

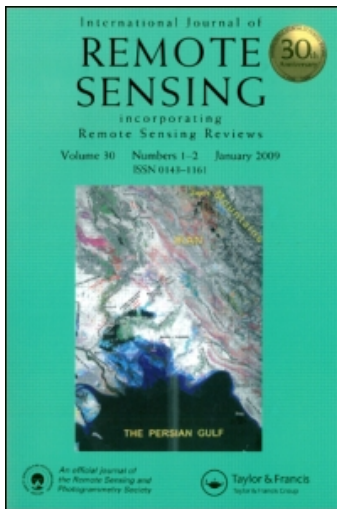
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Review Article

Principles of field spectroscopy

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Abstract. Field spectroscopy involves the study of the interrelationships between the spectral characteristics of objects and their biophysical attributes in the field environment. It is a technique of fundamental importance in remote sensing, yet its full potential is rarely exploited. In this article the principles of the subject are explained and its historical development reviewed with reference to the instruments and methods adopted. Field spectroscopy has a role to play in at least three areas of remote sensing. Firstly, it acts as a bridge between laboratory measurements of spectral reflectance and the field situation and is thus useful in the calibration of airborne and satellite sensors. Secondly, it is useful in predicting the optimum spectral bands, viewing configuration and time to perform a particular remote sensing task. Thirdly, it provides a tool for the development, refinement and testing of models relating biophysical attributes to remotely-sensed data.

1. Introduction

Field spectroscopy is a technique of fundamental importance in remote sensing, both at the level of primary research and in operational applications. However, the wide range of instruments available and the many different techniques used have resulted in problems of data comparability between studies which are in danger of seriously compromising the long-term value of such data. It is essential that all spectral data collected in the field should be supported with adequate information on the conditions of measurement as well as appropriate collateral data.

2. Development of the technique

Techniques for the measurement of the spectral properties of objects under field conditions predate the subject of quantitative remote sensing from airborne and spaceborne platforms by many years. Early this century devices were designed which recorded the energy reflected from natural objects in different parts of the spectrum (e.g. Ives 1915) for use in the study of human vision. The history of spectral radiometers since that time has been one of increasing precision and accuracy in response to improvements in the technology available to disperse incident light energy into its constituent wavelengths and then detect and analyse this energy. In the early stages of development this advance was led by the requirement for quantitative description of the colour of paints and pigments (e.g. Hunter 1942) and the characterization of light sources (e.g. Hammond *et al.* 1960).

However, the potential of quantitative multispectral remote sensing from airborne platforms was also appreciated at an early date and specialized instruments designed to

meet this need (e.g. Krinov 1953, Penndorf 1956). Throughout the 1960s developments in spectral radiometers for field use were led by the biological community, driven by a desire to understand the photosensitivity of plants. Some of these instruments were designed to scan across a range of wavelengths (e.g. Adhav 1963, Adhav and Murphy 1963, Birth and Zachariah 1971, Brach and Wiggins 1967, Bulpitt *et al.* 1965), whereas others had a limited number of fixed spectral bands, usually in regions of pigment absorption (e.g. Birth and McVey 1968, Robertson and Holmes 1963). Detector technology in the 1960s limited the instruments to sensing the region 0.4–1.1 μm but this was not a problem as most of the energy–matter interactions of interest took place within the region 0.4–0.9 μm .

With the growth of interest in quantitative remote sensing from airborne platforms in the United States in the late 1960's, instruments began to be developed which could be used to calibrate the new sensors and investigate interactions at ground level in the same wavebands. One of the first spectral radiometers designed specifically for remote sensing was described by Silva *et al.* (1971) and later became the basis of the Exotech-20 series of spectroradiometers. Following the launch of the first Landsat satellite in 1972, Exotech Inc. also released a ground radiometer sensing in four bands similar to those sensed by the new satellite, and the radiometer formed the basis of the Exotech-100 series (Exotech 1972). Since that time many spectral radiometers have been designed for field use in remote sensing, many by enthusiasts or small groups of researchers, and, as is often the case with innovation by this method, standardization of methodology and inter-calibration between devices and materials has suffered. It is against this background of many competing devices and confused procedures that this review has been prepared. The bulk of the review concerns the methodology of field spectroscopy. Brief specifications of most of the spectral radiometers available at the time of writing are presented in the Appendix.

3. Nomenclature

Within the subject of remote sensing several terms have been used to describe the measurement of spectral reflectance under field conditions, including 'hand-held radiometry' (Tucker 1978) 'ground radiometry' (Milton 1982 a), 'field radiometry' (Celis-Ceusters 1980), 'reflectance spectrometry' (Gladwell *et al.* 1983) and 'field spectroradiometry' (Silva *et al.* 1971). Longshaw (1974) introduced the term 'field spectroscopy' and this usage was supported in a review of the subject by Bauer *et al.* (1986) and will be adopted here.

Field spectroscopy involves the study of the interrelationships between the spectral characteristics of objects and their biophysical attributes in the field environment. The human eye senses only a small part of the electromagnetic spectrum, from approximately 0.4 to 0.7 μm , whereas field spectroscopy in support of remote sensing operates over a much wider range. In the sense discussed here it is restricted to visible and near-infrared wavelengths of approximately 0.4–2.4 μm , and is usually a passive technique in which solar irradiation provides the energy source. This is not invariably the case and several examples exist in the literature where artificial illumination has been provided (e.g. Bunnik *et al.* 1983, Maracci 1978). Although much of the effort in field spectroscopy goes into measuring and analysing the spectral flux from natural targets with differing biophysical attributes, these data are often required to be inverted, that is, used to predict the biophysical attributes of unknown targets from the spectral flux observed by a remote sensor. This requirement places stringent demands upon the repeatability of the technique and makes effective standardization a prerequisite for

successful integration of the technique within the main body of remote sensing methodology.

Traditionally, spectral radiometers have been divided into those which allow the wavelength sensed to be varied in a continuous fashion across a wide range (spectroradiometers or spectrometers), and those which sense in a limited number of pre-set spectral bands (radiometers). Specialized forms of these instruments used to study the visible spectrum are referred to as spectrophotometers and photometers respectively.

This twofold division grew up quite naturally as a result of the commonly used methods of splitting up the incident energy. Use of absorption or interference filters as the primary dispersing device led to radiometers in which either a number of filters are passed sequentially in front of a single detector, or a number of separate detector/filter units are used. In either case the output data comprise measurements of radiant flux in a limited number of spectral bands.

Use of a prism or diffraction grating led to spectroradiometers in which the dispersed spectrum from the target is passed across the face of one or more detectors. In this case the instantaneous spectral bandwidth is primarily determined by the range of wavelengths from the dispersed spectrum projected onto the detector, which is usually determined by the width of a metal slit at the exit port of the dispersing device. The spectrum produced from such an instrument is the result of sampling the detector output at successive positions of the dispersing device and is thus a sampled version of the true spectrum from the target, albeit one in which the wavelengths sampled are very closely spaced. It is common practice to oversample the spectrum, that is sample more frequently than the slit bandwidth might suggest, as this allows subsequent signal processing techniques to recover more of the original spectrum than otherwise would be the case. For example, the Spectron SE590 spectroradiometer (see Appendix) samples the target spectrum with a slit bandwidth (half-power) of 8 nm every 2.8 nm from 400–1100 nm.

Recent developments in detector technology have blurred the distinction between spectroradiometers and radiometers because it is now possible to use a linear array of several hundred detectors located behind a wedge-type interference filter, thus producing a radiometer with several hundred adjacent bands, each of which may have a spectral bandwidth narrower than that of a conventional spectroradiometer using a prism or grating. Instruments based on this 'multispectral linear array' (MLA) technology are more properly described as spectroradiometers, even though it may not be possible to scan across a range of wavelengths in the same way as a conventional spectroradiometer. The key feature which distinguishes a spectroradiometer from a multiband radiometer is the essentially continuous nature of the spectrum produced, even though this continuity is an illusion resulting from the close sampling interval.

4. The radiation environment

Making accurate measurements of spectral reflectance in the field environment is difficult but is necessary because the alternative approach of taking samples back to the laboratory usually results in excessive disturbance (Longshaw 1974). There is evidence that some types of material can be preserved for measurement in the laboratory (Daughtry and Biehl 1985), but these objects are in the minority. Apart from the problem of preservation, there are the further problems, firstly of ensuring that the sample preserved is truly representative of the population from which it is collected and secondly of simulating the natural radiation environment in the laboratory.

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 which constitutes the focus of interest in field spectroscopy.

The radiation geometry of the field environment is shown in the figure. In it the positions of the primary source of irradiation (the Sun) and the sensor are each defined by two angles, firstly the angle from the vertical (the zenith angle, θ) and secondly the angle measured in the horizontal plane from a reference direction (the azimuth angle, ϕ). Ignoring sky light, the energy from the Sun and the energy reflected to the sensor can be thought of as being confined to two slender elongated cones, each subtending a small angle at the target surface, termed solid angles and measured in steradians (sr). If these solid angles are sufficiently small, the reflectance of the target can be defined as

$$f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL(\theta_r, \phi_r)}{dE(\theta_i, \phi_i)} \quad (1)$$

where dL is the reflected radiance per unit solid angle and dE is the irradiance per unit solid angle, and the subscripts 'i' and 'r' denote incident and reflected rays respectively. Both the radiance and the irradiance vary in zenith and azimuth; hence to specify completely the reflectance field at the target, the reflectance must be measured at all possible source/sensor positions, resulting in the 'bi-directional reflectance distribution function' (BRDF). However, in the field environment, measurement of dE at the target surface is not possible and an alternative to the BRDF must be found.

The alternative is found through the standardization of reflected radiance by the

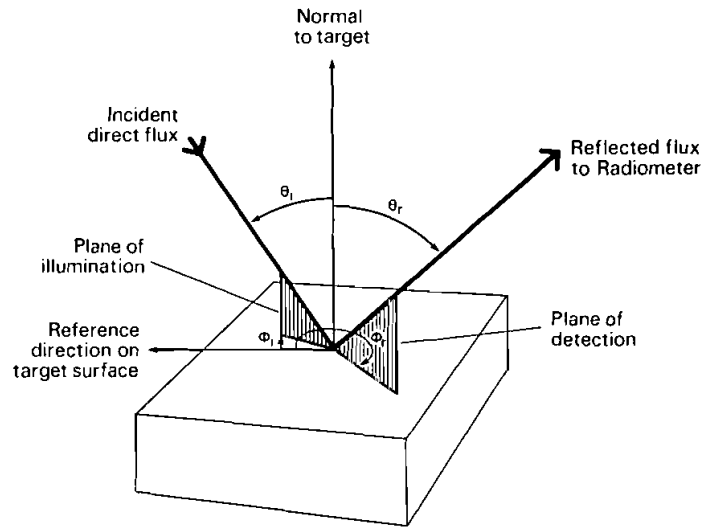


Figure 1. Radiation geometry of the field environment.

use of a panel specified to be perfectly diffuse, completely reflecting and viewed under the same irradiation conditions and in the same geometry as the target. The radiance of the target is then measured as a proportion of the radiance of the standard panel. This measurement configuration may be referred to as bi-conical, as both target and panel are sensed using instruments with a narrow, conical field-of-view. Because in practice a perfectly reflecting panel does not exist, a correction is made to account for the spectral reflectance of the panel. Thus

$$R(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_t(\theta_r, \phi_r)}{dL_p(\theta_r, \phi_r)} k(\theta_i, \phi_i; \theta_r, \phi_r) \quad (2)$$

where dL_t is the radiance of the target and dL_p is the radiance of the panel under the same specified conditions of illumination and viewing, and k is the panel correction factor. Note that k is also dependent upon the angular configuration, as perfectly Lambertian standard panels are impossible to achieve in practice. This results in the 'bi-directional reflectance factor' (BRF), which may be related to the BRDF as follows:

$$R(\theta_i, \phi_i; \theta_r, \phi_r) = \pi f(\theta_i, \phi_i; \theta_r, \phi_r) \quad (3)$$

The term bi-directional in this context refers to the two angles involved, one for the source position and one for the sensor position. In the above equations, all terms are also dependent upon wavelength, but for clarity the subscript λ has not been shown.

The use of BRF instead of BRDF to represent the spectral reflectance of natural targets involves several assumptions (see Silva 1978 and Robinson and Biehl 1979) which include the following:

- (1) The field-of-view of the sensor is less than approximately 20 degrees.
- (2) The reflectivity panel must fill the field-of-view of the sensor.
- (3) There should be no change in the irradiation amount or distribution between measurement of dL_t and dL_p .
- (4) Direct solar flux dominates the irradiation field. That is, the Sun is assumed to shine out of a black sky and sky light is ignored.
- (5) The sensor responds in a linear fashion to changes in radiant flux.
- (6) The reflectance properties of the standard panel are known and invariant over the course of the measurements.

Of these assumptions, that which is always violated in the field situation is the absence of sky light, which results in field measurements of BRF being made under an irradiance distribution which may be significantly different from the slender elongated cone referred to above. In recognition of this fact, the term 'hemispherical-directional reflectance factor' has been used by Duggin (1980) and others to refer to BRF measured in the field, although in later work (e.g. Duggin and Philipson 1985) the term 'hemispherical-conical reflectance factor' has been used to emphasize that the reflected radiance is also measured over a finite solid angle and thus is not strictly directional. Robinson and Biehl (1979) have calculated that the reflectance factor measured in the spectral band $0.5 \mu\text{m} - 0.6 \mu\text{m}$ on a hazy day (visibility = 8 km) will differ from the true reflectance factor by a systematic 3 per cent due to the presence of sky light.

An alternative approach is to monitor the irradiation directly by using an upward looking spectral sensor with a cosine-corrected receptor (that is, a sensor which shows no dependence upon the zenith or azimuth angle of the incident flux). This measurement configuration may be termed cos-conical to indicate that the target is

measured using an apertured receptor. In this case equation (2) becomes

$$R(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_i(\theta_r, \phi_r)}{dE(2\pi)} k(\theta_i, \phi_i; 0, 0) \quad (4)$$

where dE is the irradiation as measured by the upward-looking sensor and k is a correction factor relating the signal from the cosine-corrected receptor to that expected from a perfectly diffuse white panel.

Both methods of measuring spectral reflectance in the field result in a value of reflectance which is dependent upon solar elevation and azimuth and on viewing elevation and azimuth. This has led to the use of the term 'spectral indicatrix' to refer to the envelope defining the spectral reflectance factor at all possible viewing angles and for all possible source angles. Clearly, estimating the complete spectral indicatrix of a surface would involve a great many measurements, which in the field situation would be subject to error due to changes in solar position with time. Consequently, although it must be accepted that the spectral indicatrix represents the fullest statement possible of the spectral reflectance of a natural target, in practice it must be sampled, either over a limited range of wavelengths, or over a limited set of source positions, or over a limited set of sensor positions.

Often, the rationale behind the choice of sample strategy for estimating the spectral indicatrix is not stated. In some cases it may be self-evident that only a particular range of wavelengths is required, perhaps to match a particular remote sensor for example. In other cases, the choice of nadir viewing, or observations around local solar noon, may be made on logistic grounds with little or no reference to the degree to which the subsequent data truly represent the spectral reflectance of a target. If measurements of the spectral reflectance of natural targets are to have long-term value it is important that a rational sampling strategy is adopted and clearly stated. This may involve measurements at nadir or it may involve measurements at a number of zenith angles in the principal plane (the plane joining source, target and sensor) for example.

Considerable ingenuity has been applied to the problem of measuring the complete spectral indicatrix of natural targets in a fast and efficient manner. One solution to this problem is seen in highly specialized radiometers such as the PARABOLA instrument described by Deering the Leone (1986) which scans both the target radiance and the sky irradiance in a spherical fashion under the control of a dedicated microprocessor. In the laboratory environment measurement of the indicatrix is made easier, although determination of the BRDF of a surface may still require a very large number of measurements; for example, over 4×10^8 data points for a 1 degree sampling grid over the hemisphere (Hsia and Richmond 1976).

5. Field measurement of reflectance factors

Spectral flux from a natural object may be recorded and measured in several ways. Firstly, a camera fitted with a spectral filter may be used to record a two-dimensional image of the variation in scene brightness. If the relationship between optical density on the film and radiant energy entering the camera lens is known this technique may be used to measure the reflectance of objects in the scene by various standardization procedures described by Silvestro (1969), Lillesand and Kiefer (1979) and Curran (1980). Although this photographic method has the advantage of preserving the spatial relationships between objects within the scene viewed, it has the disadvantage of requiring precise control over the processing of the film. Furthermore, the several stages involved in standardization lead to errors being propagated through to the final estimate of spectral reflectance. However, for fairly crude estimates of spectral

reflectance in relatively wide bands, the technique compares favourably with the use of a simple multiband radiometer (Curran *et al.* 1981).

For accurate repeatable measurements of spectral reflectance, spectroradiometers and radiometers are generally favoured over film-based devices, although cameras are often included in the design of such instruments. Typically a camera is mounted on the optical axis of an instrument to provide a permanent record of the target sampled; more rarely the camera is used to provide the optical system for the spectral radiometer (e.g. Berry *et al.* 1978, Harvey *et al.* 1974).

In attempting to measure reflectance factors in the field, measurements of radiant flux are being made after its transmission through a dynamic, turbulent, absorbing and scattering medium: the atmosphere. Although the path length of the reflected beam through the atmosphere is usually very short, the path length of the incident beam is much longer and this, together with the contribution of sky light to the incident flux and the changes in atmospheric properties over time, means that the effect of the atmosphere upon field measurements of reflectance can be very significant.

Changes in irradiation due to the atmosphere occur on several different time scales. Firstly, streams of atmospheric particulates cause very short period fluctuations, of the order of a few milliseconds, which have been reported as producing a coefficient of variation in irradiation of approximately 1 per cent (Slater 1980). Secondly, there are longer period (seconds to minutes) changes in irradiation of the order of 5 per cent of the mean which occur in clear blue skies and are thought to be the result of high altitude cirrus clouds invisible to the human eye (Duggin 1974). Thirdly, there are the major changes in irradiation which occur when clouds pass in front of the Sun. It should be noted that there is often a period of unpredictable fluctuation in irradiation as the cloud enters and leaves the solar beam (Monteith 1973).

It is possible to remove the effect of these temporal changes in irradiation from the calculation of reflectance factors by arranging for the target radiance and the standard panel radiance to be sampled at exactly the same instant, as described by Duggin (1980). However, this requires the use of two radiometers, matched over a wide dynamic range, sensing identical wavelengths and affected in the same way by changes in temperature and other environmental variables. Careful design of the instruments in the first place and an accurate inter-calibration between the two sensors are essential preconditions for the use of the simultaneous method. Clearly, the method would still fail to account for all the consequences of a change in irradiation, as changes in the angular distribution of the incident flux may have an effect upon the reflectance factor through variations in the effectiveness of shadowing, for example. This point is discussed further by Milton (1981, 1982 b), Duggin (1982) and Duggin and Cunia (1983).

When measurements of radiance from the target and standard panel are made sequentially, it is important that the time delay between the two measurements should be as short as possible. This requirement is more easily met with radiometers as there is no wavelength scanning involved, although recent advances in the design of field spectroradiometers have enabled them to achieve very rapid scan cycles (typically 1 or 2 s to cover the range 0.4–2.4 μm). It is important to separate the scan time, which is determined by the instrument used, from the maximum delay between measurement of the target and the standard panel or cosine receptor, which is partly determined by the experimental design adopted.

In summary, neither the sequential method or the simultaneous method is suitable for periods when clouds are passing in front of the Sun, but under clear sky conditions

the simultaneous method will have reduced errors due to short-term temporal changes in irradiation, gained at the expense of possibly greater problems in instrument calibration. Probably the most important point is that researchers should become aware of the limitations of the techniques available and ensure that published or archived data include full details of the measurement configuration used.

5.1. *Cos-conical configuration*

The procedures necessary to make this measurement have been described by Duggin (1980); they involve first the calibration of the cosine-receptor to a standard panel over a range of solar zenith angles and secondly the calibration of the standard panel to a laboratory standard of reflectance. Because this measurement method requires a different angular configuration for the measurement of irradiance compared with the measurement of radiance it is most commonly used with two inter-calibrated radiometers, as described by Duggin (1980). Using the same radiometer for both sets of measurements would create an unacceptable delay between measurement of target radiance and incident flux. However, there are other factors to consider in the choice between one or two radiometers, as discussed above.

The cosine-corrected receptor must be perfectly horizontal and no part of the sky hemisphere may be obscured by the operator or other parts of the equipment. This may present problems if the receptor is mounted close to the instrument display or controls, or if it is on a short flexible connector.

5.2. *Bi-conical configuration*

The first requirement of this configuration is a standard reflectivity panel. In the laboratory pressed barium sulphate powder is often used, but this is unsuitable as a field standard. Similarly, the older laboratory standards such as smoked magnesium oxide, sodium chloride, magnesium carbonate, sulphur, aluminium oxide and opal glass are impractical in the field. Although the definition of BRDF refers to a completely reflecting (i.e. white) standard, there are several problems with the use of a white panel in the field. Firstly, and most obviously, it very soon becomes dirty and thus assumption (6) above may be violated. Secondly, the need to measure a highly reflecting panel and relatively dark terrain surfaces with the same instrument presents problems with the dynamic range and signal-to-noise ratio of the device (Milton 1980). Thirdly, it can be argued that reduced errors will occur if the spectral reflectance of the standard panel is similar to that of the target surfaces to be measured (Duggin and Philipson 1982).

Given these problems, several materials have proved to be useful field standards, although none is perfect. Kodak reflectance paint (Part 6080), an emulsion of barium sulphate paint in a binder, is commonly used sprayed on to bead-blasted aluminium sheets (Shai and Schutt 1971). Although quite expensive, this is the closest available field standard to the usual laboratory standard, and can be prepared with little specialized equipment. Each panel should last for at least 6 months if not damaged (Eastman Kodak 1980). Halon resin, a special formulation of white PFTE, has the advantages of being able to be cleaned very easily and also of being hydrophobic. In laboratory measurements it compares well with barium sulphate (Schutt *et al.* 1981). However, it has the disadvantages of being translucent in thin sheets, thus requiring the use of relatively heavy panels, and of attracting particles of dust through the build-up of static charges. Furthermore in some formulations its reflectance decreases with wavelength, thus making it less suitable than barium sulphate for measurements

around the 2.0 μm region. Goetz (1975) reported using a fibrous material called 'Fiberfrax' which has a renewable surface well suited to field conditions. Finally, Kodak grey cards (Part 152-7795) have been widely used as cheap, disposable standard panels (e.g. Egbert and Ulaby 1972, Milton 1980), although they have a relatively poor cosine response (Palmer 1982) and are only available in one small size.

The reflectivity panel chosen for use as a field standard should be referenced to a primary reflectance standard, such as those held by the National Physical Laboratory in the U.K., preferably both in terms of spectral reflectivity and goniometry (departure from Lambertian response). Several authors have published data on the reflectance properties of materials commonly used as reflectivity standards in the field, and the most important of these are listed in the table.

6. General guidelines on field technique and data processing

Several authors have published practical suggestions for improving the consistency and accuracy of field data collected using radiometers and spectroradiometers (see, for example, Robinson and Biehl 1979 and Jackson *et al.* 1980). This is important if the methodology of field spectroscopy is to be refined and standardized between different research groups; the most important points may be summarized as follows:

- (1) Use a mast or tripod to ensure a fixed geometry between the sensor, the standard panel and the target if at all possible. Hand-held measurements are less precise because of the variable geometry involved and because of the (necessarily) close proximity of the operator to the target and of the target to the radiometer.
- (2) Ensure that the sensor is at least 1 m (preferably 2 m) above the upper surface of the target.
- (3) Unless variations in reflectance factor with azimuth are being studied, be consistent in always orientating the sensor horizontal support and positioning the other field equipment (including people) in the same positions relative to the Sun. This is most easily achieved by pointing the sensor support directly towards the Sun.

Published data on the reflectance properties of materials used as field reflectivity standards.

Authors and date	Material
Clarke <i>et al.</i> (1983)	Barium sulphate Opal glass
Grum and Luckey (1968)	Painted barium sulphate Titanium dioxide Krylon
Grum and Wightman (1977)	Sprayed barium sulphate
Hsia and Richmond (1976)	Sprayed barium sulphate Pressed barium sulphate
Palmer (1982)	Kodak grey cards
Trytten and Flowers (1966)	Fiberfrax
Schutt <i>et al.</i> (1981)	PTFE (Halon)
Shai and Schutt (1971)	PTFE (Halon)
Weidner and Hsia (1981)	PTFE (Halon)
Young <i>et al.</i> (1980)	Sprayed barium sulphate Poured barium sulphate

- (4) Check that the standard panel fills the field-of-view of all bands of the sensor and that it is not shaded by the sensor.
- (5) It is useful to position a continuously recording solarimeter centrally within the field area during the time of measurements. This provides three benefits: it allows any anomalies in the data from the primary sensor to be screened and possibly corrected; it allows the atmospheric variability to be quantified on a range of time scales; it can provide data to correct for the effects of variable cloud cover (see Richardson 1981).
- (6) Operators should wear dark clothing and kneel some distance away from the target during measurements. Kimes *et al.* (1983) have shown that errors in the measurement of radiance in red and near-infrared wavelengths can approach 10 and 12 per cent respectively due to a person in white clothing kneeling 0.5 m from the target, whereas a person in black clothing kneeling at the same distance would result in an error of less than 2 per cent in both bands. Vehicles should be kept at least 3 m from the target for the same reason.
- (7) Lord *et al.* (1985) have shown that gusts of wind can cause differences of up to 60 per cent in the BRDF of barley in red wavelengths. Even if the wind is only strong enough to cause the leaves to flutter, variations of up to 12 per cent in BRDF were reported. Under these circumstances, the use of the mean BRDF to characterize a site will result in an overestimate of the true BRDF and the median may be a better estimate. Wright (1986) has reported similar variations in the ratio of infrared to red radiance from barley due to the effect of the wind.

In addition to these points of technique, it is also important that data on the target surface and the conditions of measurement are recorded. For example, reflectance measurements archived as reference material should have associated with them (as a minimum) the following information:

- (1) location of the site (latitude and longitude);
- (2) time of measurement (to the minute);
- (3) Sky conditions, particularly the type and amount of cloud cover, if any;
- (4) name of the instrument used and serial number;
- (5) Whether cos-conical or bi-conical methods were used, and following from the type of reference panel or cosine receptor, details of its calibration (spectral and angular) and the relationship between this and a recognized national standard;
- (6) the viewing geometry and whether the instrument was hand-held or supported by a mast or tripod;
- (7) the height of the instrument above the ground;
- (8) the height of the instrument above the upper surface of the ground target;
- (9) the effective size of the sampling area on the target surface;
- (10) the spectral response curves of each band sampled (multiband radiometers only);
- (11) the sampling interval and instantaneous bandwidth (spectroradiometers only);
- (12) the time taken to measure all bands (or a complete spectrum) from the target and from the reference panel or cosine receptor;
- (13) the delay between measurement of the target and measurement of the reference panel or cosine receptor (if any).

7. The role of field spectroscopy in remote sensing

Field spectroscopy has a role to play in at least three areas of remote sensing: calibration, prediction and modelling.

7.1. Calibration

One of the major outstanding problems of remote sensing concerns the inter-calibration of data from different platforms and sensors, or data from the same sensor at different times. Although in-flight calibration devices are normally provided, their use is not without problems (Slater 1983), and it may be more effective to calibrate airborne and orbital sensors using ground targets whose absolute reflectivity is known. Field spectroscopy is used to characterize the spectral indicatrix of such ground targets, and monitor their stability over time. Apart from its application in the calibration of sensing systems this type of work also has important in the study of the energy balance at the Earth's surface and may be an important input into albedo models.

To achieve this it is necessary for the radiometer(s) or spectroradiometer(s) used to be highly linear and highly stable with respect to changes in environmental conditions. These conditions are not easily met, particularly at longer wavelengths where the effect of changes in temperature upon detectors can be significant (Jackson and Robinson 1985).

In some instances it may be necessary for absolute measurements of spectral radiance as well as spectral reflectance to be made under field conditions, for example in the study of net radiation absorbed by plant canopies at different wavelengths. To do this requires that the radiometers be calibrated either using a standard lamp in the laboratory or using a field procedure such as that described by Jackson and Slater (1986).

The standard panel used in the field must be fully characterized if the reflectance data are to be used for calibration purposes. This also is not easy to achieve, as it is very difficult to obtain primary reflectance standards above $2\ \mu\text{m}$, and it may be necessary to extrapolate the spectral response based on published data, such as those given in the table. The non-Lambertian behaviour of the standard panel is also important, particularly at high solar zenith angles. Kimes and Kirchner (1982) reported errors of up to 27 per cent in estimates of irradiance from a barium sulphate painted panel with a solar zenith angle of 75 degrees.

Furthermore, when the purpose of the calibration is to inter-relate data from different platforms or with different pixel sizes there are additional considerations of the compatibility of the wavelengths sensed and the compatibility of the sampling cell size. Duggin (1985) has shown the effect of mismatch between the spectral response curves of different platforms and has illustrated how this may introduce significant errors into the analysis. Marsh and Lyon (1980) and Curran and Williamson (1985) have presented statistical treatments of the problem of incompatibility between sample cell sizes, both of which use a small pilot study to provide data which, when referenced to a sampling distribution, allows an estimate to be made of the sample size required to achieve a specified level of precision. However, these techniques ignore the spatial autocorrelation present in field spectra and it may be that geostatistical techniques based on the analysis of semivariance will eventually prove to be more useful for this task (Curran and Williamson 1986).

In summary, the first role of field spectroscopy is to act as a bridge between

laboratory measurements of spectral reflectance and the field situation and, in doing so, to reveal the nature and significance of noise sources in the natural environment which would place limits on the use of remote sensing.

7.2. Prediction

The predictive role of field spectroscopy involves its use in answering three questions. Firstly, 'what are the optimum spectral bands for a particular task?', secondly, 'what is the optimum geometric configuration of source and sensor (e.g. time of day, look angle, etc.) for a particular task?' and, thirdly, 'what is the optimum time of the year for a particular task?'. These uses require moderate accuracy but high precision; that is, the observations must be repeatable to within predictable levels of error, but need not always be referenced to a primary reflectance standard.

In this role, field spectroscopy is employed to tackle a problem already identified, possibly by a group of users who have little direct experience of the nature of energy-matter interactions occurring in natural targets. If this is the case it may be necessary to reformulate the task into one which can be broken down into a series of well-defined hypotheses stated in the language of remote sensing. Consider, for example, the problem of automatically identifying areas of degenerate heather on airborne scanner imagery. Before field spectroscopy can provide guidance on the choice of spectral bands, range of look angles and time of year for this task it is necessary to redefine what is meant by degenerate heather in terms of the association of canopy components (green leaves, twigs, shadow, etc.) presented to a remote sensor through the spectral indicatrix.

Increasingly, spectral reflectance data are being archived with sufficient collateral data on the conditions and methods of measurement that a knowledge base on the reflectance properties of natural surfaces is being established. It would be wrong to regard this as a data base of spectral signatures (except to the extent that each observation is as unique as a signature), but equally it would be folly to ignore this accumulating knowledge when using field spectroscopy in a predictive role. Sensible use of these data can simplify the search for optimum combinations of bands, geometry and time of the year to perform certain well-defined tasks.

A corollary to the use of field spectroscopy in its second, predictive role is its use in predicting the consequences of the use of sub-optimal bands, times or look angle to perform a particular task, as expressed in the most likely error. This is an area to have received very little attention to date.

7.3. Modelling

Field spectroscopy provides a tool for the development, refinement and testing of models relating biophysical attributes to remotely-sensed attributes. Such models may be classified into 'correlative models' such as the well-established relationship between green leaf area index and the infrared/red reflectance ratio (e.g. Budd and Milton 1982, Curran 1983), 'analytical models' such as the various canopy reflectance models (e.g. Suits 1972) and 'structural models' (that is those based on intrinsic data structures) (e.g. Kauth and Thomas 1976). In all cases, field spectroscopy has a prominent role to play in the modelling process and in the testing of the models subsequently derived (e.g. Kimes *et al.* 1984, Jackson 1983).

Modelling often requires extensive collateral data to be collected along with the radiometric data, since the need often arises to study likely sources of disturbance or error in the model as shown by scatter around a regression model, errors when a

canopy model is inverted or misalignment of data structures. However, time spent collecting collateral data generally means less time spent collecting radiometric data, and so must be kept to a minimum. Although the type of collateral data required varies with each individual experiment, general guidelines can be given; see, for example, Jackson *et al.* (1980) (pp. 55–61) and Milton (1987).

8. Conclusion

Field spectroscopy is a technique of fundamental importance in remote sensing. It deals with interactions between electromagnetic energy and objects in the natural environment, and provides a bridge between the theoretical understanding gained in the artificial environment of the laboratory and the largely qualitative skills of the image interpreter. It is an invaluable aid in training and education in remote sensing and also provides a means of building up a knowledge base of spectral data for use by future generations.

However, for field spectroscopic data to have long-term value they must be collected with care and the conditions of observation must be documented in a consistent fashion. To date, the subject has suffered from incompatibility between materials and methods adopted by different groups and has failed to have a major impact on the development of remote sensing because of this.

Field spectroscopy has a potential role to play within remote sensing in at least three areas, defined here as calibration, prediction and modelling. The challenge now facing the subject is largely one of methodology; the instruments required to collect spectra in the field are available, and are widely used in the training of remote sensing specialists (in the U.K. at least). To relegate field spectroscopy to a merely educational tool is to miss out on one of the most powerful methods available to the understanding of the potential and limitations of environmental remote sensing.

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Note added in proof.—Since this review was accepted for publication a special issue of the journal *Remote Sensing of Environment* has been published (Volume 22, Number 1, June 1987), which contains several papers relevant to the subject of field spectroscopy.

Appendix

Spectral radiometers

Published designs for spectroradiometers and radiometers are numerous and widely-scattered in the scientific literature. The following list is an attempt to highlight those which have received most attention from the remote sensing community. The list is necessarily selective, but an attempt has been made to include instruments from different parts of the world. The addresses of some commercial suppliers of such instruments are given at the end of the list. This is for convenience only and does not represent a recommendation either by the author or by the editorial board of the journal.

Spectroradiometers
(1) Barnes 12-550

Selected references
Boehnel *et al.* (1978, 1980)
Staetter and Schroeder (1978)

- | | |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| (2) Daedalus AA440 | New model 1987, but derived from a GEOSCAN instrument described by Yamaguchi and Lyon (1985) |
| (3) Exotech-20 | Silva <i>et al.</i> (1971)
Leamer <i>et al.</i> (1973)
Bauer <i>et al.</i> (1978)
Stoner <i>et al.</i> (1980) |
| (4) EG & G | Maracci (1978)
Boehnel <i>et al.</i> (1978, 1980)
Miller and Pearson (1971)
Longshaw (1974)
Miller <i>et al.</i> (1976) |
| (5) Gamma Sci. 2020 | Gramms and Boyle (1971) |
| (6) G.E.R.† IRIS Mk IV | New model 1987 |
| (7) G.E.R. Mini IRIS | New model 1987 |
| (8) ISCO SR‡ | Duggin (1974)
Duggin and Philipson (1982) |
| (9) JPL-PFRS | Goetz (1975) |
| (10) Li-Cor LI-1800 | Daughtry and Biehl (1985)
Lee and Graham (1986) |
| (11) N.D.R.E.§ | Myrabo <i>et al.</i> (1982) |
| (12) Optronix 740 | Maracci (1978) |
| (13) Moniteq PROBAR | Buxton <i>et al.</i> (1982)
Hollinger <i>et al.</i> (1983) |
| (14) Barringer REFSPEC | Barber and Horler (1981)
Daubner <i>et al.</i> (1981)
Gladwell <i>et al.</i> (1983) |
| (15) Spectrascan SP2000 | Drewett (1976)
Brown and Ahern (1980)
Ahern <i>et al.</i> (1981) |
| (16) Spectron SE-590 | Williams <i>et al.</i> (1984) |

† G.E.R. = Geophysical Environmental Research Corporation.

‡ ISCO-SR is no longer manufactured.

§ N.D.R.E. = Norwegian Defence Research Establishment.

Multiband radiometers

- (1) Barnes MMR
- (2) Cimel CE-310
- (3) CROPSCAN
- (4) Exotech-100

Selected references

- Robinson *et al.* (1979)
Jackson and Robinson (1985)
New model 1986
Pederson and Nutter (1982)
Pederson (1985)
Duggin (1974, 1980)
Bauer *et al.* (1978)
Maracci (1979)
Celis-Ceusters (1980)
Jackson *et al.* (1980)
Kowalik *et al.* (1980)
Vetrella *et al.* (1977)

- | | |
|--------------------------|-------------------------------------------------------------------------------------------------------------------|
| (5) NASA/GSFC† | Tucker <i>et al.</i> (1980)
Tucker <i>et al.</i> (1981)
Jackson <i>et al.</i> (1980)
Richardson (1981) |
| (6) Barringer HHRR | Daubner <i>et al.</i> (1981)
Gladwell <i>et al.</i> (1983) |
| (7) ISOH-010 | Mishev <i>et al.</i> (1979) |
| (8) Macam | Steven and Biscoe (1981) |
| (9) Matra | |
| (10) Geodata Unit MMR | Milton (1980)
Budd and Milton (1982)
Milton and Webb (1987)
Rothery and Lefebvre (1985)
Curran (1983) |
| (11) OCSM‡ | Kishino <i>et al.</i> (1983) |
| (12) MPPH§ | Zwick <i>et al.</i> (1980) |
| (13) PARABOLA | Deering and Leone (1986) |
| (14) Radiometrics RMR-10 | Palmer (1982) |
| (15) Skye SKR 100 | Woodward (1983)
King <i>et al.</i> (1986) |
| (16) Spectrascan MSP1000 | |
| (17) Tektronix J16-TV | Oliver <i>et al.</i> (1975)
Pearson <i>et al.</i> (1976)
Drake (1976) |

† NASA/GSFC = NASA Goddard Space Flight Center.

‡ OCSM = Ocean colour spectrum meter.

§ MPPH = Miller–Pieau photometer.

Addresses of some commercial suppliers

Barnes Engineering, Stamford, Connecticut 06904, U.S.A.

Barringer Research Ltd., 304 Carlingview Drive, Metropolitan Toronto, Rexdale, Ontario, Canada M9W 5G2. Telex: 06-989183.

CIMEL Electronique, 5 Cité de Phalsbourg, 75011—Paris, France.

CROPSCAN, Vernyl D. Pederson, 3221 Cherry Lane, Fargo, North Dakota 58102, U.S.A.

Daedalus Enterprises Inc., P.O. Box 1869, Ann Arbor, Michigan 48106, U.S.A. Telex: 230530.

Exotech Inc., 1200 Quince Orchard Boulevard, Gaithersburg, Maryland 20878, U.S.A. Telex: 710-828-9746.

Geodata Unit, Faculty of Science, University of Southampton, Southampton SO9 5NH, England. Telex: 47661.

Geophysical Environmental Research Corp., G.P.O. Box 340, New York, New York 10001, U.S.A.

Li-Cor Inc., P.O. Box 4425, Lincoln, Nebraska 68504, U.S.A. Telex: 910-621-8116.

Macam Photometrics Ltd., 10 Kelvin Square, Livingston EH54 5PF, Scotland.

MATRA Optique, 37 Avenue Louis Bréguet, BP 1, 78146—Vélizy Villacoublay Cedex, France. Telex: MATRA 698 007 F.

- MONITEQ Ltd., 630 Rivermead Road, Concord, Ontario, Canada L4K 2H7. Telex: 06-964776.
- Skye Instruments Ltd., The Old Manse, Skeabost Bridge, by Portree, Isle of Skye IV51 9XE, Scotland.
- SPECTRASCAN Ltd., 42 New Brighton Road, Emsworth, Hampshire PO10 7QR, England. Telex: 86402.
- SPECTRON Engineering, 800 West 9th Avenue, Denver, Colorado 80204, U.S.A. Telex: 910-932-2298.
- TEKTRONIX UK Ltd, Fourth Avenue, Globe Park, Marlow, Buckinghamshire SL7 1YD, England. Telex: 847277.

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