Estimating spectral irradiance from measurements in seven spectral bands

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Abstract

Accurate measurement and characterisation of fluctuations in the irradiance environment is important for 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. Earlier work established the potential for estimating spectral irradiance from multi-band data using a neural network technique (Milton *et al.*, 2000). The approach described here uses linear regression analysis to regenerate the irradiance spectrum from data in seven reference wavelengths. The method was tested using data from a specially designed multiband radiometer – the INdependent SPectral IRradiance Estimator (INSPIRE). 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 precision of the method was found to be better than ±5% over most wavelengths from 400nm to 1100nm. Furthermore, the slope coefficients of the individual regression models were found to be sensitive to the sky radiance conditions, especially over the region 600-760nm, and improvement in the precision of the predicted spectrum (to within ±3%) was obtained by taking the diffuse-to-global (D:G) irradiance ratio at the time of measurement into account.

1   Introduction

Many areas of optical remote sensing demand accurate measurement and characterisation of the incident spectral irradiance. In field spectroscopy, temporal variability in 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. In addition, some methods of reflectance calibration and atmospheric correction applied to data from airborne and satellite sensors require irradiance measurements at the ground simultaneous with the

image acquisition and 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 other aerosol particles. There is a high degree of autocorrelation in high spectral resolution measurements of irradiance, partly because of the measuring devices commonly used (CCD arrays) have spectral bandwidths broader than the spectral sampling interval. However, it is a characteristic of the global irradiance spectrum itself that systematic relationships exist between irradiance at different specific wavelengths. For example, previous work has found variation in the flux around the oxygen absorption feature at 762nm to correlate with variations around the atmospheric water vapour absorption feature around 940nm. In contrast, the flux around 880nm remains largely independent of these variations.

Earlier 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 relies 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   Methodology

2.1   *Phase 1- testing the linear regression model on single sensor data*

The first phase of the research was to characterise the degree of correlation between (a) the spectral irradiance measured with the spectroradiometer at any given wavelength and (b) irradiance at each of the seven reference wavelengths. The bands selected for this work are positioned at: 430nm, 500nm, 780nm, 820nm, 830nm, 880nm and 950nm. These are referred to here as the reference wavelengths. Figure 1 shows the bands in relation to a spectrum of global irradiance.

This was done initially using data collected in the UK with three different calibrated spectroradiometers, each fitted with a cosine-corrected hemispherical receptor to measure the incident irradiance. Several data sets were obtained with the instruments under clear sky conditions and covering solar zenith ranges between 30 and 60 degrees. For each data set at

least 80 spectra were obtained at a sampling interval of between 1 minute and 5 minutes and covering a period of between 30 minutes and 2 hours. Table 1 summarises the spectroradiometer data sets.

Each data set was dealt with separately, the raw spectra being initially calibrated to irradiance using instrument specific functions of calibration coefficients. In all cases the sensor was fitted with a cosine corrected hemispherical receptor which measured the incident irradiance flux directly and was calibrated to irradiance. All the sensor irradiance calibrations were derived by laboratory calibration against the EPFS in-house irradiance standard, an Optronics Laboratory 1000W FEL lamp, calibrated by the UK National Physical Laboratory (NPL). Data from the GER1500 and the ASD FieldSpec Pro were interpolated to 1nm after application of the irradiance calibration while those from the Spectron SE590 remained at the original sampling resolution of (nominally) 3nm.
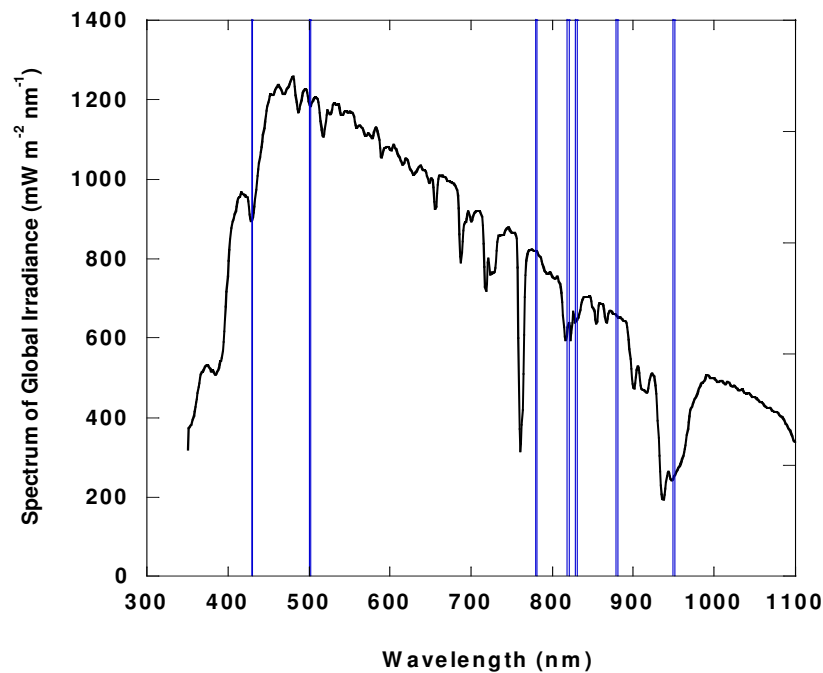

FIGURE 1   Reference band positions in relation to a spectrum of global irradiance.

Date	Instrument/ Serial No	Bandwidth/ Sampling Interval	Interpolated to 1nm
21May99	Spectron SE590 / 2002	10nm/3nm	✘
24July 01	ASDFieldSpec Pro / 6239	1.5nm	✓
18June 02	GER1500 / 2003	1.5nm	✓
28June 02	GER1500 / 2003	1.5nm	✓
16April03	Spectron SE590 / 2002	10nm/3nm	✘
29May03	Spectron SE590 / 2002	10nm/3nm	✘
16June03	Spectron SE590 / 2002	10nm/3nm	✘

TABLE 1: Summary of spectroradiometer irradiance data sets

Once the data were calibrated, the irradiance values at the seven reference wavelengths were extracted from all the scans in each data set. Product moment correlation coefficients were then derived for the irradiance at each instrument channel against the irradiance measured in all seven reference wavelengths (Figure 2).
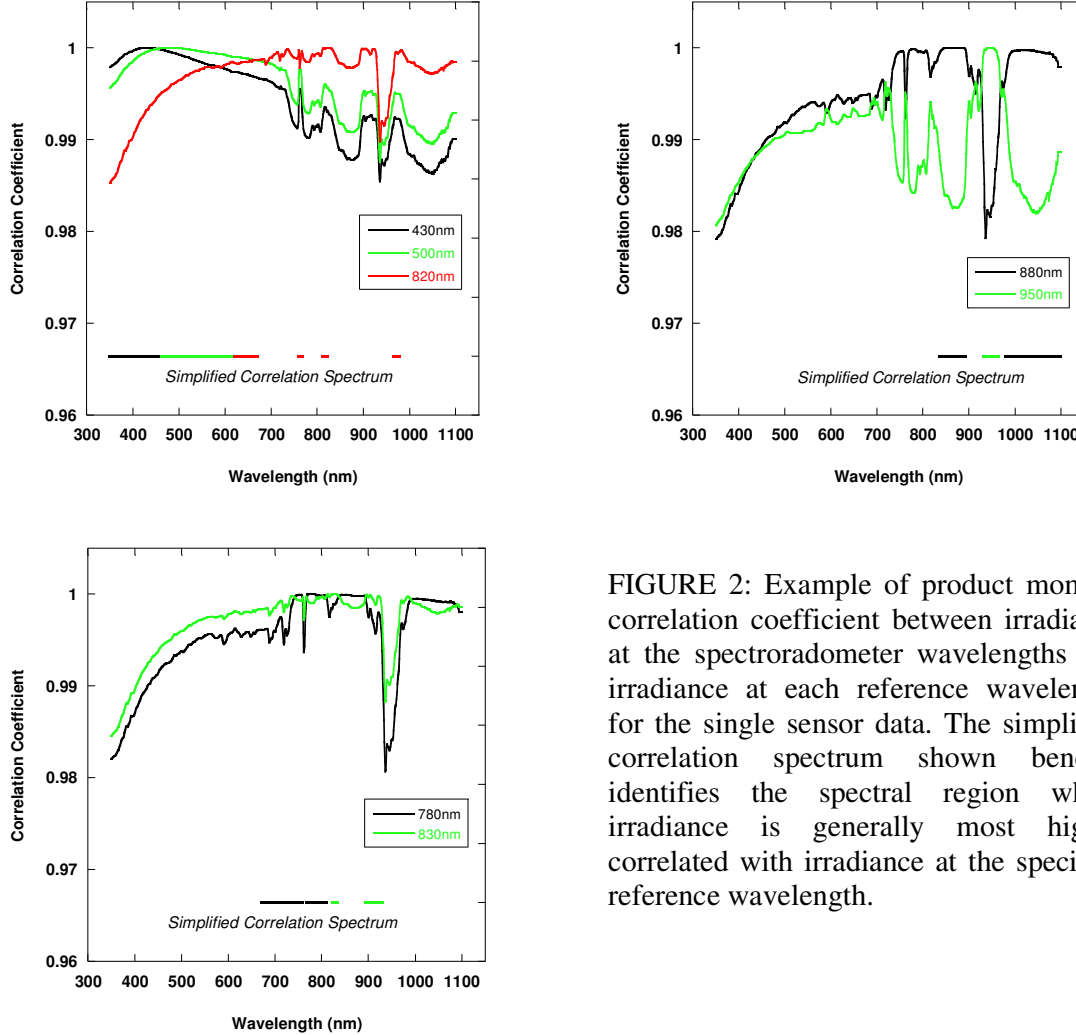

FIGURE 2: Example of product moment correlation coefficient between irradiance at the spectroradometer wavelengths and irradiance at each reference wavelength for the single sensor data. The simplified correlation spectrum shown beneath identifies the spectral region where irradiance is generally most highly correlated with irradiance at the specified reference wavelength.

Comparison of the correlation spectra for all the data sets revealed a high degree of consistency in the pattern across dates and instruments. A simplified peak correlation spectrum was derived to summarise the dependence of irradiance at any specific wavelength on irradiance at one of the reference wavelengths (Figure 2).

Applying the simplified correlation spectrum to each data set, the slope coefficient for the linear regression of the irradiance at each dependent wavelength as a function of the irradiance at the appropriate reference wavelength was determined for every data series. The slope coefficient was determined by least squares fit through the origin. Figure 3 shows the slope coefficients derived for all seven data series. There is marked consistency in the slope values for all the data sets across most wavelength regions, despite the range of sensors, providing further support for the systematic relationship between irradiance across definable spectral regions and irradiance at the

seven reference wavelengths. Variation in the slope coefficient between dates are most marked in the region 600-760nm. This reflects the lower correlation coefficient found for that region (see Figure 2) in most data sets. Also, the wavelength at which the peak correlation changed from the 500nm band to the 820nm band also varied between data sets, so the use of the simplified correlation spectrum may be not be ideal for this region. Further work is planned to determine whether the changeover position is related to some other factor, for example sky radiance distribution.
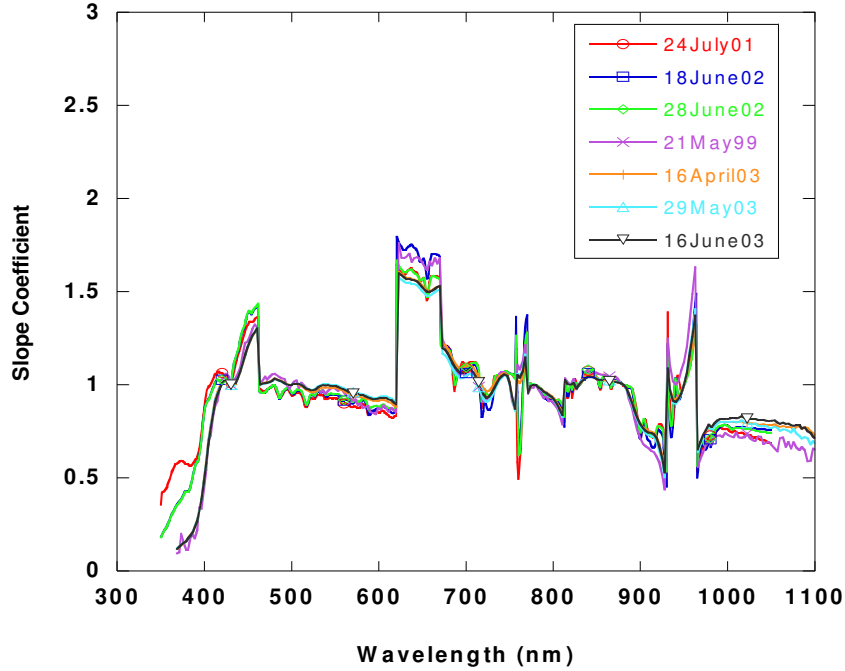

FIGURE 3: Comparison of slope coefficients from seven dates for linear regression of irradiance at spectroradiometer wavelengths as a function of irradiance at the reference wavelength specified by simplified correlation spectrum.

2.2 Phase 2 – the seven band instrument

The second phase of the project was to apply the linear regression model to a separate multi-band instrument working alongside the 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 (less than 10nm FWHM) spectral filters. The operational version of the instrument functions as a radiometer, measuring the radiance of a calibrated Spectralon™ panel, with all seven bands recorded simultaneously. The instrument is calibrated in the EPFS laboratory to units of radiance against the EPFS in-house radiance standard, a Hoffman LS-64-8D Rev A integrating sphere, which is calibrated by the UK NPL. In the field, the seven band radiometer can be triggered manually, but for this work, the scans were triggered by input from a second high spectral resolution instrument when it performed a scan. The

scan triggering and data logging for the seven band instrument was done via a Delta-T DL2e data logger.

Four data sets have so far been obtained using the INSPIRE in conjunction with a Spectron Engineering SE590 spectroradiometer. In all cases the SE590 sensor was fitted with cosine corrected hemispherical receptor to measure the incident irradiance flux synchronised with the seven band radiometer panel radiance measurements. Each data set includes at least 100 scans obtained at (nominally) 1 minute intervals over a period of at least 60 minutes.

Data processing was undertaken as follows. The SE590 data were calibrated to irradiance units by application of the calibration function. The INSPIRE data were initially calibrated to radiance, then a panel correction was applied to account for the spectral reflectivity of the Spectralon™ panel used. This factor varies with wavelength. The panel radiance values were then multiplied by π to obtain the equivalent incident irradiance flux value.

The radiometric calibration of both sensors was validated using a field technique. For all four data sets simultaneous measurement of the radiant flux of a calibrated Spectralon™ panel with a third instrument provided independent validation of the radiometric calibration of the INSPIRE data. On the 16 April 2003 a GER1500 sensor fitted with 3° field-stop was used, while on the other three dates a Spectron SE590 sensor fitted with 15° field-stop was used. Synchronised measurements with these sensors and the INSPIRE enabled normalisation of the seven band radiance data to those of the other system.

Three of the data sets (collected on 16 April, 29 May and 16 June 2003) were used to repeat the correlation and regression analysis described in section 3.1, but this time correlating the seven-band radiometer measurements (converted to irradiance) with the high spectral resolution irradiance data obtained with the spectroradiometer. The simplified correlation spectrum established in phase 1 and shown in Figure 2, was used to define the linear regression relationship between the irradiance at any given wavelength in the complete spectrum and that measured at the appropriate reference wavelength with the INSPIRE. The slope coefficients obtained for all three data series are presented in Figure 4.

Overall, the three functions are generally very similar, although greater variation in the slope coefficients is apparent over the 600nm to 760nm region. This may reflect the lower correlation coefficients for these wavelengths (as discussed in relation to Figure 3). The data were collected over a range of turbidity conditions as indicated by the diffuse-to-global irradiance ratio measured on the three dates (Table 2). Analysis shows that variation in the slope coefficients derived from the INSPIRE instrument appears to be related to the spectral distribution of irradiance (Figure 5). Furthermore, it appears that the relationship is complex in the region between 600nm and 700nm, with the variation in slope with D:G ratio changing from positive to negative between 600nm and 650nm. This aspect of the investigation will be pursued with further experimental work.
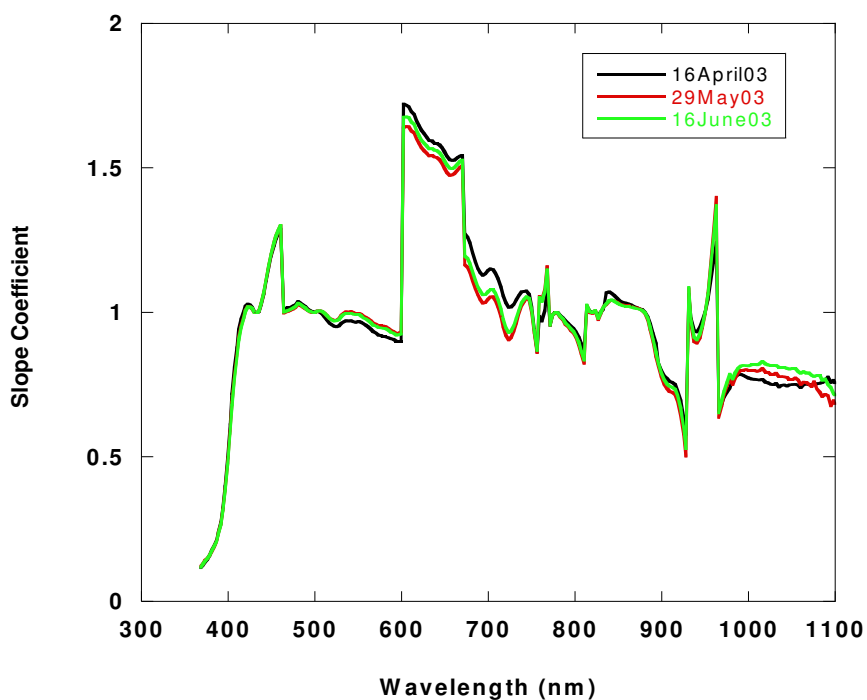
FIGURE 4: Slope coefficients for the relationship between spectral irradiance and irradiance measured at the reference wavelength with the INSPIRE instrument.
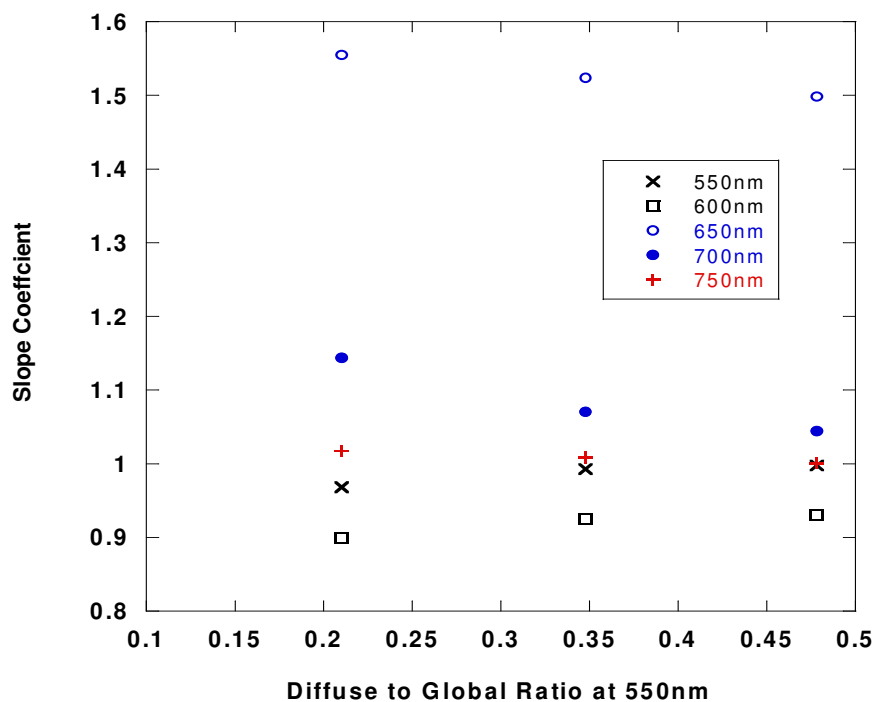

FIGURE 5: Diffuse-to-Global ratio at 550nm measured with the spectroradiometer plotted against the slope coefficient at selected wavelengths derived from the INSPIRE data for a three dates.

7

	16April2003	29May2003	16June2003
D:G at 550nm	0.21	0.48	0.36

TABLE 2 Diffuse-to-Global Irradiance Ratio at 550nm

2.3 Phase 3 – testing the empirically derived model

Results so far indicate that the empirically derived slope coefficients define the relationship between the seven band irradiance measurements and the irradiance spectrum (at the resolution of the spectroradiometer system). The validity of using the 'common' slope coefficient for predicting the irradiance spectrum was tested as follows. First, the mean slope for three data sets shown in Figure 4 was calculated. The mean slope values were then applied to a separate data set (the fourth series) obtained on 13 June 2003, to estimate the spectroradiometer irradiance spectrum from the irradiance measured simultaneously with the INSPIRE.

In addition, because Figure 5 suggests that the common slope coefficients include some sensitivity to the sky radiance distribution, the irradiance was estimated was using the slope coefficients for the 'clearest' day (16April 2003) and the 'haziest' day (29 May 2003). These are subsequently referred to as clear and hazy respectively. On 13 June 2003, atmospheric turbidity was very low with the D:G at 550nm measured as 0.15.

Results of applying then mean slope and the two extreme slope coefficients to the INSPIRE data collected on 13 June 2003 are shown in Figure 6 for a representative spectrum and in comparison to the irradiance spectrum measured with the spectroradiometer at the same time as the INSPIRE measurements. The percentage difference between measured and predicted was calculated according the Equation 1:

$$\left(\frac{measured - predicted}{measured}\right) \bullet 100 \qquad (1)$$

The percentage difference spectra for all three predictions are shown in Figure 7. These results confirm that the slope coefficients for the clear day produce better results than those from the hazy day, while the mean slope coefficient results in reasonable prediction of the irradiance spectrum. For the prediction based on the mean slope coefficients differences are less than ±5% over most of the 400-1000nm range although 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. However, Figure 7 also reveals that the percentage difference between the measured and predicted irradiance when the clear day slope coefficients are used is less than ±3% over most of the range 400-1000nm. This suggests improvements to the model, especially over the 600-760nm region, should be possible by incorporating sensitivity to the sky radiance distribution in the form of the D:G ratio.
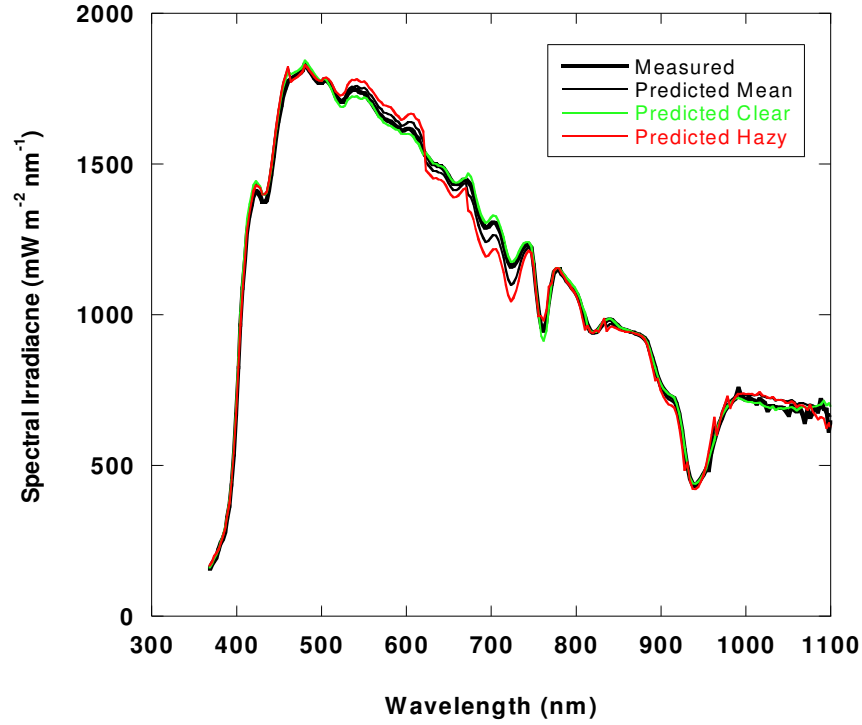
FIGURE 6: Measured and predicted irradiance spectrum from 13 June 2003. Prediction is based on *mean* slope coefficients for the three dates shown in Figure 5, the coefficient for the *clear* day and those for the *hazy* day.
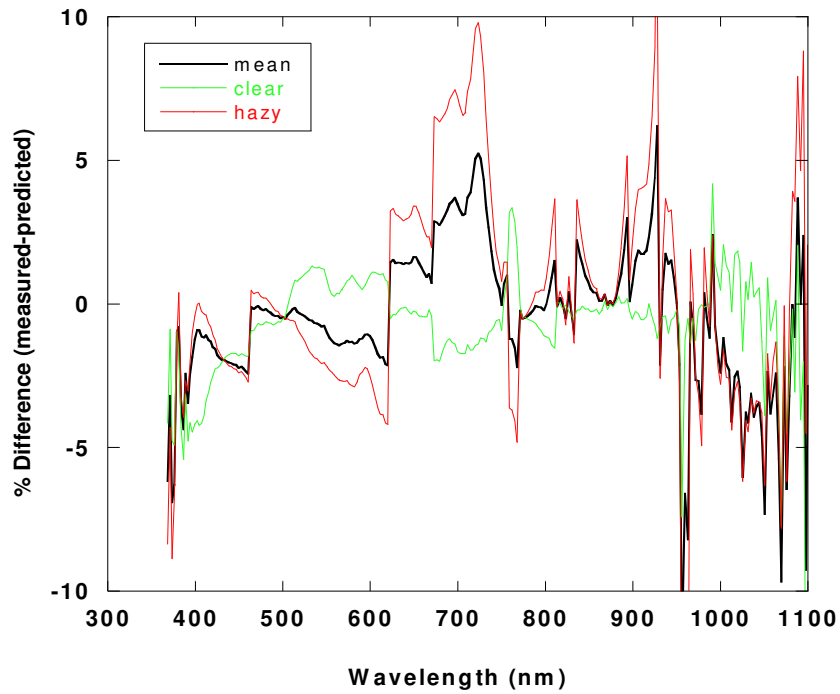

FIGURE 7: Percentage difference (measured-predicted) for application of the model to 13 June INSPIRE data with the mean, clear and hazy slope coefficients.

3 Conclusions

Preliminary 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 the INSPIRE on a different date. However, 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. This was especially true of the 600-760nm region. Future work planned for summer 2003 will, a) refine how the model incorporates sky radiance (D:G) information and b) improve field inter-calibration procedures, both of which are expected to significantly improve the accuracy of the retrieved spectrum as well as help establish the limits of the technique in terms of sky conditions.

4 Acknowledgements

5 References

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