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Progress in field spectroscopy

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Abstract

This paper reviews developments in the science of field spectroscopy, focusing on the last twenty years in particular. During this period field spectroscopy has become established as an important technique for characterising the reflectance of natural surfaces in situ, for supporting the vicarious calibration of airborne and satellite sensors, and for providing a means of scaling-up measurements from small areas (e.g. leaves, rocks) to composite scenes (e.g. vegetation canopies), and ultimately to pixels. This paper describes the physical basis of the subject and evaluates the different methods and instruments which have been employed across a range of studies. The development and use of field goniometers is described, and related to methods for estimating the bidirectional reflectance distribution function (BRDF) from directional reflectance measurements in the field. The paper also considers the practical aspects of field spectroscopy, and identifies a number of factors affecting the useability of field spectroradiometers, including the weight and cost of the instruments, limitations of some commonly used methodologies and practical issues such as the legibility of displays and limited battery life. The prospects for the future of field spectroscopy are considered in relation to the increasingly important contribution that field spectral data will make to EO-based global measurement and monitoring systems, specifically through their assimilation into numerical models. However, for this to be achieved it is essential that the data are of high quality, with stated levels of accuracy and uncertainty, and that common protocols are developed and maintained to ensure the long-term value of field spectroscopic data. The importance of employing a precise terminology for describing the geometric configuration of measurements is highlighted in relation to issues of repeatability and reproducibility. Through such refinements in methodology, field spectroscopy will establish its credentials as a reliable method of environmental measurement, underpinning quantitative Earth observation and its applications in the environmental and Earth sciences.

Keywords: Reflectance; Methodology; BRDF; Goniometer; Field portable spectrometers; Spectroscopy

1. Introduction

Field spectroscopy pre-dates the development of imaging spectrometry by many years, but the two technologies have much in common, as they share the common goal of acquiring accurate data on the spectral reflectance of Earth surface materials from a remote location. Field spectroscopy is technically less challenging, as the sensing instrument can remain fixed over the subject of interest for much longer, and the path length between the instrument and the object being measured is reduced. However, field spectroradiometers generally measure a much smaller area, therefore, how to sample the surface of interest becomes an additional consideration.

Field spectroradiometers were first used to study human colour vision, and in particular the colour of the Earth's surface from the air (Penndorf, 1956). The development of airborne multispectral scanners in the 1960s spurred on the development of the first instruments capable of making accurate measurements of spectral reflectance in the field environment. One of the key challenges during the 1970s was to make accurate measurements in the short-wave infra-red region (1.1–2.4 μm) which was known from laboratory measurements to be a very important part of the electromagnetic spectrum for geological

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applications. Goetz (1975) described the first portable field spectroradiometer capable of measuring in this region as well as the visible and near infra-red, the Portable Field Reflectance Spectrometer (PFRS). Data from this instrument were influential in the design of early imaging spectrometers (see the paper by Goetz in this Special Issue), as well as encouraging the development of more capable field spectrometers such as the Jet Propulsion Laboratory PIDAS field spectroradiometer (Goetz, 1987). Alex Goetz subsequently set-up the company known as Analytical Spectral Devices (ASD Inc.) with a colleague, Brian Curtiss, and this continues to this day as a leading manufacturer of field spectroradiometers, as well as being influential in the development of methodology in the subject (e.g. Curtiss & Goetz, 1994; www.fieldspectroscopy.com). Spectra Vista, another leading manufacturer of field spectroradiometers can also trace its origins back to this period, as its predecessor, Geophysical Environmental Research Corp., was established by the late William Collins and Sheng-Huei Chang, who with Hong Yee Chiu developed the first airborne spectrometer for vegetation stress applications based on variations in the wavelength position of the red-edge (Chiu & Collins, 1978).

The aim of this paper is to describe the contribution of field spectroscopy to Earth observation at the present time, highlighting, in particular, its relationship with imaging spectroscopy. The paper will also highlight a number of areas where further development is needed, and make recommendations on best practice in the subject. Further information about the history of field spectroscopy in Earth observation, about the instruments available in the 1970s and 1980s, some of which are shown in Fig. 1, and about the development of methodology is provided in papers by Slater (1985), Milton (1987), Deering (1989) and Milton et al. (1994, 1995).

2. The role of field spectroscopy in Earth observation

Over the last twenty years a key role for field spectroscopy has emerged, as a means of scaling-up understanding of energy–matter interactions from the fine scale of individual measurement elements such as the leaf, to coarser canopy-scale studies (Gamon et al., 2006a). This has been reinforced by developments in airborne and satellite sensors which mean that spectral reflectance data from well-characterised areas of the Earth's surface are now essential to validate models and to maintain sensor calibration post-launch. Distinct methodologies are emerging to address different aspects of this role. First, there are methods designed to measure the spectral properties of individual elements of the scene, such as leaves or minerals. Second, there are methods designed to measure the reflectance of areas of the Earth's surface comprising spatial assemblages of these elemental components, organised into vegetation canopies or soil surfaces. Third, there are methodologies for the vicarious calibration of airborne and satellite sensors and for atmospheric correction, in which the need to match the spatial scale (size of support) of field spectroscopic data to that of a particular remote sensing system is paramount. Each of these approaches shares a belief in the importance of making such measurements in the field environment, with all of the challenges and difficulties that this entails. Field spectroscopy also has an important and continuing role in the education and training of remote sensing scientists, and is an especially powerful way of 'learning by doing'.

2.1. Spectral measurements of natural scenes

The most widely used methodology in field spectroscopy concerns measurement of the reflectance of composite surfaces in situ. Increasingly, spectral data are being incorporated into process-based models of the Earth's surface and atmosphere, and it is therefore necessary to acquire data from terrain surfaces, both to provide the data to parameterise models and to assist in scaling-up data from the leaf scale to that of the pixel. The recent establishment of SpecNet (Gamon et al., 2006a) exemplifies this approach in relation to the existing worldwide network of flux towers. Most data are collected with the sensor mounted vertically over the surface (nadir view), but some spectral libraries contain data measured in other configurations, such as along the solar principal plane (maximum anisotropy) or

Fig. 1. Some early field spectroradiometers in use in the field (source unknown).

at the antisolar peak or 'hot spot' (minimum shadow; Coulson, 1966).

In most cases, the reflectance of a vegetation canopy or a soil surface is presented as a 'reflectance factor'. Nicodemus et al. (1977) introduced the concept of a reflectance factor, being the "ratio of the radiant flux actually reflected by a sample surface to that which would be reflected into the same reflected-beam geometry by an ideal (lossless) perfectly diffuse (Lambertian) standard surface irradiated in exactly the same way as the sample". This simplification of the measurement environment has proved a mixed blessing. It provided a practical method to make reflectance measurements in the field but it also introduced a second reflecting surface into the measurement procedure, the spectral and angular properties of which would affect the resulting reflectance. Despite considerable efforts by calibration panel manufacturers, reference panels are neither perfectly reflecting nor perfectly diffuse, and because of the degree to which both these properties vary with wavelength, it has become necessary to pay close attention to the properties of the reference panel used (Bruegge et al., 2001; Gu & Guyot, 1993; Kimes & Kirchner, 1982; Rollin et al., 2000). In particular, reference panels and spectroradiometer entrance optics must be carefully levelled, and care taken that the panel completely fills the field-of-view of the spectroradiometer, which is often difficult to check as very few spectroradiometers have provision for viewing the area measured.

The review of field spectroscopy by Milton (1987) described several materials which were commonly used to make reference panels at that time. Since then, Spectralon[1] has become established as the material of choice. It has a high and stable reflectance throughout the optical region and is washable, although it has the disadvantage of generating a static charge such that insects and dust particles cling to it under some conditions. The reflectance of Spectralon is traceable to the U.S. National Institute of Standards and Technology (NIST). Procedures for the calibration of field reference panels are discussed by Biggar et al. (1988), Bruegge et al. (1991), Jackson et al. (1992) and Voss and Zhang (2006).

The high cost of field spectroradiometers means that most measurements are 'single-beam', that is, the same instrument is used to measure the spectral radiance of the target and the reference panel. A limitation of single-beam devices is that the assumption of identical illumination conditions for both the reference panel and the target surface is rarely met due to the time lag between scans. Often, this is addressed by performing reference panel scans before and after that from the target, and then interpolating the reference panel radiance at the instant the target is measured. However, this assumes that irradiance is changing in a predictable manner between successive reference panel scans, which is true for smoothly varying variation, such as that due to solar zenith angle, but is unlikely to be true for short-term episodic changes, for example those due to the passage of sub-visual clouds through the direct solar beam. 'Dual-beam' methodologies overcome this limitation, employing two sensors to measure the target and the panel simultaneously, and were first used over 20 years ago, when instruments such as the dual-beam GER IRIS was introduced. Generally speaking, dual-beam instruments produce more precise results than their single-beam counterparts, although this requires that the two sets of detectors are very well matched. The method used by the GER IRIS involved an oscillating chopper alternately interrupting the light falling on two sets of detectors mounted on a common baseplate. This minimised the effect of temperature variations, but restricted the range of geometric configurations that could be used, as the reference panel was necessarily located immediately adjacent to the surface being measured. Other dual-beam systems have mainly used fibre-optic inputs which avoids this problem.

Dual-beam spectroradiometers can also be created from matched pairs of single-beam instruments, but the challenges in deriving and maintaining the inter-calibration function between the two separate instruments can be considerable. Anderson et al. (2006) found that matching of two GER1500 spectroradiometers was best performed under field conditions using a Spectralon panel, rather than using an integrating sphere in the laboratory. Furthermore, the inter-calibration function was shown to be temporally variable due to changes in solar zenith angle, sky irradiance distribution and sensor-specific variations. Consequently, the recommended method for deriving the inter-calibration function is to collect the measurements under solar illumination, close in time to the data requiring correction (Anderson et al., 2006).

An alternative dual-beam approach, which avoids the expense of a second spectroradiometer, was described by Milton and Goetz (1997), and involves estimating the complete irradiance spectrum from measurements of irradiance made in a small number of narrow bands using a much simpler filter-based radiometer. The initial method was limited to a particular instrument, but more recently the method has been generalised so as to work with absolute radiance data (Milton & Rollin, 2006).

2.2. Optimising the measurement geometry for field spectroradiometric measurements

Measurements with field spectroradiometers are often hand-held, usually with the sensor head mounted on a pole or yoke to keep it away from the operator's body (Fig. 2). This is necessary in order to minimise the amount of scattered light from bright clothing falling on the surface being measured (Kimes et al., 1983).

For repeated measurements over the same point(s) a fixed frame or support can be used and many different types of support have been used for field spectral measurements, ranging from lightweight masts to dedicated towers and tramways (Milton et al., 1994). Mobile platforms such as aerial lift trucks ("cherry pickers") are often used, although off-road access is obviously limited with this method and the presence of a large reflective vehicle so close to the surface being measured can be a problem. An alternative approach is to use a mobile vehicle designed for off-road use, such as the tractor-mounted system described by Steven (2004) or a specially-designed buggy (see Fig. 2e).

[1] Spectralon is a registered trade mark of Labsphere Inc.

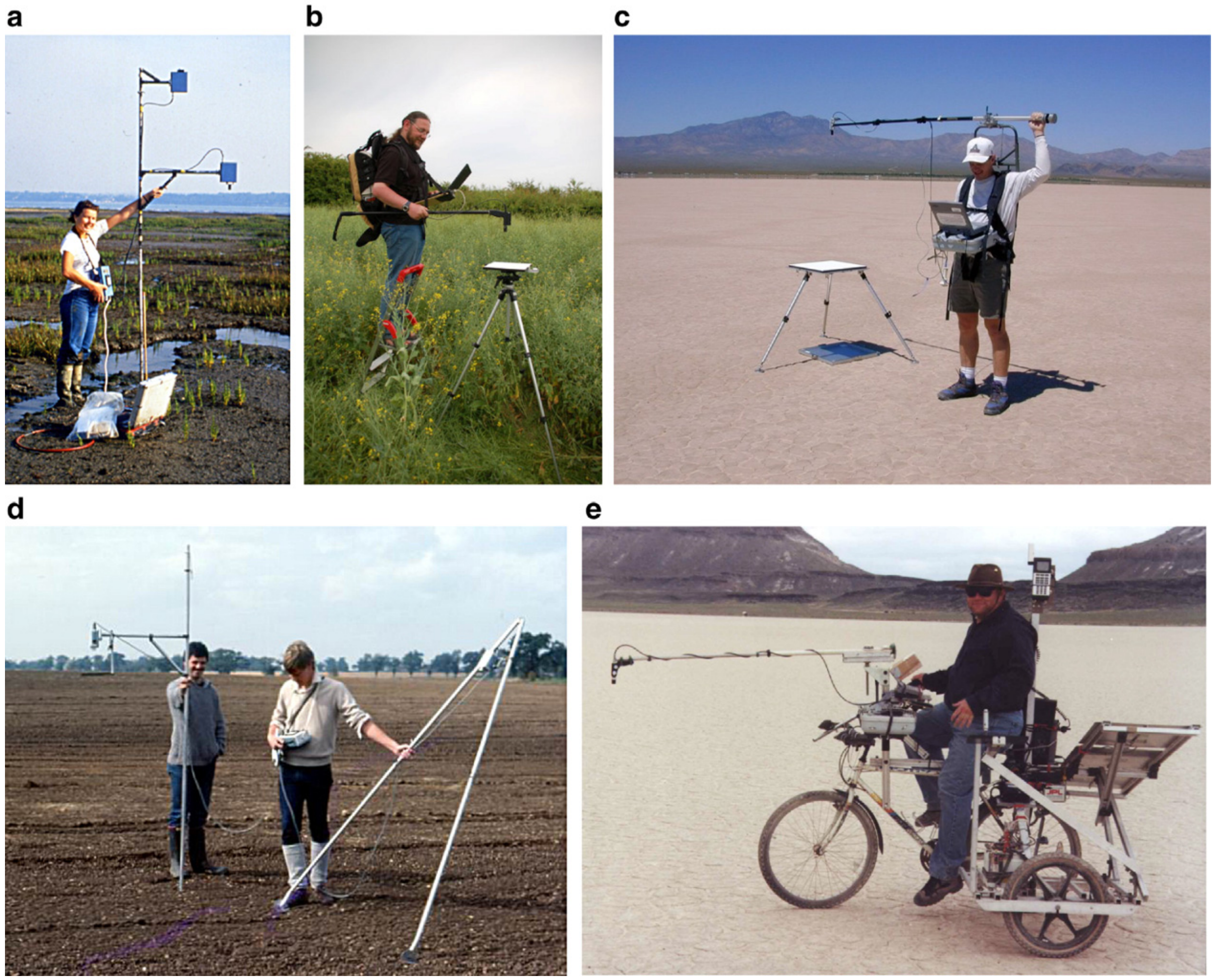

Fig. 2. Variations on the 'hand-held' methodology. (a) a dual-beam Spectron SE590 being used from a lightweight mast to measure the reflectance of intertidal vegetation, (b) measuring a Spectralon reference panel in a field of oil-seed rape, and (c), the same procedure at a vicarious calibration site (source University of Arizona), (d) a dual-beam multiband radiometer being used with an A-frame mast to measure the off-nadir reflectance of a soil surface, and (e) the NASA JPL 'Reflectomobile' in use at Lunar Lake, Nevada (source NASA JPL).

Gamon et al. (2006b) described the use of a fibre-optic based dual-beam PP Systems DC spectroradiometer from an automated tramway over chapparal vegetation in southern California. The same system has also been used over tundra vegetation in the Arctic and is useful in providing highly repeatable spatial sampling with minimum disturbance to the vegetation canopy. The system incorporated a degree of on-board control and could use wireless transmission of data and control signals, facilitating the collection of a large data set over an extended period of time. Caldwell and Vanderbilt (1989) described an interesting hybrid arrangement in which four inter-calibrated radiometers were mounted on a 7 m long boom, which was then used from an aerial lift truck to measure the spectral reflectance of a walnut orchard. This raises the question of whether it is more useful to have multiple relatively low-cost instruments or a single high-performance (and thus expensive) instrument.

Obtaining accurate spectral data from tall vegetation is always a challenge, as not only is it necessary to suspend and operate the instrument over the canopy, but also record the mixture of scene elements within the field-of-view of the sensor. Chen and Vierling (2006) tackled this issue when using a dual-beam ASD FieldSpec from a tethered balloon to measure reflectance spectra from a grassland/conifer forest ecotone. They mounted a colour video camera next to the downward looking spectroradiometer fibre and used the video imagery to screen the spectral data after collection, choosing samples from periods when the platform was relatively stable. An early study by Berry et al. (1978) describes a photographic method to achieve precise co-location using a modified Hasselblad camera to simultaneously record both the composition and the spectral reflectance of a lodgepole pine canopy. A triangular network of 15 m high towers, positioned 45 m apart was used to create three aerial tramways along which the instrument bogey could run. The idea of bore-sighting a spectroradiometer through a conventional camera optical system was also adopted by Milton et al. (2000), who also added a co-aligned digital camera to provide real-time display of the surface being measured by the spectroradiometer to the operator.

Standardising the spectral measurements for variations in irradiance is a challenge for remotely mounted instruments, but even in the early literature there are examples of innovative and far-sighted solutions to this problem, for example, Brach et al.

(1983) described a track-mounted instrument which also had a shadow-band radiometer mounted at one end of the track to provide regular measurements of global and diffuse irradiance. Leuning et al. (2006) described a system deployed on a 70 m high tower in *Eucalypt* forest in Australia which used a periscope-based arrangement to alternate the field-of-view of the spectroradiometer between the forest canopy (at various view angles) and an opal glass diffuser. The domed shape and shiny surface of the diffuser provided a degree of self-cleansing, important given the difficulty of accessing instruments on top of such a high tower.

Field spectral measurements have also been made from kites, tethered balloons, microlight aircraft and helicopters, all of which provide full three-dimensional maneouverability. The presence of the operator on-board the platform means that some of the control and pointing operations are made easier, however, human factors, such as good teamwork and organisation become paramount in such a difficult and unfamilar working environment as a helicopter (Milton et al., 1994; Williams et al., 1984). The widespread use of wireless communications and the growth of autonomous sensor networks is likely to greatly increase the range and capabililty of platforms for field spectroradiometry in the future. An indication of the current state of the art is shown by the system described by Vierling et al. (2006), which comprises a dual-beam spectroradiometer mounted on a tethered balloon capable of lifting a comprehensive instrument package to an altitude of 2000 m, the whole system being wireless controlled from the ground.

2.3. The terminology of reflectance measurements and the importance of metadata

The terms to describe reflectance measurements have a sound physical basis in the seminal papers by Nicodemus and co-workers (Nicodemus, 1970; Nicodemus, 1976; Nicodemus et al., 1977). These papers introduced the concept of the bidirectional reflectance-distribution function (BRDF), a mathematical function "relating the irradiance incident from one given direction to its contribution to the reflected radiance in another direction" (Nicodemus et al., 1977). Importantly, BRDF was defined as a conceptual property of the surface, at infinitesimally small angles.

The extension of this work to the real-world field situation is fraught with difficulty. Many of the basic radiometric concepts are difficult to understand or expressed in unfamiliar terms, and the nature of the field environment means that erroneous or misleading approximations are sometimes made. As a consequence real measurements of irradiance and radiance over finite solid angles can only ever provide an averaged estimate of the true BRDF. Reflectance terminology has since been updated by Martonchik et al. (2000) and Schaepman-Strub et al. (2006) based on the nomenclature originally proposed by Nicodemus and colleagues. The concepts and terminology introduced by Nicodemus et al. may be summarised in nine reflectance geometries (Fig. 3), of which four are realisable in practice.

Most field spectral measurements reported in the literature should properly be described as hemispherical–conical reflectance factors (HCRF), however, they are often referred to as hemispherical–directional reflectance factors (HDRF) (c.f., Case 7 in Fig. 3). This numerical approximation may be valid if the instrument used to measure the target radiance has a very narrow field-of-view (e.g. 3° or less) and if it is assumed that within this FOV no directional effects are present and the target is homogeneous. In a strict physical sense, all field spectrometers have a finite FOV and therefore will always measure HCRF (corresponding to Case 8 in Fig. 3). This applies whether

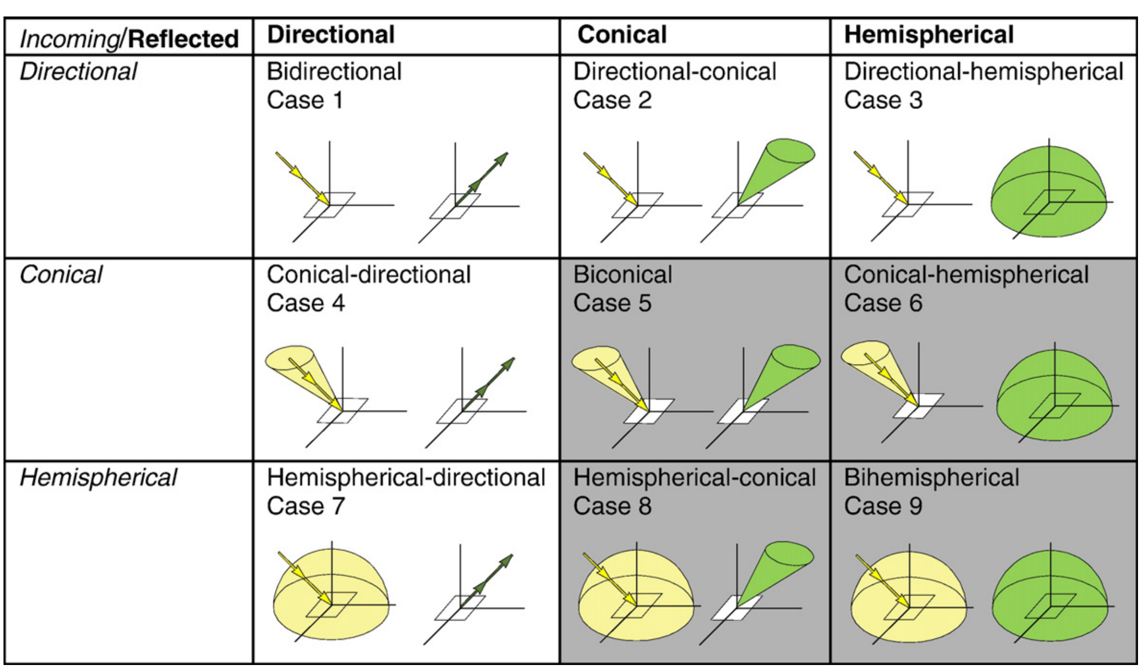

Fig. 3. Relation of incoming and reflected radiance terminology used to describe reflectance quantities. The labeling with 'Case' corresponds to the nomenclature of Nicodemus et al. (1977). Grey fields correspond to measurable quantities (Cases 5, 6, 8 and 9), the others (Cases 1–3, 4 and 7) denote conceptual quantities (from Schaepman-Strub et al., 2006).

the irradiance was measured using a reference panel or a cosine-corrected receptor. In both cases, the irradiance is integrated over the incident hemisphere and no information is preserved on the angular distribution of irradiance.

The angular distribution of irradiance encountered in the field environment is anisotropic as it is a combination of direct sunlight and diffuse light scattered from the sky and adjacent objects, all of which are spectrally variable. Thus, definitions of reflectance based on conical or hemispherical incidence geometries will be subject to uncertainty caused by variations in the precise mix of diffuse and direct light within the measured solid angle, and therefore reflectance factors derived from those measurements may vary, even if the BRDF of the target is constant. A practical consequence of this is that HCRF measured in the field is subject to uncertainty introduced by the irradiation environment, and are therefore not solely related to properties of the surface (Abdou et al., 2000; Kriebel, 1978; Steven, 2004). For this reason, it is recommended that simultaneous measurements of sky haziness are routinely made to supplement measurements of HCRF. This may be achieved by using a dedicated instrument, such as the PARABOLA sphere-scanning radiometer (Bruegge et al., 2000). More simply, a small parasol on the end of a long pole may be used to shade the panel or cosine receptor from the direct solar beam (Fig. 4). In this case, two measurements of irradiance are made. The first with the sensor shaded, and then a second with the sun unobscured and the parasol obscuring part of the sky at the same zenith angle, but at 90° relative azimuth. The ratio of the 'sun obscured' and 'sky obscured' measurements provides an estimate of the proportion of irradiance originating from the sky, compared with that from the sun and sky combined. Occasionally, field spectroradiometer measurements are supported by rotating shadow-band radiometers (Harrison et al., 1994), which achieves the benefits of the above approach, although with the disadvantage of having to use two instruments simultaneously.

In order to maximise the long-term value of field spectral measurements, it is essential that appropriate metadata are stored with the measured spectra. Typical metadata are listed in Table 1.

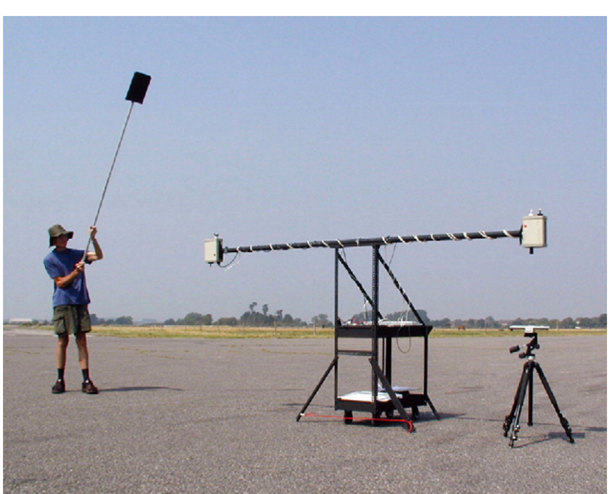

Fig. 4. Use of a parasol to measure the ratio of direct-to-diffuse spectral irradiance. The spectroradiometer is a trolley-mounted dual-beam instrument comprising two matched GER1500 spectroradiometers (Anderson et al., 2006).

Emergent best practice in the area of metadata for field spectral measurements is discussed further in the reviews listed in the Introduction to this paper and in papers by Ruby and Fischer (2002), Bojinski et al. (2003), Clark et al. (2002), Milton (2004), Pfitzner et al. (2006) and Hüni and Tuohy (2006), Hüni et al. (2007b).

2.4. Multiple view angle approaches to reflectance characterisation

So far, we have considered the simplified case of measuring reflectance at fixed viewing geometries. In recent years, however, there has been an upsurge in the attention dedicated towards multiple view angle reflectance measurements, primarily for characterisation of natural surface BRDF. BRDF is a conceptual property, and cannot be measured directly in the field, but there is growing interest in trying to estimate BRDF from field measurements. Directional measurements of reflectance anisotropy can provide information on surface structure, and are necessary for up-scaling studies of albedo, an integrated measure of reflectance over the full hemisphere. In addition, new spaceborne sensors such as the Multi-Angle Imaging Spectrometer (MISR) and the Compact High Resolution Imaging Spectrometer (CHRIS on Proba) have directional capabilities, and the wide field-of-view of many airborne sensors dictates the need for a quantitative understanding of directional reflectance quantities. Related to this is the recognition that more information should be collected on the angular distribution of spectral irradiance, as this affects the value of HCRF measured with a conventional nadir-pointing spectroradiometer. This implies measurement of biconical reflectance factors (as opposed to HCRF) — Case 5 in Fig. 3.

A stable platform is essential if multiple off-nadir measurements are to be made, and how to achieve an efficient, repeatable sampling of the hemisphere of reflected flux has tested the ingenuity of researchers over the years. To illustrate the progress in measurement of reflectance from multiple view angles we can compare two designs for goniospectrometers designed to measure the reflectance of snow surfaces, separated by a period of 50 years. The first instrument was described by Knowles-Middleton and Mungall (1952) and comprised an enclosed semi-circular box, within which a photomultiplier tube was mounted on chain-driven track which the operator could advance by turning a crank (Fig. 5). A chart recording mechanism recorded the output voltage of the photomultiplier so that a real-time record of the directional luminance of the snow surface was recorded. Illumination was provided by a lamp at the top of the enclosure. The entire instrument was suspended from a tripod to prevent disturbance to the snow surface and to allow different azimuths to be sampled.

The second snow goniospectrometer was described by Painter et al. (2003). It is representative of a class of goniometer design in which the spectroradiometer entrance optic moves through a range of view zenith angles and view azimuth angles. The same basic idea has been used with most types of gonio-spectroradiometer, either manually operated (Giardino & Brivio, 2003; Milton & Webb, 1987) or automated (Sandmeier & Itten, 1999). The instrument described by Painter is interesting because it makes use of kinematic theory from robotics to control the

Table 1
Typical metadata required in a spectral library.

	Variable (recommended unit)	Comment
1. Location of the site	(i) Latitude and longitude of the site (decimal degrees). (ii) Location of individual sample points. (iii) Altitude above sea level (m).	(ii) The locations of individual sample points should be in a coordinate system consistent with other spatially-referenced data collected.
2. Description of the site	Land cover class. Other descriptors as appropriate.	This will depend on the purpose of the study, but should be based upon an internationally recognised scheme such those recognised by the Land Product Validation sub-group of the CEOS Working Group on Calibration and Validation (http://lpvs.gsfc.nasa.gov/).
3. Time of measurements	(i) Coordinated Universal Time (UTC).	Readily accessed in the field from a GPS unit. Time, coupled with location, can then be used to determine the solar zenith angle for each spectral measurement.
4. Sky conditions at the time of measurement	(i) Type of cloud (WMO cloud genera). (ii) Extent of cloud cover (oktas). (iii) Whether the Sun is obscured.	(iii) Can be safely assessed by describing the intensity and distinctiveness of shadows formed on a white surface, or by hemispherical photography.
5. Meteorological data	(i) Air temperature (°C). (ii) Relative humidity (%). (iii) Surface air pressure (kPa). (iv) Proportion of direct to diffuse irradiance. (v) Aerosol Optical Thickness (AOT, unitless) (vi) Water Vapour amount (equivalent thickness, cm)	Average wind speed and its variation (gusts) can also be important, especially when measuring the reflectance of flexible vegetation such as crops. (v,vi) A portable sunphotometer is useful for measuring AOT and water vapour amount.
6. Instrument parameters	(i) Model and serial number. (ii) Most recent calibration date. (iii) Angular field of view (degrees). (iv) Spectral response of each band (radiometers only). (v) Spectral sampling interval and half-power bandwidth (spectroradiometers only).	Spectrometer calibration typically includes the accuracy and repeatability of wavelength and spectral radiance, radiometric linearity, shape and sharpness of the field-of-view, polarisation sensitivity and temperature sensitivity. Other factors such as the sensor point spread function and wavelength-dependency of the signal-to-noise ratio are often also considered.
7. Measurement method	(i) Apertured. (ii) Cos-conical. (iii) Type of reference panel, serial number, and date of calibration. (iv) Type of cosine-corrected receptor, serial number, and date of calibration.	'Cos-conical' refers to the use of a cosine-corrected receptor rather than a reference panel (bi-conical).
8. Field technique	(i) Viewing geometry (usually expressed as an angle from the nadir (0°) viewing zenith). (ii) Description of the apparatus used to hold the sensor over the surface. (iii) Height of the sensor above ground (m). (iv) Height of the sensor above the top of the surface being measured (m). (v) Sampling method and spatial arrangement of samples. (vi) Time taken to measure all bands (or a complete spectrum) from the target and from the reference panel or cosine-corrected receptor (s). (vii) Delay between measurements of the target and the reference panel or cosine-corrected receptor (if any) (s).	(vii) In single beam measurements, where only one sensor head is used to make sequential reference and target measurements, the time lapse since the last reference measurement should be recorded.
9. Parameter measured	(i) Radiance. (ii) Reflectance factor.	'Reflectance factor' to be further qualified as either biconical, conical–hemispherical, hemispherical–conical or bihemispherical.

motion of the entrance optics. The spectroradiometer used by Painter was the ASD FieldSpec FR, and it was possible to collect a complete 15° sampling in zenith and azimuth in under 3 min, assuming symmetry across the solar principal plane.

Single beam goniometers provide the means to measure HCRF as a function of view angle, but they do not allow us to measure the change in biconical reflectance factor with angle, as the irradiance distribution is not sampled at the same zenith and azimuth angles as the spectral radiance from the target. A new goniometer called GRASS, capable of near-simultaneous measurements of biconical reflectance factor at many different view/illumination angles is currently under development at the UK National Physical Laboratory (Pegrum et al., 2006).

The University of Zurich Remote Sensing Laboratories (RSL) have developed a field goniometer system called FIGOS which has recently been upgraded to allow it to measure hemispherical–conical reflectance factors (HCRF). FIGOS Mk II includes two ASD FieldSpec 3 spectroradiometers, one pointing at the surface and the other measuring the spectral irradiance at the same zenith/azimuth angle (Schopfer et al., 2007) (Fig. 6). This has produced the first simultaneous measurements of downward and reflected radiation at the same angular and high spectral resolution. The BRDF is retrieved from FIGOS data following the procedures proposed by Martonchik et al. (2000) and Lyapustin and Privette (1994), and transferred to laboratory conditions using the procedure proposed by Dangel et al. (2005). This method corrects the measurements for the diffuse illumination, effectively extracting the BRDF from the observed HCRF. In its single beam configuration FIGOS had been used extensively for the validation of spectrodirectional data, the acquisition of a priori information for BRDF correction, and for estimating biophysical variables (Beisl, 2001; Strub et al., 2002; Strub et al., 2003).

Researchers at RSL have also used FIGOS in a laboratory environment (LAboratory GOS), based around the design of FIGOS with the addition of a 1000-W brightness-stabilized quartz tungsten halogen lamp and lens system (Dangel et al., 2003, 2005). The observation geometry is exactly the same as that of FIGOS. However, even when the same target and

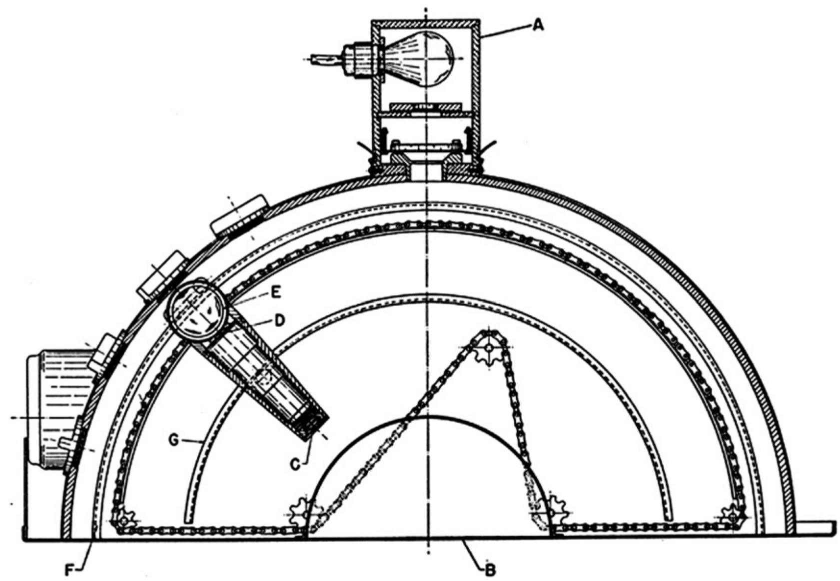

Fig. 5. The snow goniometer designed by Knowles-Middleton and Mungall (1952). The labelled objects are, A: lamp housing, B: sample port, C: entrance optics, D–G: mechanical assembly to move the sensor and ensure that it is pointing at the sample port at all times.

goniometer system are used, field and laboratory results cannot directly be compared due to inherent differences in the illumination conditions (Dangel et al., 2005). This highlights an important theme in the reproducibility of spectral measurements: the ability to compare and combine measurements from different instrumental designs is critical to ensure sensor cross-calibration and for all applications that rely on measurements obtained with different types of instruments. To solve this problem, RSL chose an approach that consists of retrieving the BRDF of the targets of interest separately for each case (field/laboratory) and comparing these, since theoretically they are independent of the particular conditions of illumination and observation. This involves a correction for diffuse incoming radiation in the case of field measurements, and a correction for conicality and inhomogeneity of illumination in the case of laboratory measurements (Dangel et al., 2005; Schopfer et al., 2005).

Directional reflectance measurements may also be made using a mobile platform to position the sensor at the required positions. Measurements in a single azimuthal plane can be achieved using a linear tramway, such as that described by Gamon et al. (2006a) and arranging for the sensor to rotate as the tram traverses over the target. A similar system was used by Milton et al. (1994) from a helicopter. A more flexible system is described by Purgold et al. (1994), in which a rotating mount on a helicopter is used to provide continuously varying view azimuth as the platform follows a predetermined figure-of-eight track above the surface of interest. Developments in robotics and autonomous platforms are also beginning to impact upon this area, as shown by the remote controlled stabilised platform described by Vierling et al. (2006)

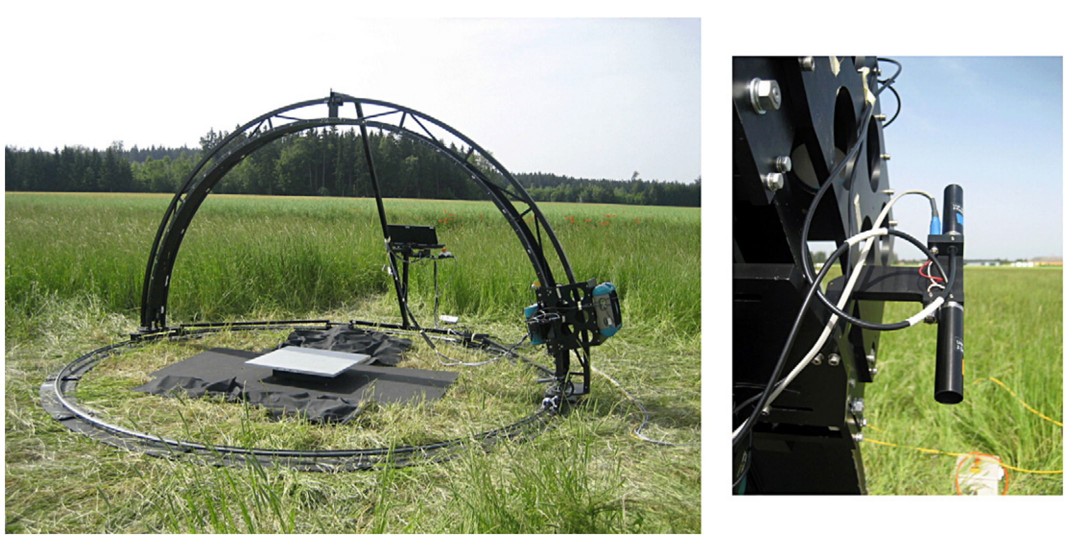

Fig. 6. The University of Zürich Remote Sensing Laboratories field goniometer system allows simultaneous measurements of incoming and reflected radiation at the same angular resolution using two ASD FieldSpec3 spectroradiometers. Right-hand picture shows a close-up of the dual-beam arrangement.

which allows spectral measurements of directional reflectance to be made from a tethered balloon.

Part of the reason a mechanical goniometer is complicated is the need to keep the ground-projected field-of-view fixed as the zenith and azimuth varies. This requirement can be relaxed if it is assumed that the surface to be measured is spatially uniform, and this approach is used in the PARABOLA instrument (Deering & Leone, 1986), amongst others (Bausch et al., 1990; Leuning et al., 2006). The original PARABOLA instrument measured in three spectral bands and had a 15° field-of-view, but later development led to the PARABOLA III which has eight spectral bands and a 5° field-of-view, allowing finer sampling of the angular radiance distribution from both the sky and the ground (Bruegge et al., 2000). The PARABOLA III instrument is particularly suitable for characterising the directional reflectance factor of extensive uniform areas, such as the dry lake beds often used for vicarious calibration (Abdou et al., 2000).

Advances in digital imaging systems offer a promising new approach to the measurement of directional reflectance at ground level, although the calibration problems for such sensors can be formidable. Systems have been demonstrated based on a linear array (Demircan et al., 2000), a 2D camera (Dymond & Trotter, 1997) and an imaging spectrometer (Milton & Emery, 1995). A detailed review of various systems is found in Bruegge et al. (2004).

2.5. Spectral measurements of individual scene elements

All of the methods discussed so far are passive optical methods which require optimal illumination conditions in the field environment. This requirement can often act as a constraint against operational use: ideally users require clear atmospheric conditions, with low atmospheric water vapour content and low aerosol content. Furthermore, varying solar zenith conditions and temporally varying atmospheric haze contributions lead to variability in field measured reflectance factors where non-Lambertian surfaces are concerned (Kriebel, 1978). These constraints imposed by the complex natural illumination environment, have led to the development of several instruments with integral sources of illumination, most of which have emerged since the late 1980's. A notable earlier example is the 'hot-spot' spectroradiometer described by Bunnik et al. (1983) which used a photographic flash unit inside a portable tent to measure the reflectance of grass canopies at the angle of maximum backscatter.

While an integral light source limits the size of objects that can be measured, it does permit data collection within atmospheric water vapour bands and provides standardised illumination conditions and a high signal, so that subtle absorption features (especially in the short-wave infra-red) may be clearly detected. As a result of this, a range of "contact" spectroradiometric devices have been designed for diagnostic use on small samples in the laboratory, or in the field. Analytical Spectral Devices Inc. have developed a 'contact probe' for use with the ASD FieldSpec Pro range of instruments (ASD Inc., 2006). This is a hand-held device containing a high-intensity 100 W quartz-halogen lamp and a grip to locate the existing fibre-optic input to the spectroradiometer (Lau et al., 2003). Spectra are measured by pressing the hardened quartz window of the probe against the surface of interest. A low-intensity version is available for use with surfaces that are easily damaged by heat, such as plant leaves. Integrated Spectronics Pty Ltd have also developed the PIMA SP spectrometer specifically for mineral identification based on reflectance in the region 1300 to 2500 nm (Integrated Spectronics Pty Ltd., Merry & Pontual, 1999). The PIMA SP contains software to match measured spectra against those in its target database, allowing convenient geological and mineralogical classification of rock samples in situ (Merry & Pontual, 1999). Another less-sophisticated instrument, the Alta™ Reflectance Spectrometer (Lunar and Planetary Institute, 2005), has been designed primarily for use in remote sensing education. It is an active optical multiband radiometer in which 11 LEDs provide a multispectral source of illumination in the range 470–940 nm. Reflectance spectra are acquired by pressing the instrument against the surface to be measured, activating each LED in turn.

Using devices such as these, highly reproducible measurements can be made. The fixed sample/illumination geometry greatly reduces the uncertainty which is characteristic of ad hoc measurement configurations such as those used by Castro-Esau et al. (2006). In their study, significant differences were found between spectral indices measured using three different spectroradiometers, due in part to differences in measurement and illumination geometry. Such measurements may also be useful for spectral library development, mineralogical studies, and investigation of spectral endmembers. However, artificial light sources can never reproduce the fine spectral structure of sunlight, which can be important in some applications (e.g. Meroni & Colombo, 2006).

2.6. Field spectroscopy for vicarious calibration and atmospheric correction

Field spectroscopy has been used for the calibration of aircraft and satellite sensors since the 1970s (Ballew, 1975), but it is only over the last 10–20 years that 'vicarious calibration' has become widely adopted as the means to provide independent assurance of the quality of remotely sensed data from spaceborne sensors. Much of the credit for this must go to Slater and co-workers at the University of Arizona, who have devised and published various methodologies for vicarious calibration (Thome, 2004). The first is the 'reflectance-based' method (Slater et al., 1987) in which the reflectance of a flat, featureless and extensive area of bare ground having near-Lambertian reflectance is measured and these data are then used in a radiative transfer model together with data on the state of the atmosphere at the time of satellite data acquisition to predict the radiance at the top of the atmosphere within the satellite sensor bands. High altitude dry lake beds are widely used as vicarious calibration targets, for example White Sands Missile Range, New Mexico, Railroad Valley, Nevada, and Lunar Lake, Nevada in the US (Thome et al., 1998), Salar de Uyuni in Bolivia, Salar de Arizaro and Barreal Blanco in Argentina, Tuz Gölü in Turkey, and Lake Eyre in Australia. It is wrong to assume that such sites are stable and unchanging, as seasonal changes in reflectance in response to fluctuations in groundwater levels have been observed at the White Sands site (Thome et al., 1993) and at Railroad Valley (Bannari et al., 2004), amongst others. Furthermore, those sites in which the evaporation of saline water has resulted in salt crusts may have significant microrelief as well as being subject to seasonal and episodic changes in reflectance. Polygonal cracks are also a feature of the dry lake beds which are commonly used for vicarious calibration (Abdou et al., 2000). Other terrestrial surfaces that have been used for this purpose include La Crau sèche, an ancient river delta in southern France (Rondeaux et al., 1998), an extensive site near Dunhuang in the Gobi desert (Wu et al., 1997) and the Dome Concordia area in Antarctica (Six et al., 2004). None of these is perfect for this purpose, however, an alternative (at least for fine spatial resolution sensors) is to use an artificial target such as the gravel runway used by Secker et al. (2001) to perform a vicarious calibration of the CASI airborne imaging spectrometer.

The radiance-based method of vicarious calibration also involves the use of an extensive ground site, but this time the spectroradiometer is operated from a helicopter or aircraft platform. Slater et al. (1987) found that radiance data collected from an altitude of 3000 m above the White Sands calibration site were remarkably similar to top-of-atmosphere radiance measured by a sensor in space, and suggested that this 'radiance-based' approach would have merit as an independent check on the reflectance-based method. This is necessary because the absolute accuracy of both methods is expected to be much less than their precision. The total error (1 SD) of the reflectance-based method has been estimated at ±4.9% by Biggar et al. (1994), compared with ±2.8% for the radiance-based method. An 'improved reflectance-based' method has been described by the same group, which also incorporates ground-based measurements of the diffuse-to-global irradiance ratio at the time of the satellite overpass and at the solar zenith angle corresponding to the sensor view angle. This method is estimated to have an error (1 SD) of ±3.5% (Biggar et al., 1994). The methods developed by the Arizona group have been adopted by others, including the USGS for calibration of the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1990), CNES for vicarious calibration of the SPOT HRV instruments (Santer et al., 1992) and ESA for calibration of MERIS (Kneubühler et al., 2003).

The 'reflectance-based' and 'radiance-based' methods have also been combined to create a generalised approach to quality assurance and stability reference monitoring (QUASAR) for Earth observation data (Teillet et al., 2001a). The conceptual basis of this has been developed further in the proposal for a Global Instrumented and Automated Network of Test Sites (GIANTS) (Teillet et al., 2001b), each of which would be based upon automated sensor technologies such as that described in the Intelligent Sensorweb for Integrated Earth Sensing (ISIES) project (Teillet et al., 2005). The potential for autonomous field spectral measurement devices, transmitting data by wireless to a central web-enabled server, is seen in the tramway-based dual-beam spectroradiometer developed by Gamon et al. (2006b) to collect data over chapparal vegetation in southern California. The flat topography of vicarious calibration sites would lend themselves very well to robotic mobile spectroradiometers.

The growing demand for well-characterised ground targets, for use both in vicarious calibration and for atmospheric correction (Clark et al., 2002; Moran et al., 1992; Moran et al., 2003) means that candidate type surfaces need to be studied in detail to assess temporal dynamics. Highly reproducible measurements using well-characterised field spectroradiometers are essential if uncertainty arising from the instrument and its method of use is to be separated from uncertainty introduced by the environment. Anderson and Milton (2006) used a matched pair of GER1500 spectroradiometers in dual-beam mode to measure the hemispherical–conical reflectance factor (HCRF) of a concrete airfield runway over two years, and found that the surface was subject to measurable changes over different time scales. Seasonally, the HCRF was affected by a bloom of microphytes which caused lowered HCRFs in Spring. Daily variations in HCRF were observed due to the non-Lambertian effects causing HCRFs to vary with solar zenith angle. Episodic changes in reflectance over periods of a few hours were caused by the onset of a sea breeze, which activated the photosynthetic algae due to high relative humidity (Lange et al., 2001). These results highlight the dynamic reflectance behaviour of what might have previously been considered as an inert, stable surface, and demonstrate the importance of understanding the controls upon the reflectance of ground calibration targets, whether by measurement or through validated physical models.

The considerable difficulty inherent in any vicarious calibration system relying upon terrestrial targets has encouraged some scientists to seek a space-based solution, whether the moon (Kieffer & Wildey, 1985), distant stars (Bowen, 2002), or a dedicated orbital standards laboratory such as is envisaged by a proposal known as TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio Studies; Fox et al., 2003).

A holistic approach to the problem of vicarious calibration would recognise that ground targets cannot provide all the answers, and would combine the terrestrial sites envisaged by GIANTS with extra-terrestrial standards, and thereby define common calibration targets viewable by all spaceborne sensors. The benefits of such a system would be immense in terms of providing users with greater confidence in measurements made from the panoply of Earth orbiting sensors that will be necessary to deliver the goals of ambitious international programmes such as the Global Earth Observing System of Systems (GEOSS) (Group on Earth Observations, 2005).

3. Some outstanding issues

3.1. The traceability of spectral measurements

The dominant paradigm of field spectroscopy is based on relative measurements, in which the radiance of the target is compared with that of a reference panel. In this case, absolute radiance calibration of the instrument is not essential, provided that the instrument has a linear response, and the critical factor is the calibration of the reference panel which is used to convert the measured relative reflectance to an absolute scale. However, there is growing interest amongst users in measuring radiance in the field. Radiance provides more information on the complete radiation environment in which the measurements take place; it means that the primary measurements are expressed in SI units and therefore clearly defined and traceable to international standards, and it matches more closely what our remote sensors measure. The additional steps necessary to calibrate field spectroradiometers to radiance involve the use of transfer standards, notably integrating spheres and standard lamps, the performance of which we will now describe briefly. However, it must be remembered, that spectroradiometric measurements remain one of the least reliable of all physical measurements (Kostkowski, 1997). Three major reasons for large errors in spectroradiometry are first, the measurement is a multidimensional problem, second, the instability of measuring instruments and the uncertainty of the standards used to calibrate these instruments are frequently 1% or more during the complete measurement process, and third, the principles and techniques used for eliminating (or reducing) measurement errors due to this multidimensionality or instability have not been widely disseminated.

The stability of integrating spheres needs considering as these are widely used to transfer radiance calibrations to spectroradiometers and to check their performance (Guenther, 1987). Goetz et al. (1998) describe a 'round robin' set of measurements using an ASD FieldSpec FR spectroradiometer to measure the spectral radiance of eight integrating spheres operated at several NASA centres, Los Alamos National Laboratory and the University of Arizona. The spectroradiometer used was assessed as having a precision of better than ±2% at wavelengths greater than 500 nm, rising to 6% at 350 nm. The study found significant variability between the various integrating spheres, but overall this was within ±5% for wavelengths greater than 500 nm. The authors identified the absorption of water vapour by the barium sulphate coating of several of the larger spheres as being a particular problem and recommended that they be kept flushed with dry nitrogen. The effect of sphere calibrations being interpolated from measurements made at a limited number of wavelengths was also noted. If uncorrected these could introduce spectral features from the material used to coat the surface of the integrating sphere into the resultant spectra.

In most applications to date, the accuracy of such integrating spheres has not been a critical issue, as applications and users have been satisfied with error levels of around 5%. However, as quantitative Earth observation matures and demand from users stimulates the need for improvement this will become more of a limiting factor. The objective of an integrating sphere is to homogenise radiation into a spatially uniform (or at least Lambertian) source, but this is rarely achieved in practice, and spatial non-uniformities of several percent are typical from such sources (Knee, 1999). Without some form of independent and spectrally discriminating monitoring device, the output radiance will rapidly lose its traceability to primary sources. It is also important to note that when using integrating spheres in close proximity to any instrument, they are a very large source of stray light and highly susceptible to inter-reflections.

Recognising these issues, the National Physical Laboratory (NPL), the UK national standards laboratory, has designed a transportable integrating sphere specifically to calibrate remote sensing systems in the field and this has been used with satellite and aircraft sensors as well as field spectroradiometers. It is known as the NPL Transfer Standard and Absolute Radiance Source (TSARS) (Pegrum et al., 2004) and is calibrated at NPL by direct comparison with the primary black body source (Woolliams et al., 2002). It has been specifically designed to be spatially uniform (<0.5% over its exit port of up to 100 mm diameter) and encompasses a set of filter radiometers to monitor its calibration. The overall error budget for the NPL TSARS gives an uncertainty between 450 and 500 nm, between 0.70% and 0.99% at the 95% confidence level. Within the spectral region of 500–700 nm, the 95% confidence uncertainty is better still, between 0.56% and 0.74%. Above 700 nm the uncertainties are between 0.61% and 1.18%. These uncertainties were improved before the TSARS was recently deployed during the NCAVEO 2006 field campaign (www.ncaveo.ac.uk) and used to calibrate six spectroradiometers from ten different research groups participating in the experiment. A similar portable integrating sphere is described by Brown and Johnson (2003). Here, NASA worked with the National Institute of Standards and Technology (NIST) to develop a portable integrating sphere source, called the NIST Portable Radiance Source (NPR), aimed at complementing existing detector-based measurement strategies and to enhance the capabilities of the EOS calibration programme. The NPR is calibrated for spectral radiance over the range 400 nm to 2400 nm at the primary US facility for irradiance and radiance calibrations.

Since the 1980's National Metrology Institutes (NMI) have worked towards basing all radiometric scales, including spectral radiance and irradiance, on traceability to a primary standard detector, the cryogenic radiometer (Fox, 1996). This instrument defines a scale of spectral responsivity (a monochromatic characteristic of a detector) and then calibrates filter radiometers (detector-spectral filter combination) to allow measurements of real world polychromatic sources e.g. lamps, Sun, Earth-reflected solar irradiance (radiance). This is carried out by spectrally tuning a beam of monochromatic radiation (calibrated with reference to a standard detector) over the entrance aperture of a filter radiometer. Each of the field spectroradiometers listed in Table 2 are a form of filter radiometer and in principle could be calibrated directly in such a way, to measure spectral radiance. Alternatively, and more commonly, a few standard filter radiometers can be used to measure the thermodynamic temperature of a black body source from which spectral radiance and irradiance can then be derived. Again, although a field spectroradiometer could be calibrated by viewing such a black body directly it is more common to calibrate a transfer standard lamp as a source. The most commonly used transfer lamps are tungsten halogen 1000 W FEL type. Such a traceability diagram is shown in Fig. 7 which shows the route of traceability for an Earth observation satellite sensor by both pre-flight and vicarious routes. It should be noted that evidence recently obtained from a large study of such lamps undertaken by NPL as part of an international comparison of spectral irradiance suggests that one in three lamps is subject to a change in its output on transfer from NMI to the user (Woolliams et al., 2006). This is particularly worrying since many users only have one standard and in some cases this is used to establish secondary standards provided to others.

Table 2
Some examples of current field spectroradiometers.

Spectroradiometer	Spectral region		Optical input[a]		Sensing method		Integral data storage[b]	Wireless comms	Comment	Manufacturer[f]
	VNIR 350–1000 nm[c]	SWIR 1000–2500 nm[d]	Lens	Fibre-optic	Single-beam	Dual-beam[e]				
FieldSpec HandHeld	•		•		•					Analytical Spectral Devices Incorporated (http://www.asdi.com/)
ASD FieldSpec Pro FR	•	•		•	•					
ASD FieldSpec3	•	•		•	•			•	The FieldSpec3 is a development of the FieldSpec Pro FR.	
Ocean Optics HR4000/USB2000	•			•	•				Miniature spectroradiometer. Modular system with a wide range of optional accessories.	Ocean Optics (http://www.oceanoptics.com/)
UniSpec-SC	•			•	•					PP Systems (http://www.ppsystems.com/)
UniSpec-DC	•			•		•				
GER1500	•		•		•	•	•			Spectra Vista Corporation (http://www.spectravista.com/)
GER2600	•	•	•		•					
GER3700	•	•	•		•					
SVC HR-1024	•	•	•		•		•	•	Employs a PDA with sunlight-readable screen	
PIMA SP[g]		•			•		•		On-board data processing for mineral identification	Integrated Spectronics (http://www.intspec.com/)

[a] This is the standard input. Several systems offer a choice of fibre-optic or lens.
[b] This means that it is possible to collect data in the field without using a separate computer.
[c] Most VNIR spectroradiometers employ silicon photodiode detectors, and have a spectral bandwidth around 2 nm.
[d] Most SWIR spectroradiometers employ either lead sulphide (PbS) or Indium Gallium Arsenide (InGAs) detector arrays and have spectral bandwidths of better than 10 nm.
[e] Native mode of operation. Most instruments can be combined in pairs to produce a dual-beam configuration.
[f] URLs checked May 2007.
[g] The PIMA SP is a contact spectroradiometer and is limited to the range 1300–2500 nm.

A transportable radiance standard based on a 1000 W calibrated quartz-halogen lamp and Spectralon reference panel has been developed for laboratory and hangar-based validation of the radiometric calibration of the AVIRIS imaging spectrometer, and found to have an estimated accuracy of around 1% in the visible region, reducing to 6.5% at 2500 nm (Chrien et al., 2000). Such a transportable radiance standard could also be used to check the radiometric calibration of spectroradiometers in the field. As the science of remote sensing matures and models become more sophisticated, the demand for accurate measurements of spectral radiance (as opposed to reflectance) in the field will increase. Furthermore, advances in metrology mean that it is now more accurate to calibrate and measure in terms of spectral radiance than reflectance. Taken together, these two developments can be expected to steer the development of new methodologies in field spectroscopy to those which provide increased rigour, demonstrable traceability for individual measurements, and improved intercomparability between research groups (Fox, 2004).

3.2. Spatial sampling for field spectral measurements

Natural variability within fields or terrain units must be considered when measuring the reflectance of areas with a field spectroradiometer in order to ensure that the HCRF is representative of the whole area. In practice, this relates to the field-of-view of the sensor, the height it is held above the surface, and the number of samples per field. The angular field-of-view should be sharply delimited so as to define the area measured. A narrow angular field-of-view helps ensure that the HCRF is a reasonable approximation to the HDRF, however, if the aim is accurate BRDF retrieval using the method proposed by Lyapustin and Privette (1994), it is more important to achieve detailed sampling of the angular incoming radiance distribution at the same time as the target radiance is measured. Practical constraints usually determine the maximum height a sensor can be supported over the surface of interest, but common sense and the modelled results of Jackson et al. (1980) for row crops indicate that, in general the higher the better.

The consideration of a sensor's point spread function, and spatial uncertainty in positioning are critical considerations where temporal variations in reflectance are to be retrieved. One recommendation is that the user should seek to ensure that reflectance measurements characterise variations in the inherent properties of the surface, and not positional variations in the location of the device. Robust experimental design is critical here — the operator must seek to achieve a reproducible

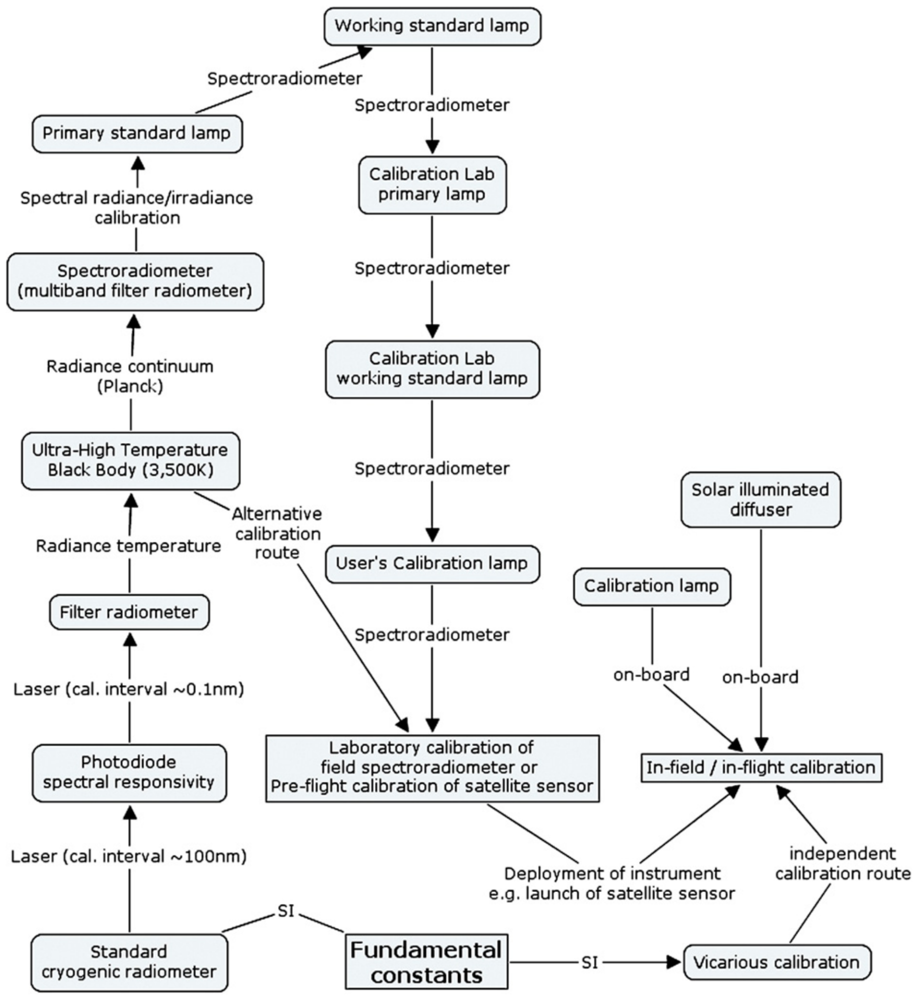

Fig. 7. Schematic representation of the route of traceability for the Earth Observation community. The left and middle paths describe the typical procedure from the primary standard to the user.

measurement position, such that the same point (within a known window of uncertainty) is measured on each visit.

The question of how many samples are needed to characterise a surface has been addressed experimentally and statistically. Daughtry et al. (1982) used experimental data to investigate the most efficient sampling of row crops and concluded that systematic sampling at odd multiples of 0.5 times the row spacing interval required fewer measurements than simple random sampling. They cautioned extreme care in interpreting data acquired at sensor heights where the diameter of the field-of-view at the top of the canopy is smaller than several multiples of the row spacing.

Statistical approaches have either considered each sample as an independent entity (Curran & Williamson, 1986) or have taken account of the spatial autocorrelation inherent in the field environment (Webster et al., 1989). Geostatistical approaches have much to offer to field spectroscopy, for example the use of cokriging to estimate biophysical variables from more easily measured field spectral data (Atkinson et al., 1992) and the incorporation of spatial uncertainty into empirical atmospheric correction methods (Hamm et al., 2004).

3.3. The useability of field spectroradiometers

The field environment is a very challenging one for instrument designers. Field spectroradiometers must have a wide dynamic range so as to cope with the extremes of peak solar radiation reflected from very bright surfaces such as white reference panels and the very low values of radiance typical of dark surfaces such as water, or organic soils in regions of the spectrum where the atmosphere absorbs most of the incident radiation. Grey reference panels would reduce the dynamic range required, but grey Spectralon is less Lambertian than the white variety, and in any case this would introduce an additional step in the calibration to absolute reflectance which is undesirable.

Temperature effects are a serious problem (Markham et al., 1995), especially as many field spectroradiometers use multiple detectors in order to cover the required spectral range. An example of one such instrument is the ASD FieldSpec Pro, which combines a VNIR silicon photodiode array (350–1000 nm) with two Indium Gallium Arsenide (InGAs) photodiode detectors for measurement in the SWIR (1000–2500 nm). Slight drift in any one region, or mismatch between detectors is often characterised by 'steps' in spectra which most frequently appear at the 'overlap' regions covered by more than one detector. These can be reduced for some instruments by warming them up prior to making measurements, but even a three-hour warm-up was insufficient for one Spectra Vista GER3700 spectroradiometer tested by Brown et al. (2001). Instruments using a single photodiode array are similarly affected, as shown by the results of an experiment in which three examples of the Spectron Engineering SE590 spectroradiometer were found to have calibration constants for wavelengths less than 390 nm and longer than 940 nm that were especially sensitive to changes in temperature, such that the error in irradiance and radiance at 1000 nm was around 30% if temperature effects were not taken into account (Starks et al., 1995). In the case of the ASD FieldSpec FR spectroradiometer, the involvement of users was important in devising a method to deal with temperature-related drift so that the integrity of the data and ease of use in the field were not compromised (Beal & Eamon, personal communication, 1996).

Anomalous 'steps' in field spectra are common, especially in instruments that use multiple detectors to cover a wide spectral range, although such steps can sometimes be masked from the user by empirical curve matching procedures implemented in data collection software. Tracking down the source of these steps is very difficult but often involves spatial heterogeneity of the illumination field at a similar scale to that of variability in the spectral properties of the target, uncorrected temperature effects within the instrument, damage to multi-strand fibre-optics or a combination of these. Real-time display of reflectance spectra can reveal when such steps are occurring, but this is not always possible with current instruments, or may not be desirable, for example if this leads to a reduction in the speed at which data may be acquired.

When tracking down the source of steps in field spectra it is very important to be able to see the precise field-of-view of the spectroradiometer and to know how the sensitivity of the instrument varies across the field-of-view. Few modern field spectroradiometers offer 'through-the-optics' viewing, so definition of these parameters often relies on manufacturer's data, supplemented by ad hoc measurements by the user, such as those reported by MacArthur et al. (2006) on GER3700 and ASD FieldSpec Pro FR spectroradiometers. The absence of standardised protocols and procedures for making such measurements is a problem when trying to compare different instruments.

The technology of sunlight-readable notebook PC screens is not good enough for field instruments that will almost always be used in bright sunlight. This problem is compounded by the operator (perhaps wearing sunglasses) having to move their gaze from a bright sunlit surface to the screen. This is a problem that has got worse as reflective monochrome LCD screens were replaced by the first generation colour screens, which were just about useable, and then the current generation of transmissive colour screens, which are almost impossible to use in direct sunshine. A related problem concerns the temperature range over which typical notebook computers will operate. Field spectral measurements are commonly made at air temperatures in excess of 30 °C, and sometimes at sub-zero temperatures, resulting in display devices becoming sluggish or not operating at all. Developments in this area will be driven by the requirements of much larger consumer markets for mobile phones and digital cameras, so the situation is likely to improve over time. Currently, the best solutions are found on those spectroradiometers controlled by hand-held PDAs or those still able to be controlled by a DOS-based notebook computer with a monochrome screen.

Human factors should not only influence the design of spectroradiometers but should also be considered when planning data acquisition. Lengthy periods of exposure to the Sun and the need to look frequently at the sky for evidence of small clouds are both areas of potential risk to human health and should be considered as part of risk assessment prior to fieldwork.

Last, but not least, field spectroradiometers are very expensive for individual research groups to purchase. This need not be an insurmountable problem, as the establishment of a shared 'equipment pool' in the UK has shown (Rollin & Milton, 1991), but it does limit the number of instruments that can be deployed in experiments, and can lead to the situation in which an expensive instrument is rarely used, but is held to be infallible, despite its calibration not having been maintained since purchase.

4. Conclusion

This paper has sought to provide a review of the current status of field spectroscopy, with particular reference to advances in the subject since the late 1980s. We have demonstrated how, over the last 20 years, improvements in instrument and detector design have led to an upsurge in the number of field-portable spectroradiometric devices on the market. In some cases, the new systems may be considered more field-capable than those which existed pre-1980. Some technological issues still remain, specifically in relation to the useability of the most advanced instruments in the field. The most obvious limitations to operational field use are caused by the size and weight of some instruments, coupled with the poor readability of laptop screens in bright sunlight. Furthermore, the price of the most complex instruments limits their widespread use. Some manufacturers have attempted to overcome such limitations and have produced highly portable, miniaturised systems, and while these address issues of affordability and portability, their poorer signal-to-noise characteristics and susceptibility to temperature effects are often a problem in the field environment. Despite these limitations, the past 20 years have seen some great developments in the scope and direction of the subject. In this paper, we have demonstrated that one of the greatest advances in methodology and understanding has been gained through the development of multiple view angle goniometric instruments for characterising surface BRDF. This advancement has largely been driven by the recognition that BRDF is a fundamentally important variable underpinning a vast number of activities in Earth Observation science. Further to this, we have also demonstrated how field spectroscopy has made a significant contribution to vicarious calibration activities, which represents a success story in the upscaling of hyperspectral field data to airborne, and space-borne sensors.

The collection of accurate metadata to accompany field spectral measurements remains an important consideration, and the sharing of spectral data among researchers is very much in need of standardised data representation. Recognition of the need for detailed information on sky radiance conditions and distributions, is also necessary. Promising advances are now starting to appear in this area with the development of spectral databases like SPECCHIO supporting this need (Bojinski et al., 2003; Hüni et al., 2007a).

Through this paper, we have demonstrated that there are some remaining, generic issues which need addressing by the community at large. While the use of field spectroscopy has spread throughout a range of disciplines, there is a growing community who recognise the need to take the science of field spectroscopy "back to its roots". In some senses, the expansion of the subject (in an applied sense) has been good for raising awareness of the importance of field spectroscopy as an underpinning technology, but it is fair to say that many of the modern users of field spectral measurements neglect to address the full complexities associated with the field measurement scenario. In particular, we refer to uncertainties caused by variations in the hemispherical distribution of incoming radiance in the field.

Field spectroradiometric data are making an increasingly important contribution to EO-based global measurement and monitoring systems through the assimilation of in situ spectral measurements (Schaepman, 2007). A major determinant of the success of such assimilation-based systems is the quality of the data provided by the ground instruments (spatial distribution, calibration, measurement uncertainties, etc.). Now that the power and relevance of field spectroscopy in the wider context is understood, there is a need to return to a more quantitative, physically-based approach, by documenting more precisely the conditions under which measurements are made, and by considering sources of uncertainty in such measurements. Only by doing this can field spectroscopy establish its credentials as a reliable method of environmental measurements, vital to EO and also of importance to the wider applications of EO in the environmental and Earth sciences.

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