signal-to-noise ratio in regions of the spectrum where the incident energy is very low and no signal at all in those wavelengths in which the atmosphere is totally absorbing. The main constituents of the atmosphere that affect the signal available for field spectroscopy are aerosols, water vapour, oxygen, ozone, and carbon dioxide **(see** *Physical Basis of Remote Sensing***)**. The spectral absorption of aerosols depends upon their size, shape, and composition and is very difficult to generalise, whereas that due to water vapour, the main absorbing gases, and molecular scattering is more predictable and is shown in Figure 3.

The leaf spectrum presented in Figure 1 was measured in the laboratory using an intense light source. Figure 4 shows a *reflectance* spectrum of a dense vegetation canopy measured using a high quality field spectrometer but in the natural environment using the sun as the light source. The regions of the spectrum in which the signal-to-noise ratio is very small are clearly shown by the greatly increased variability in reflectance. There are also small steps in the spectrum that reveal that the full spectrum is actually composed of three sections, each covering a limited range of wavelengths. Both of these deficiencies are normally corrected as part of a pre-processing and calibration procedure specific to each field spectrometer, resulting in a clean reflectance spectrum such as that shown in Figure 5.
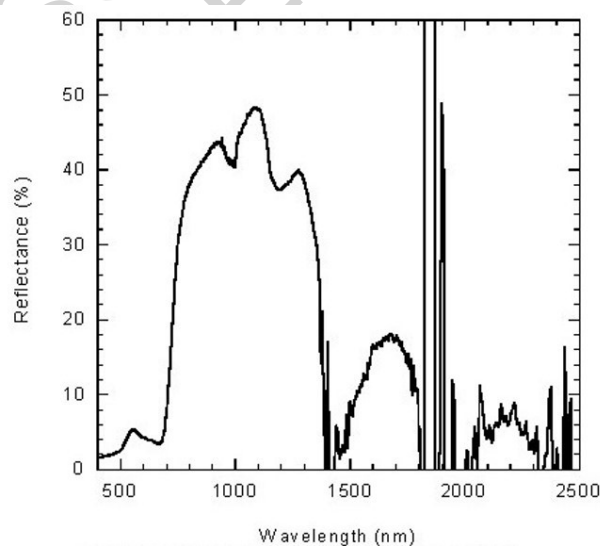

Figure 4. Unprocessed reflectance spectrum of a dense vegetation canopy, measured
with a GER3700 spectrometer under natural sunlight
(*Source*: Data from the NERC-EPFS)

2. Principles of Spectroscopy

EMR is most commonly represented as a waveform in remote sensing but, for spectroscopy, the alternative representation of EMR as "packets of energy" is quite helpful. In 1900, Max Planck observed that changes in the energy absorbed and emitted by matter occur in discrete units, which he called "quanta," and this was the basis for quantum mechanics, which has done so much to advance understanding of matter at the molecular level.
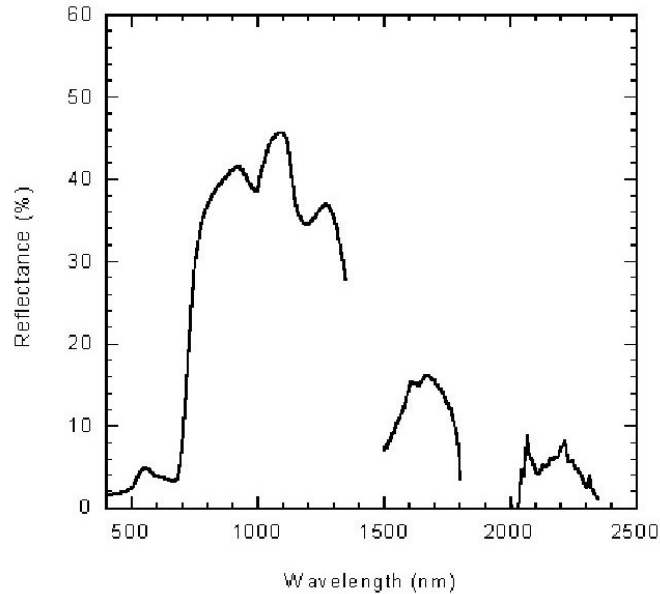

Figure 5. The canopy reflectance spectrum shown in Figure 4, after pre-processing to remove the regions of the spectrum affected by absorption in the atmosphere and after correction for the characteristics of the spectrometer used
(*Source*: Data from the NERC-EPFS)

A molecule of matter stores and releases energy in many different ways. It can possess rotational energy due to its rotation about its centre of gravity; it will have vibrational energy due to the atoms within it oscillating about their equilibrium positions; and it will have electronic energy since the electrons associated with each atom or bond are in constant motion. Each of these three types of energy are "quantized," that is, changes to any of them occur as sudden increases or decreases of a finite amount of energy. This can be thought of as a step between two energy levels, Q_1 and Q_2, in which ΔQ is the change in energy necessary to achieve this increase in energy, or, alternatively, the energy that would be released by the molecule changing between Q_2 and Q_1. Planck showed that ΔQ was a function of the frequency of the EMR (ν, and thus could be represented as:

$$\Delta Q = h\,\nu \text{ joules} \tag{1}$$

where h = Planck's constant, 6.63×10^{-34} Js **(see also *Physical Basis of Remote Sensing*)**.

The significance of this for remote sensing is that, if a molecule of material X in energy state Q_1 is illuminated by a source that emits uniformly over a wide range of frequencies ("white light"), and the spectral distribution of the reflected (or transmitted) light is then measured, it will be seen to have lost energy at one specific frequency, ν $\Delta Q/h$. This will have been absorbed by the molecule and used to raise its energy state to Q_2. The resulting spectrum is referred to as an absorption spectrum (Figure 6).
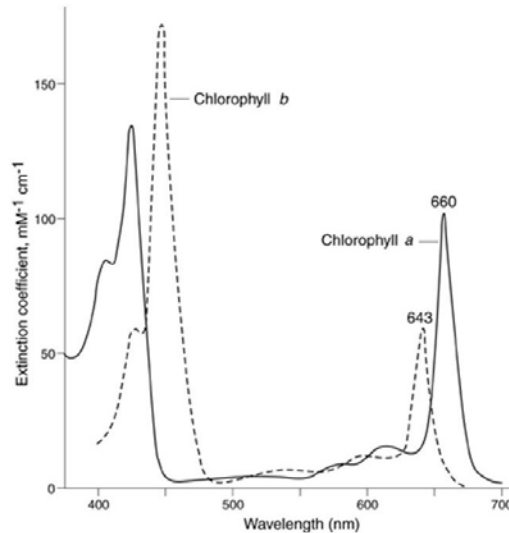

Figure 6. Absorption spectra of two types of chlorophyll extracted in acetone
(*Source*: D.O. Hall and K.K. Rao, *Photosynthesis* (London: Edward Arnold, 1987))

At this point, the worlds of spectroscopy and remote sensing begin to diverge in two respects. First, spectroscopists tend to base their studies around absorption spectra, often determined by measuring the amount of energy transmitted *through* the object of interest. Second, they generally present their absorption spectra with units of *frequency*, or more typically *wavenumbers* ($1/\nu$, on the x-axis since this is directly related to the energy levels involved. In remote sensing it is more usual to focus on energy *reflected* or *emitted* from objects and to plot these spectra against *wavelength*, which is more meaningful when discussing the capabilities of different detectors, for example. Note, however, that in remote sensing we still talk about "absorption features present in reflectance spectra" to indicate regions of the spectrum where the surface of interest is absorbing the incident light.

Laboratory spectral measurements offer the prospect of increased precision compared with the field environment and have been used for soils, rocks, individual plant parts, and mosses, but these cannot totally replace *in situ* measurements. First, there is the difficulty of relocating the surface of interest to the laboratory without damaging it. Second, it is necessary to sample a sufficiently extensive area of the surface to provide a representative measurement, which may be very difficult to achieve in the laboratory (e.g. for a vegetation canopy). Third, if the aim is to simulate what an airborne or orbital

remote sensor would measure it is necessary to recreate the illumination environment of the field in the laboratory, whereas most laboratory instruments are designed to measure reflectance under closely controlled and highly artificial conditions.

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Useful Websites (December 2003)

http://speclab.cr.usgs.gov/ [Important site providing access to the USGS spectral library and an excellent tutorial on the use of field spectroscopy to calibrate data from airborne imaging spectometers, amongst other things.]

http://www.asdi.com/ [Website of Analytical Spectral Devices, containing a number of very useful technical notes and tutorials as well as full information on the range of ASD instruments.]

http://www.geo.unizh.ch/rsl/research/SpectroLab/ [Website of the Spectroscopy Laboratory in the Department of Geography at the University of Zurich. Contains details of the FIGOS goniospectrometer and research papers on field spectroscopy and the calibration of an airborne imaging spectrometer.]

http://www.soton.ac.uk/~epfs/ [Website of the U.K. Natural Environment Research Council Equipment Pool for Field Spectrscopy (NERC-EPFS). Includes information on the instruments in the pool, information on over 400 research projects that have used NERC-EPFS equipment, and extensive reference material on field spectroscopy.]

Biographical Sketch

Edward Milton is Professor of Geography at the University of Southampton, UK, and was formerly Director of the UK Natural Environment Research Council Equipment Pool for Field Spectroscopy (NERC-EPFS). His main research interests are field spectroscopy, the calibration and validation of Earth observation data, and airborne imaging spectrometry.