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On the reproducibility of field-measured reflectance factors in the context of vegetation studies

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A B S T R A C T

This paper describes a study aimed at quantifying uncertainty in field measurements of vegetation canopy hemispherical conical reflectance factors (HCRF). The use of field spectroradiometers is common for this purpose, but the reliability of such measurements is still in question. In this paper we demonstrate the impact of various measurement uncertainties on vegetation canopy HCRF, using a combined laboratory and field experiment employing three spectroradiometers of the same broad specification (GER 1500). The results show that all three instruments performed similarly in the laboratory when a stable radiance source was measured (NEΔL<1 mW m^{-2} sr^{-1} nm^{-1} in the range of 400–1000 nm). In contrast, field-derived standard uncertainties (u = SD of 10 consecutive measurements of the same surface measured in ideal atmospheric conditions) significantly differed from the lab-based uncertainty characterisation for two targets: a control (75% Spectralon panel) and a cropped grassland surface. Results indicated that field measurements made by a single instrument of the vegetation surface were reproducible to within $\pm$0.015 HCRF and of the control surface to within $\pm$0.006 HCRF (400–1000 nm ($\pm 1\sigma$)). Field measurements made by all instruments of the vegetation surface were reproducible to within $\pm$0.019 HCRF and of the control surface to within $\pm$0.008 HCRF (400–1000 nm ($\pm 1\sigma$)). Statistical analysis revealed that even though the field conditions were carefully controlled and the absolute values of u were small, different instruments yielded significantly different reflectance values for the same target. The results also show that laboratory-derived uncertainty quantities do not present a useful means of quantifying all uncertainties in the field. The paper demonstrates a simple method for u characterisation, using internationally accepted terms, in field scenarios. This provides an experiment-specific measure of u that helps to put measurements in context and forms the basis for comparison with other studies.

1. Introduction

Measurements of reflectance quantities collected in natural environmental conditions are of fundamental importance in Earth observation (EO) science because they underpin a range of quantitative pre-processing techniques including: vicarious calibration (Moran et al., 2001; Teillet et al., 2001; Thome, 2001), atmospheric correction (Karpouzli & Malthus, 2003; Smith & Milton, 1999), EO product validation (Liang et al., 2002), and establishment of spectral bandsets for environmental monitoring (Armitage et al., 2004; Thomson et al., 1998). Additionally, close-range spectroradiometric measurements are useful for characterising changes in surface properties through time (Anderson & Milton, 2006b; Harris et al., 2005) and in space (Atkinson & Emery, 1999; Gamon et al., 2006a). Despite these successes, one of the biggest challenges continues to be the accurate, reproducible characterisation of natural surface reflectance properties measured in the solar radiation environment (Milton et al., 2009).

One key problem is that the term "reflectance" is unspecific and offers little insight into the particular conditions in which measurements were collected. The general lack of standardization in application of reflectance terminology therefore leads to uncertainties in data reporting and interpretation (Milton et al., 2009; Schaepman-Strub et al., 2006). In applying the correct nomenclature, the user of field spectroscopic methods must be mindful of both the three-dimensional nature of the incident and reflected radiation field (Nicodemus et al., 1977) and the heterogeneity of the natural hemispherical illumination environment (Gilabert & Melia, 1993; Kriebel, 1976). All of these complexities are compounded by differences imposed by measurement systems with varying physical capabilities (e.g. spectral resolution, field-of-view), field deployment modes, and calibration protocols. Recent research has suggested that reflectance quantities are not reproducible across multiple

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spectroradiometric instruments, even when standardised laboratory light sources are used (Castro-Esau et al., 2006). Schaepman-Strub et al. (2006) further suggest that quantitative comparisons of reflectance products provided by different systems and accompanied by inconsistent definitions or data descriptions can be "difficult, inaccurate, or impossible". Methodological refinements are therefore needed to ensure that field spectroscopy can establish its credentials as a "reliable method of environmental measurement" for underpinning quantitative EO activities (Milton et al., 2009). An approach that provides methodologically relevant, quantitative expressions of uncertainty is needed (JCGM 100:, 2008; Taylor & Kuyatt, 1994). The "standard uncertainty" expression is the internationally accepted way to quantitatively express the repeatability (under fixed conditions) or reproducibility (under changing conditions) of a measurement. Application of such an approach will be useful in multi-temporal or spatial studies, as well as for comparisons across treatment effects or for aggregating measurements to larger spatial units.

2. Aims

This paper is focused on identifying and then quantifying the key sources of measurement uncertainty in hemispherical conical reflectance factors (HCRF) measured in the field and demonstrating a simple method by which field-measured uncertainties can be characterised by users of spectroradiometric equipment.

The work presented is focused on measurements of vegetation spectral reflectance factors, because these are a key focus of many experiments employing proximal measurement methods (Bilouris et al., 2007; Gitelson et al., 2009; Harris, 2008), and vegetation remains high on the agenda of international agencies in relation to climate change monitoring (Betts et al., 1997; Ichii et al., 2002). Spectral data and vegetation parameters derived from them are also key requirements for modelling the relationship between EO-derived variables and flux tower data (Gamon et al., 2006b; Hilker et al., 2007, 2008, 2009).

Our approach was focused around an empirical study, using both field- and laboratory-derived data, to:

1. Demonstrate the link between laboratory-determined instrument characterisations and standard uncertainties (Taylor & Kuyatt, 1994) in field-measured HCRF through application of an uncertainty propagation approach;
2. Design and demonstrate a simple methodology for characterising instrument-specific standard uncertainties in operational measurement conditions, which can be applied by all users of field spectroradiometric data;
3. Show the importance of considering standard uncertainties when comparing HCRF quantities about vegetation that are measured using different spectroradiometers.

3. Method

3.1. Approach

We first considered the various sources of variability present in vegetation HCRF data and how these could be controlled for (and in some cases, quantified) within the experimental approach. Four key sources of variability in HCRF were identified and managed through various methodological approaches (Table 1). The first three sources of variability listed in Table 1 are those that experimenters normally try to minimize so that variation in the fourth source, the state and activity of the vegetation, can be measured. The central purpose of the method used in this study was to create a field scenario in which the state and activity of the vegetation could be assumed constant so that variation from the other three sources could be quantified. It is variation due to these other sources that represents the "noise" in a spectral vegetation measurement.

3.2. Instrumentation

Three spectroradiometers of the same make and model were used (Spectravista GER1500 visible-to-near infrared instruments (range 350–1100 nm)), with a 3 degree lens (Spectravista Corporation, 2009). The use of three instruments with broadly identical characteristics is justified in relation to the complexity associated with comparing data from different instruments with varying radiometric and geometric characteristics (Castro-Esau et al., 2006). At the time of the experiment, each instrument had been recently calibrated against traceable radiance sources and the wavelength calibration for each was known to be accurate (Table 2). These instruments were compared using uncertainty measures derived from: (a) measurements acquired in controlled laboratory conditions; and (b) measurements acquired in field conditions. The following sections describe these approaches.

3.3. Laboratory characterization

3.3.1. Noise equivalent delta radiance (NEΔL) characterization

To provide a quantitative baseline against which the 3 sensors could be compared, their noise equivalent delta radiance (NEΔL) was determined through a laboratory procedure carried out at NASA Ames Research Centre on 9th May 2008. NEΔL is defined as the quantity of radiance at the sensor that produces a change in sensor output equal to the environmental noise level of the particular remote sensing system (Schott, 1997; Wettle et al., 2004) and is a standard uncertainty under repeatable conditions (Taylor & Kuyatt, 1994). NEΔL provides a measure of inherent system uncertainty that is less ambiguous than a "signal-to-noise ratio", because it provides a wavelength-dependent radiance value describing system performance.

Table 1
Sources of variability in spectral HCRF measurements of vegetation canopies and how they were controlled for or characterised in the measurement approach.

Source of variability in HCRF measurements of vegetation	Management / characterisation of variability in experimental design
1. Instrument electro-optical characteristics (Markham et al., 1995)	Three spectroradiometers with identical manufacturer's specifications were used in the experiment. Their radiometric performance was compared in laboratory and stable field conditions.
2. 3-dimensional distribution of down-welling irradiance and its interaction with non-Lambertian aspects of the vegetation canopy (Gilabert & Melia, 1993; Kriebel, 1976, 1978, 1979)	Collection of metadata on atmospheric condition during spectral measurement scenarios and selection of a dataset which was subjected to minimal variations in measurement condition
3. Ground-projected field of view — influenced by platform and sampling design (Slater, 1985)	A carefully designed experimental approach which sought to maintain reproducible measurement geometries
4. State and activity of the vegetation (i.e. the photosynthetic function, biochemical composition, leaf area index etc. — the variables of interest to the user)	Measuring a cropped grassland canopy over tightly constrained time periods (2 h) where vegetation state and condition was assumed to remain constant