Estimating spectral irradiance from a limited number of discrete bands in the visible / near infrared

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Abstract – Accurate measurement and characterisation of fluctuations in the irradiance environment is important in many areas of optical remote sensing. This paper reports a method of estimating spectral irradiance over the VNIR region (400 - 1100nm) from the radiance of a calibrated reference panel, measured in seven narrow (10nm) spectral bands. The irradiance spectrum was partitioned into a number of distinct regions within each of which the spectral irradiance was estimated from irradiance measured at one of the reference wavelengths. The accuracy of the method was found to be better than ±5% over most wavelengths from 400nm to 1100nm.

Keywords: spectral irradiance, field spectroscopy, atmosphere, methodology, calibration.

1. INTRODUCTION

Many areas of optical remote sensing demand accurate measurement and characterisation of the incident spectral irradiance. In field spectroscopy, temporal variability of irradiance at a range of frequencies is a major factor affecting the accuracy with which the Bidirectional Reflectance Factor (BRF) of a target surface can be determined (Milton *et al.*, 1995, Milton and Goetz, 1997). However, with limited availability of truly simultaneous dual-beam field spectroradiometers, measuring the incident irradiance at a high enough frequency remains a fundamental problem for field spectroscopy, with implications for the precision of BRF and Bidirectional Reflectance Distribution Function (BRDF) measurements. Furthermore, some methods of reflectance calibration and atmospheric correction applied to data from airborne and satellite sensors require simultaneous irradiance measurements at the ground at a spectral resolution corresponding with that of the remote sensor, and for these purposes a simple, low-cost means of estimating the irradiance spectrum is very desirable.

The spectrum of incident global irradiance is dominated by the direct beam which is primarily a function of the solar spectrum, modified by absorption and scattering by atmospheric gases, water vapour and aerosol particles. There is a high degree of autocorrelation in high spectral resolution measurements of irradiance, partly because the bands sensed have spectral bandwidths broader than the spectral sampling interval. However, it is also a characteristic of the global irradiance spectrum itself that systematic relationships exist between irradiance at different wavelengths.

Previous research has demonstrated the principle of using calibrated measurements in a small number of narrow, carefully positioned spectral bands in order to estimate the complete spectrum of global irradiance (Milton and Goetz, 1997; Milton *et. al.*, 2000). In those 'proof of concept' studies, an artificial neural network technique was successful in estimating the full irradiance spectrum from data measured in seven narrow bands, for a range of sky conditions and for a single sensor data set. The aim of this work is to further validate the method using a separate, calibrated, seven-band device alongside a calibrated spectroradiometer. Whereas the earlier method was limited to use with the same multiband instrument as that used to derive the artificial neural network, the method described here is independent of the instrument as it is based upon absolute calibration.

The overall objective of the work is to develop a robust method of deriving the full irradiance spectrum from measurements obtained with a calibrated seven-band instrument. Such an instrument might then be routinely deployed for a wide range of remote sensing applications where irradiance measurements are required but no calibrated high spectral resolution instrument is available and to supplement field spectral measurement of reflectance.

2. METHODS

2.1 Single Sensor Data

In the first phase of this project, single sensor data were used to establish the relationship between spectral irradiance and irradiance at seven reference wavelengths positioned at: 430nm, 500nm, 780nm, 820nm, 830nm, 880nm and 950nm. Initial tests were performed on data collected in the UK with three different calibrated spectroradiometers (Table 1). These were fitted with cosine-corrected receptors and were calibrated in the laboratory against a 1000w FEL Lamp traceable to the UK National Physical Laboratory (NPL).

Table 1. The spectroradiometers used in the experiments described in this paper

Date	Instrument	Bandwidth/ Sampling Interval	Interpolated to 1nm
21May99	Spectron SE590	10nm/3nm	×
24July 01	ASDFieldSpec Pro	1.5nm	✓
18June 02	GER1500	1.5nm	✓
28June 02	GER1500	1.5nm	✓
16April03	Spectron SE590	10nm/3nm	×
29May03	Spectron SE590	10nm/3nm	×
16June03	Spectron SE590	10nm/3nm	×

Seven data sets were obtained with the instruments under clear sky conditions and covering solar zenith ranges between 30° and 60°. Each data set comprised at least 80 spectra obtained with a sampling interval of between 1 minute and 5 minutes and covering a period of between 30 minutes and 2 hours. All spectra were

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calibrated to irradiance and irradiance at each of the seven reference wavelengths was extracted. For each date, correlation analysis was used to derive the coefficient of determination (r^2) for the irradiance measured at every spectrometer wavelength *vs*. irradiance at each of the seven reference wavelengths (Figure 1).

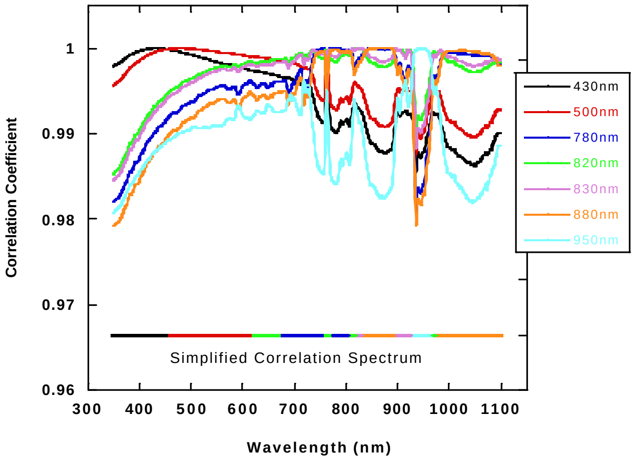

Figure 1. Coefficients of determination (r^2) for irradiance at the spectroradiometer wavelengths *vs*. irradiance at each reference wavelength for the single sensor data.

Figure 1 shows that, in general, the proportion of the total variance in irradiance which was explained by variation in any one reference wavelength decreased away from the reference wavelength as would be expected. This allowed us to divide up the spectrum into regions, within which the variation in signal could best be represented by variations at a particular reference wavelength. The result of this is shown by the 'simplified correlation spectrum' at the bottom of Figure 1 (original in colour).

2.2 Seven Band Instrument (INSPIRE)

The second phase of the project focused on validating the method using a separate, calibrated, seven-band device alongside a calibrated spectroradiometer. A dedicated instrument was designed and developed in-house. This instrument – the INdependent SPectral IRradiance Estimator (INSPIRE) – measures radiance in seven narrow spectral bands, positioned at the key reference wavelengths. The instrument uses seven silicon photodiodes fitted with narrow-band (< 10nm FWHM) thin-film interference filters. The operational version functions as a radiometer, measuring the radiance of a calibrated Spectralon™ panel, with all bands recorded simultaneously. In the field, measurements are triggered by input from a spectroradiometer via a Delta-T DL2e data logger, which is also used to log the data. INSPIRE was calibrated using a Hoffman LS-64-8D Rev A integrating sphere traceable to the UK NPL.

Four data sets were obtained using INSPIRE in conjunction with a Spectron Engineering SE590 spectroradiometer fitted with cosine-corrected receptor. The SE590 data were calibrated to irradiance. INSPIRE data were initially calibrated to radiance then converted to irradiance by correcting for the Spectralon™ panel reflectivity and multiplying by π. Data from three dates (16 April, 29 May and 16 June 2003) were then used to derive linear regression slope coefficients for the prediction of the spectral irradiance at every spectroradiometer channel, from the relevant band measured with INSPIRE, based on the Simplified Correlation Spectrum. The results of this are shown in Figure 2.

Generally, the three slope functions were very similar, although greater variation in the slope coefficients was apparent over the 600nm to 760nm region.

The data were collected over a range of turbidity conditions as indicated by the diffuse-to-global (D:G) irradiance ratio measured on the three dates (see Table 2). Figure 3 shows that some of the variation in slope coefficients may be related to variation in the D:G ratio.

Table 2. Diffuse:Global ratio at 550nm on each of the dates data were collected

16April2003	29May2003	13June2003	16June2003
0.21	0.48	0.15	0.36

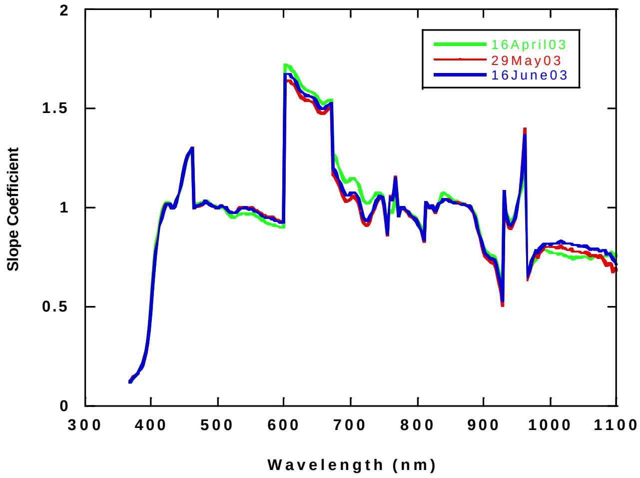

Figure 2. Linear regression slope coefficients for the INSPIRE data, obtained by relating spectroradiometer irradiance at every wavelength to INSPIRE irradiance at the specified reference wavelength, as defined by the Simplified Correlation Spectrum.

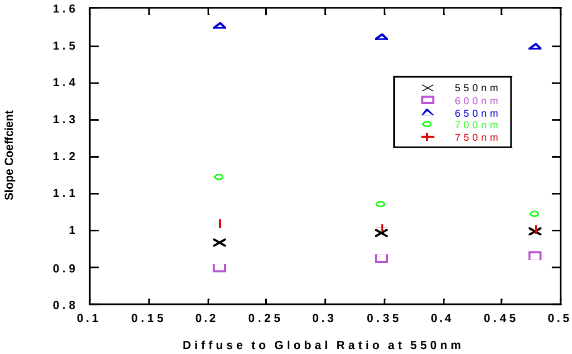

Figure 3. Variation in slope coefficient with atmospheric turbidity.

3. RESULTS

The method was tested using the data from a separate INSPIRE data set obtained on 13 June 2003. First, the mean slope coefficients for the three data sets shown in Figure 2 were calculated and used to regenerate the spectroradiometer irradiance from the INSPIRE data collected on 13 June. Spectral irradiance was also reproduced using the slope coefficients relating to the 'clearest' day (16 April 2003) and the 'haziest' day (29 May 2003). On 13 June 2003, atmospheric turbidity was very clear (D:G ratio = 0.15). Figure 4 compares the three estimates of spectral irradiance with that measured and shows there is good agreement in all cases. Plots of the percentage difference between the measured and estimated irradiance (Figure 5) reveal that the slope coefficients for the clear day produced the best results. The percentage difference between the measured and predicted irradiance when the clear day slope coefficients were used was less than ±3% over most of the range 400-1000nm. This compares with measured-predicted differences of less than ±5% over the same wavelength range for the prediction based on the mean slope coefficients. In all cases, larger differences occur around the atmospheric water vapour absorption feature at 940nm and at the extreme upper and lower limits of the spectrum where the instrument signal-to-noise ratio is reduced. These results suggests that improvements to the generalised model should be possible by incorporating sensitivity to the sky radiance distribution in the form of the D:G ratio.

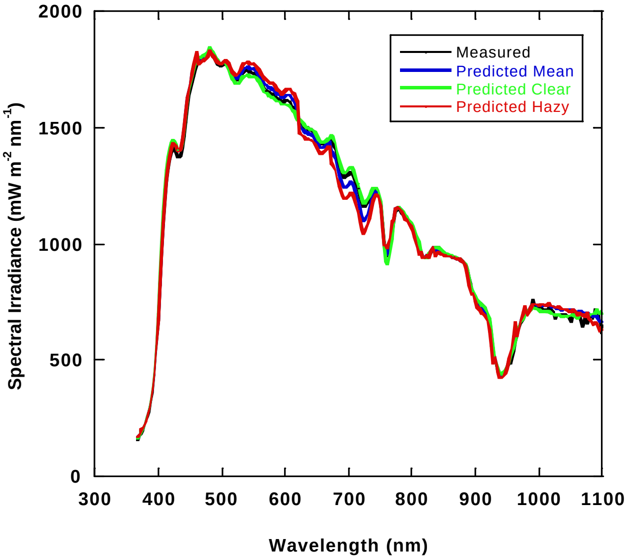

Figure 4. Measured and predicted spectral irradiance for the test data set (13 June).

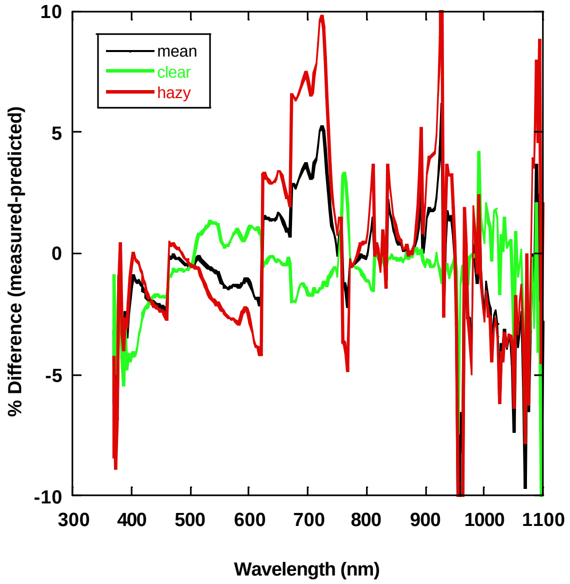

Figure 5 Percentage difference between measured and predicted spectral irradiance for the test data set (13 June).

4. Conclusions

Results from the newly-developed INSPIRE instrument indicate the viability of a method of estimating the full spectrum of global irradiance over the VNIR wavelengths from measurements obtained with a calibrated seven band radiometer, and empirically derived slope coefficients. Using the mean slope coefficients derived from three separate days resulted in realistic estimates of the spectral irradiance collected with INSPIRE on a different date. Sensitivity of the slope coefficients to the sky radiance distribution meant that the best estimates of spectral irradiance (within ±3% of the measured value) were obtained by using slope coefficients derived under similar D:G conditions.

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