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The use of diode array spectroradiometers for dosimetry in phototherapy

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Abstract

An evaluation of two diode array radiometers, an UV spectroradiometer, Type SC-MP-A, from 4D Controls (Redruth, UK) and an USB2000-UV-VIS spectrometer from Ocean Optics (Duiven, NL), was carried out at the Photobiology Unit, University of Dundee. Three parameters of the instruments' performance were investigated, having been identified as the most likely sources of error in phototherapy dosimetry: (1) calibration, (2) stray light rejection, (3) angular response. An assessment was then made of the reliability of this type of instrument for dosimetry in clinical practice by measurement of a selection of phototherapy sources, in direct comparison with calibrated radiometers. Both instruments were found to have significant stray light levels (SC: 13% and USB: 39%). The use of stray light compensation and a high output calibration source improves accuracy to within acceptable limits. Angular responses were satisfactory: f_2 values (±60°) of 5.9% and 7.8% for SC and USB, respectively. The SC spectroradiometer is supplied as a calibrated instrument. Using the supplied calibration resulted in errors in measuring phototherapy sources of up to 44% in UVA. Alternative calibration reduced the error in measuring UVA and UVB sources to within 12%. The USB spectrometer was found to have insufficient responsivity in both UVB and UVA to provide reproducible measurements of most phototherapy sources.

1. Introduction

Within photomedicine, the need for accurate dosimetry of therapeutic UV radiation has long been recognized (Diffey 1978, Green *et al* 1992). If treatment times are kept to a minimum and accurately monitored then the risk of carcinogenesis is minimized, treatments can be optimized and there is also the potential for patients to transfer treatment centres without jeopardizing the course of their therapy. Any instrument that is used for dosimetry should measure to within 10% (Coleman *et al* 2000, Moseley 2001) because errors in dosimetry are clinically significant and may lead to painful erythematous reactions (Moseley *et al* 1993, Hansen *et al* 1994). There are currently three different options for measuring UV radiation for health hazard or phototherapeutic assessment, namely spectroradiometers, personal dosemeters and filtered radiometers (Driscoll 1993).

Spectroradiometry is beneficial because it allows the operator to resolve the spectrum of the lamp being measured. If spectral data are collected then there is the potential to apply different action spectra to the output of the lamp. Therefore, the risk of exposure can be assessed for patients with different skin conditions that exhibit different spectral sensitivities. This idea can also be extrapolated to other light sources in order to give advice to photodermatoses patients on exposure levels to all types of light. Absolute spectral irradiance measurements can be achieved at an uncertainty level of 4% in spectroradiometry (Kostkowski 1997) but the technique involves expensive, bulky and complex equipment and can require a large period of time to take measurements. Within a busy treatment centre, transporting bulky equipment to measure outputs from phototherapy sources is impractical.

Studies of personal phototherapy source dosimetry have been conducted, primarily using polysulphone film badges (Fanselow *et al* 1987, Jekler *et al* 1990, Knuschke and Barth 1996) since their introduction as personal dosemeters for UV radiation (Davis *et al* 1976). These badges can provide useful information regarding the distribution of phototherapy radiation over a patient's skin. Other commercial personal dosemeters incorporating UV sensitivity are available. These are generally based on solid state detector technology, e.g. the sp3 (Tunbridge Wells, Kent) 'Sunwatch'™ which is based on a solid state gallium nitride detector.

Output measurements from UV treatment cabinets and lamps have traditionally been carried out using filtered radiometers, calibrated against sources similar to those being measured. These broad or narrow band radiometers do have limited accuracy and cannot resolve the spectrum of the lamp of interest but by following guidelines for meter calibrations against a spectroradiometer (Norris *et al* 1994; Diffey and Hart 1997), doses can be measured to within 10% with relative ease. This type of meter is currently the preferred option for health hazard assessment (Driscoll 1993).

The relatively new technology of the diode array spectroradiometer provides potentially the perfect answer to the trade off between spectral data collected with a cumbersome instrument and the ease and speed of the filtered radiometer: a portable instrument that will acquire spectral data (Ridyard 2000). An example of the optical layout of such a spectroradiometer is shown in figure 1. After incoming radiation has been split into its constituent wavelengths by a diffraction grating, a series of fixed, silicon photodetector pixels transduce the radiation into an electrical signal. As all the pixels have fixed positions, it is possible to predict the wavelengths that will fall on each pixel and a spectrum can therefore be determined using appropriate software. Before this type of instrument becomes widely used in the medical field, it is important to assess the limitations of their use and the reliability and accuracy of the data collected from them. If diode array instruments are to become the dosimetry instrument of choice in the future and filtered radiometers are to be usurped then the same requirements for accuracy should apply in both cases.

During 2001 and 2002, two diode array instruments, from different manufacturers, were evaluated at the Photobiology Unit, University of Dundee. This is a well-equipped laboratory with ISO 9001 registration and standards traceable to the National Physical Laboratory (NPL) (Teddington, UK) spectral irradiance scale. A number of investigations were carried out to assess the performance parameters of these instruments. There are three areas of performance which were investigated as these were identified as, potentially, the largest sources of error in using the instruments—calibration, stray light rejection and angular response.

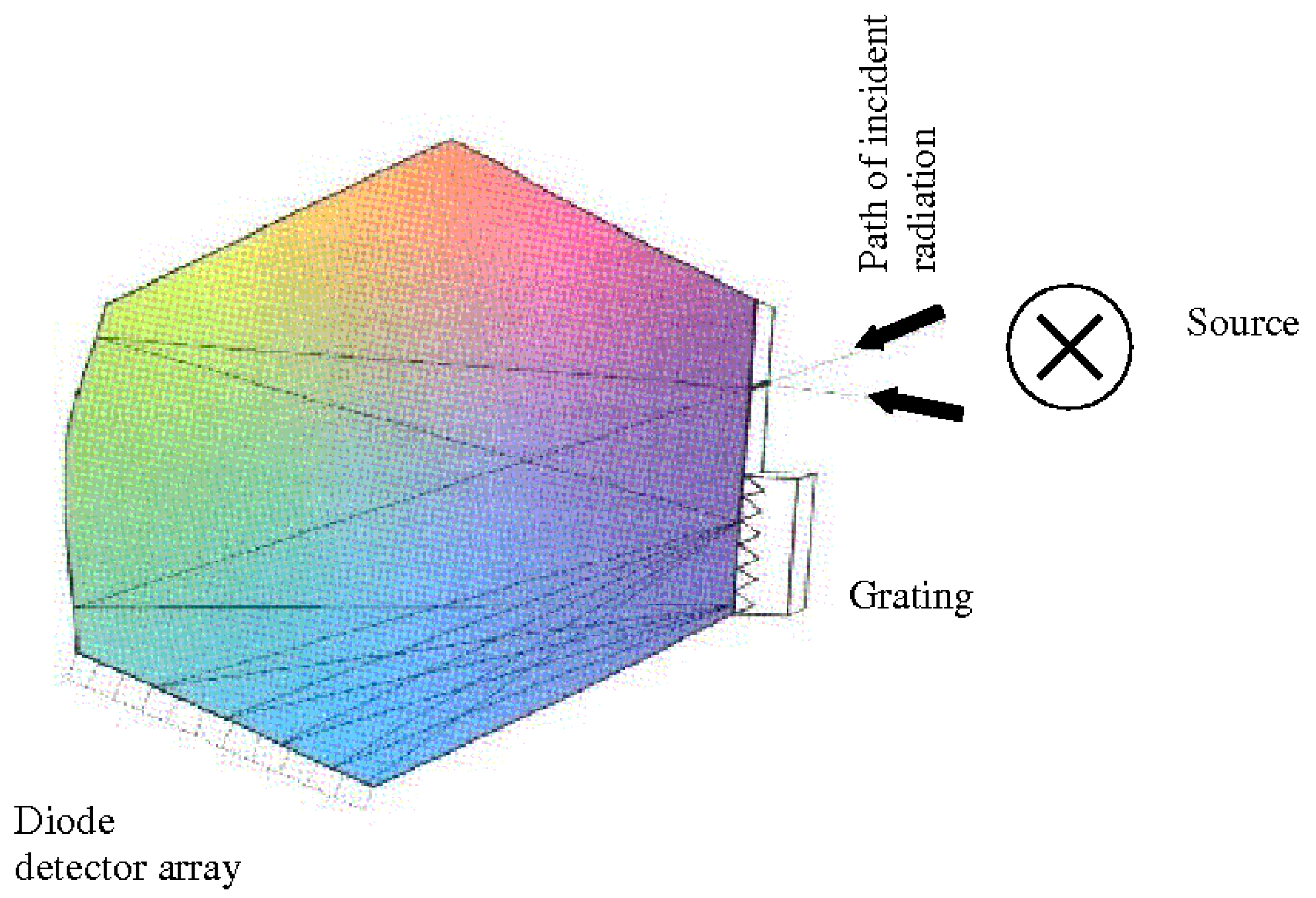

Figure 1. Diagram showing the optical layout of a diode array spectroradiometer. (Graphic courtesy of 4D Controls.)

(This figure is in colour only in the electronic version)

The calibration of the instruments must be traceable to national standards and should agree with a calibrated, double grating, bench based spectroradiometer (Coleman *et al* 2000). This ensures reliability of readings and facilitates transfer of doses between centres.

In the case of diode array instruments, stray light is the radiation that is detected by the 'wrong' pixel for the wavelength of the radiation. This phenomenon is common to spectroradiometric systems although in the case of most bench based spectroradiometers, two successive gratings are used to improve the wavelength selection. These diode array instruments are single grating, portable instruments and as such would be expected to have poor stray light levels which will affect the overall calculated dose for any phototherapy instrument.

As phototherapy sources are diffuse, wide angled and non-directional, it is important that any instrument for use in photomedicine will detect radiation at all the input angles from which radiation will be incident on the skin. Phototherapy cabinets are often 360° sources and the expectation of radiometers is that they have an error margin (f_2 value) of 10% or better (Pye and Martin 2000, Moseley 2001).

In order to give an assessment of the reliability of this type of instrument in clinical practice, the calibration of the instrument and the influence of its angular and spectral responses should be checked by measuring a number of phototherapy sources against calibrated radiometers or a spectroradiometer.

An UV spectroradiometer, Type SC-MP-A, from 4D Controls (Redruth, UK) (hereafter referred to as Sola Scope) and an USB2000-UV-VIS spectrometer from Ocean Optics (Duiven, NL) (hereafter referred to as Ocean Optics) were both evaluated at the Photobiology Unit, University of Dundee.

The Sola Scope is a self-contained spectroradiometric instrument which consists of a hand held 'sensor head' with a domed Teflon diffuser forming the input optics to the single grating and diode array, all contained in one compact box. The sensor head then connects to another hand held unit containing the software, control keypad and a display panel to enable spectra of measured lamps to be visualized. Data from the Sola Scope can be easily uploaded to a PC spreadsheet for analysis via the supplied (Sola-Term 2000) software.

The Ocean Optics consists of a flat Teflon diffuser head attached to an optical fibre which forms the input optics to the spectrometer (single grating and diode array) which is a unit no bigger than a pack of cards. The spectrometer connects to a laptop PC via an USB port and the spectrometer can then be controlled using the supplied (OOIBase32) software.

2. Methods and materials

2.1. Calibration

The instruments differed slightly in their mode of use. The Ocean Optics was designed for use as a comparative radiometer, or spectrometer. The idea is to use a standard reference lamp to record a spectrum in the software. The standard lamp's colour temperature can then be input into the software and during any subsequent measurement the software derives the measured lamp's spectrum from the colour temperature profile (based on a black body emission spectrum) of the standard reference lamp. The Sola Scope is sold as a calibrated instrument that will give readings in absolute units, traceable to NPL.

To set the wavelength scale on the Ocean Optics instrument, a low-pressure mercury Pen-Ray lamp was used. The position of eight known spectral lines (between 253.65 nm and 579.07 nm) and the pixel that detected these lines were analysed by linear regression and the regression coefficients were input into the software. The wavelength scale was then calculated by the software. For absolute unit calibration, the Ocean Optics instrument was calibrated by the investigator against a 1 kW incandescent quartz halogen lamp (designated type FEL) calibrated at NPL. The lamp was allowed 30 min warm-up time and was run at a current of 8.33 A. From the response of the Ocean Optics, a calibration template was derived at each wavelength such that

$$\mathrm{SF}_\lambda = \frac{E_\lambda}{R_\lambda}$$

where SF_λ is the sensitivity factor at a given wavelength, E_λ is the lamp irradiance at the same wavelength and R_λ is the instrument response at that wavelength.

The Sola Scope's in-built calibration factor is derived by the manufacturer from a deuterium lamp. However, the software allows a custom calibration file to be created by recording a spectrum of a standard lamp, in the same way that the calibration template was created for the Ocean Optics. A calibration of this type was performed using the same 1 kW FEL lamp. The wavelength of the instrument was checked by sampling the spectrum of a low-pressure mercury lamp.

2.2. Stray light

Stray light levels were assessed in these instruments by the use of a xenon arc lamp, filtered for infrared radiation (IR) with a $H_2SO_4 \cdot CuSO_4$ solution and a cut on filter (WG305, Schott). The lamp was allowed at least 15 min to stabilize before the spectra were measured by the diode array instruments. The advantage of using a source with a broad spectral output is the fact that stray light contributions from longer wavelengths, which may be detected as short wavelengths, can be identified more easily than if a monochromatic source or a source with clear emission lines is used. As the filter has a well-known transmission profile, the stray light present in the recorded spectra can be expressed as a ratio of the signal level at a given wavelength (Kaye 1981).

There is a method recommended to correct the stray light in the signal recorded from the Sola Scope. This method involves using an orange filter which only transmits radiation above 355 nm. The filter is placed over the input optics of the Sola Scope and the resulting irradiance profile is then subtracted from subsequent scans. This procedure must be repeated before each lamp measurement because there will be a different stray light ‘profile’ according to the spectral distribution of the lamp of interest.

There is no method to remove stray light from the Ocean Optics instrument although the same procedure may be applicable. The calibration derived from the 1 kW FEL lamp should calibrate the stray light levels in the signal although this will be subject to some error due to the differing stray light ‘profiles’ of the calibration source compared to what is measured. A recording of the dark spectrum was made before each measurement run and the dark current or noise is, therefore, subtracted from each spectrum.

2.3. *Angular response*

A measurement of the angular response of the instruments was made using a xenon arc lamp. The lamp (as used for assessing stray light) was allowed 15 min to stabilize after ignition. The instruments were positioned with the input optics at the centre of rotation of a turntable. The turntable is marked at 1° intervals. The turntable was moved manually and a spectrum was recorded at each 5° step over the interval ±60°.

The angular response of the Sola Scope was measured in the planes parallel to the grating and perpendicular to the grating. The response of the Ocean Optics was considered in one orientation only as there is an optical fibre coupled to the diffuser so that all radiation is scrambled within the fibre.

A value (f_2) for the cosine response can be calculated as

$$f_2 = \frac{\sum \left| 1 - \frac{R_\theta}{R_0 \cos\theta} \right|}{n} \times 100$$

where θ is the angle of measurement, R_0 is the response of the instrument at 0°, R_θ is the response at the angle of measurement and n is the number of measurements.

2.4. *Measurement of phototherapy sources*

Any instrument intended for use in phototherapy dosimetry should be able to record an accurate dose (to within 10%), of any phototherapy lamp. A number of different sources in the unit were measured, ranging from whole body treatment cabinets to single fluorescent tubes. These measurements were made at a nominal distance of 30 cm from the source and at least 5 min was always allowed for the output from the lamps to stabilize.

Measurements were made in direct comparison with either the unit’s IL1400 radiometer (Able Instruments, Reading, UK), which has attachments for measuring both UVA and UVB; or a bench based double grating spectroradiometer (Bentham DM150). In accordance with guidelines, the radiometer was calibrated against sources with similar spectral outputs to those to be measured (CIE 1984), in direct comparison with the Bentham spectroradiometer.

The calibration of the Bentham is traceable to NPL and has an estimated expanded uncertainty at the 95% confidence level, of 5.72% in UVB and 3.48% in UVA. These uncertainties have been calculated in accordance with NPL guidelines (Bell 2001) and include consideration of the uncertainty in the calibration sources used, alignment errors and uncertainty in the current from the cooled (−20 °C ± 2 °C) photomultiplier tube. The transfer standard for UVA radiation measurements (315–400 nm) is a 100 W frosted glass tungsten lamp, and a 30 W deuterium discharge lamp is used as a transfer standard for UVB (280–315 nm).

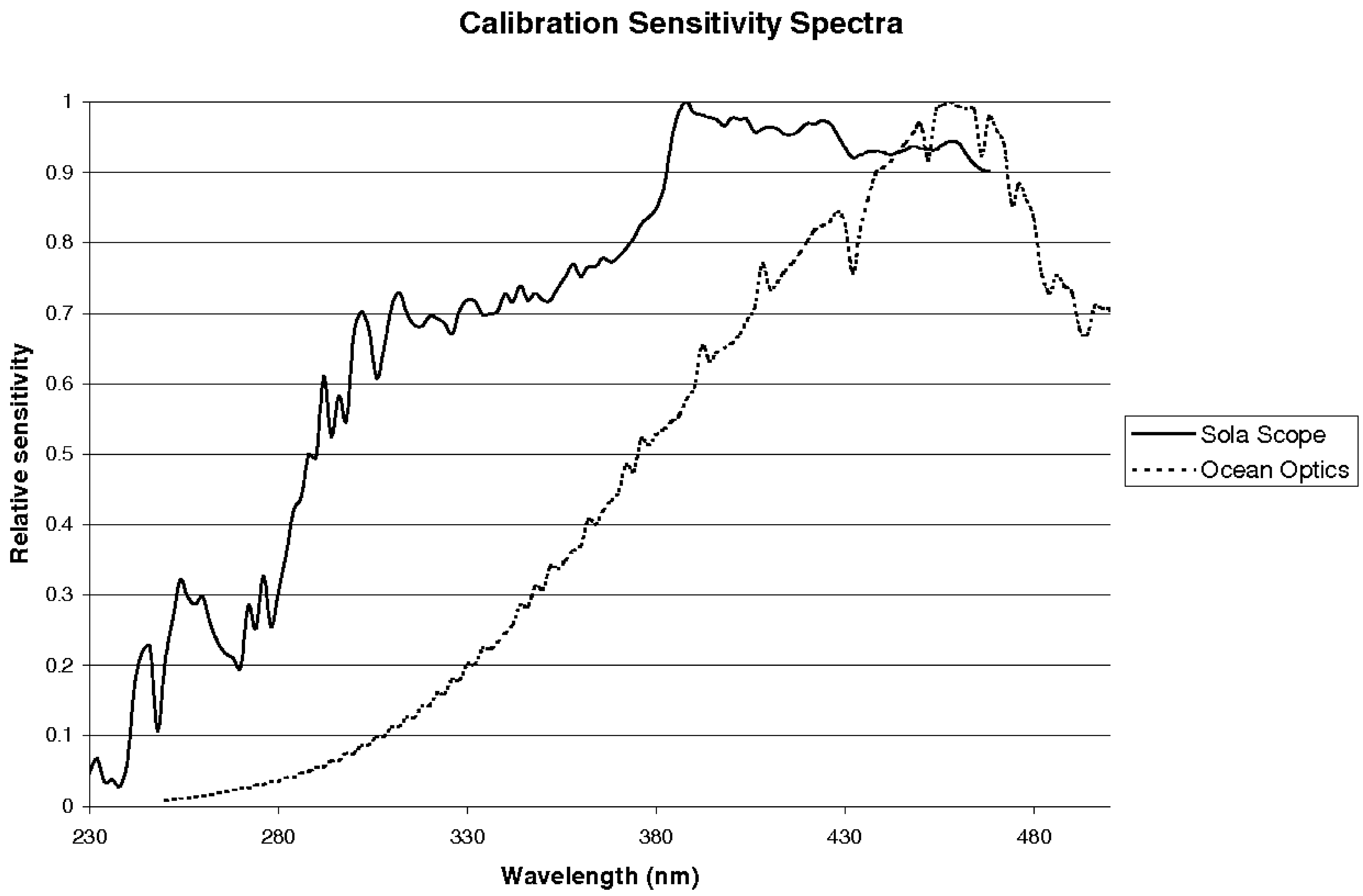

Figure 2. Graph showing the relative spectral responsivities of both the Ocean Optics and the Sola Scope.

Table 1. Wavelength error of Sola Scope.

Spectral line (nm)	Recorded position (nm)	Error (nm)
253.65	253.5	−0.15
313.10	313.0	−0.10
365.00	365.0	0.00
404.70	404.5	−0.20
435.80	436.0	0.20

Table 2. Stray light ratios from the diode array instruments. The percentage value expressed is the ratio of the signal at 250 nm to that at 430 nm.

Instrument	Without compensation or calibration	With compensation or calibration
Sola Scope	13%	2.0%
Ocean Optics	39%	0.4%
Bentham DM150 Spectroradiometer	<0.001%	<0.001%

3. Results

3.1. Calibration

The calibrations of both instruments reveal significant differences in the relative responsivities (see figure 2). Wavelength error for the Sola Scope is shown in table 1 and was satisfactorily small to be considered negligible. There was a significant amount of noise in the signals from both instruments.

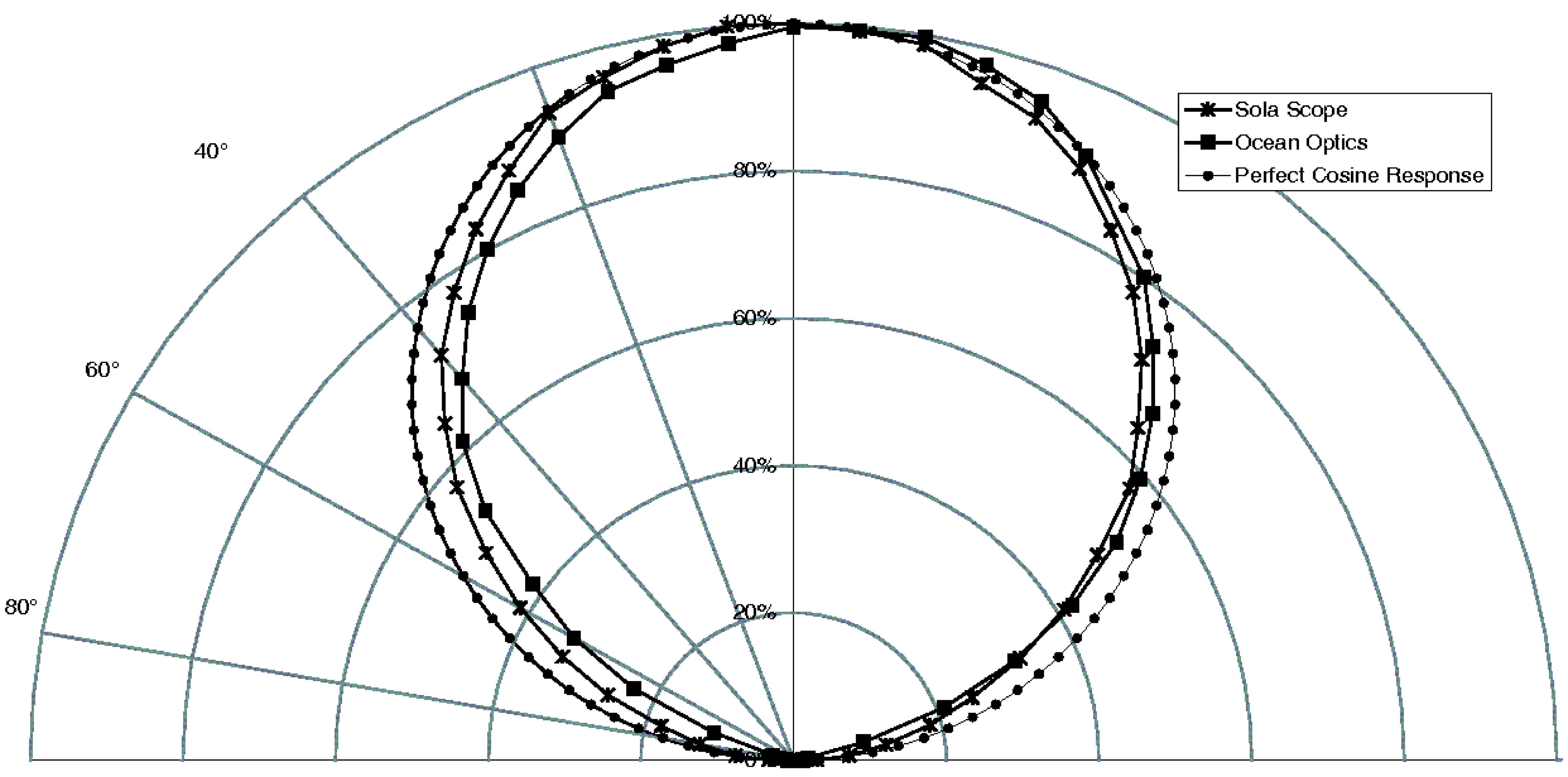

Figure 3. Polar plot to represent spatially the cosine responses (as a percentage of the maximum) of the Ocean Optics and Sola Scope at incident radiation angles from 90° to −90°.

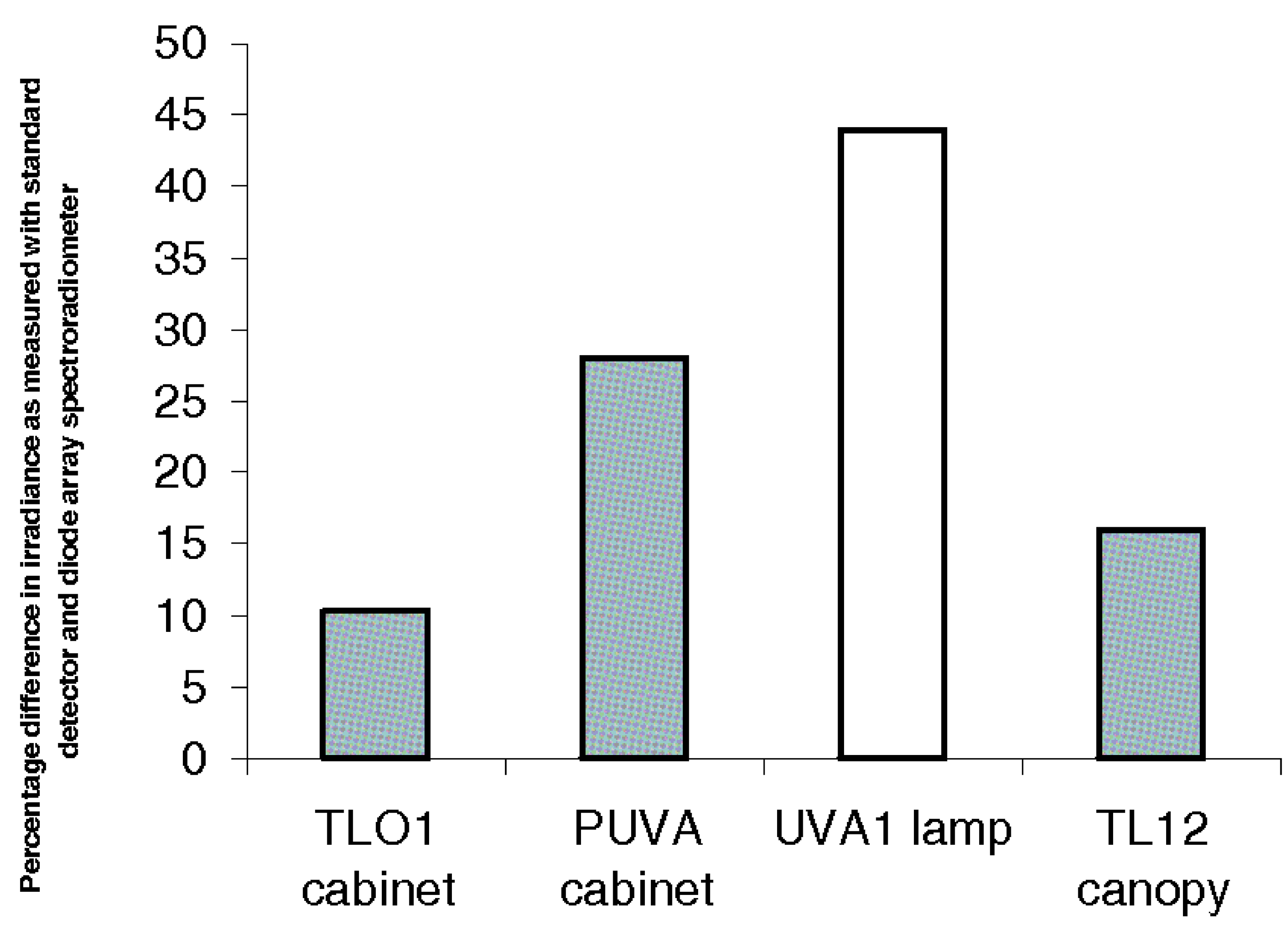

Figure 4. Graph to show the differences in measured irradiances when comparing manufacturer calibrated Sola Scope with IL1400 radiometer and, in the case of the UVA1 lamp, the Bentham spectroradiometer. TLO1 and TL12 values from the integrated irradiance 280–315 nm. PUVA and UVA1 from integrated irradiance 315–400 nm.

3.2. Stray light

The stray light levels with both instruments were significant, as was expected. The method of correcting stray light with the orange filter reduced the stray light significantly. Table 2 shows the stray light ratios if the signal at 250 nm (no irradiance, Schott 1993) is compared with that at 430 nm (maximum irradiance). The levels are significantly reduced when the Sola Scope's stray light compensation method is used and when the calibration is applied to the Ocean Optics' raw signal.

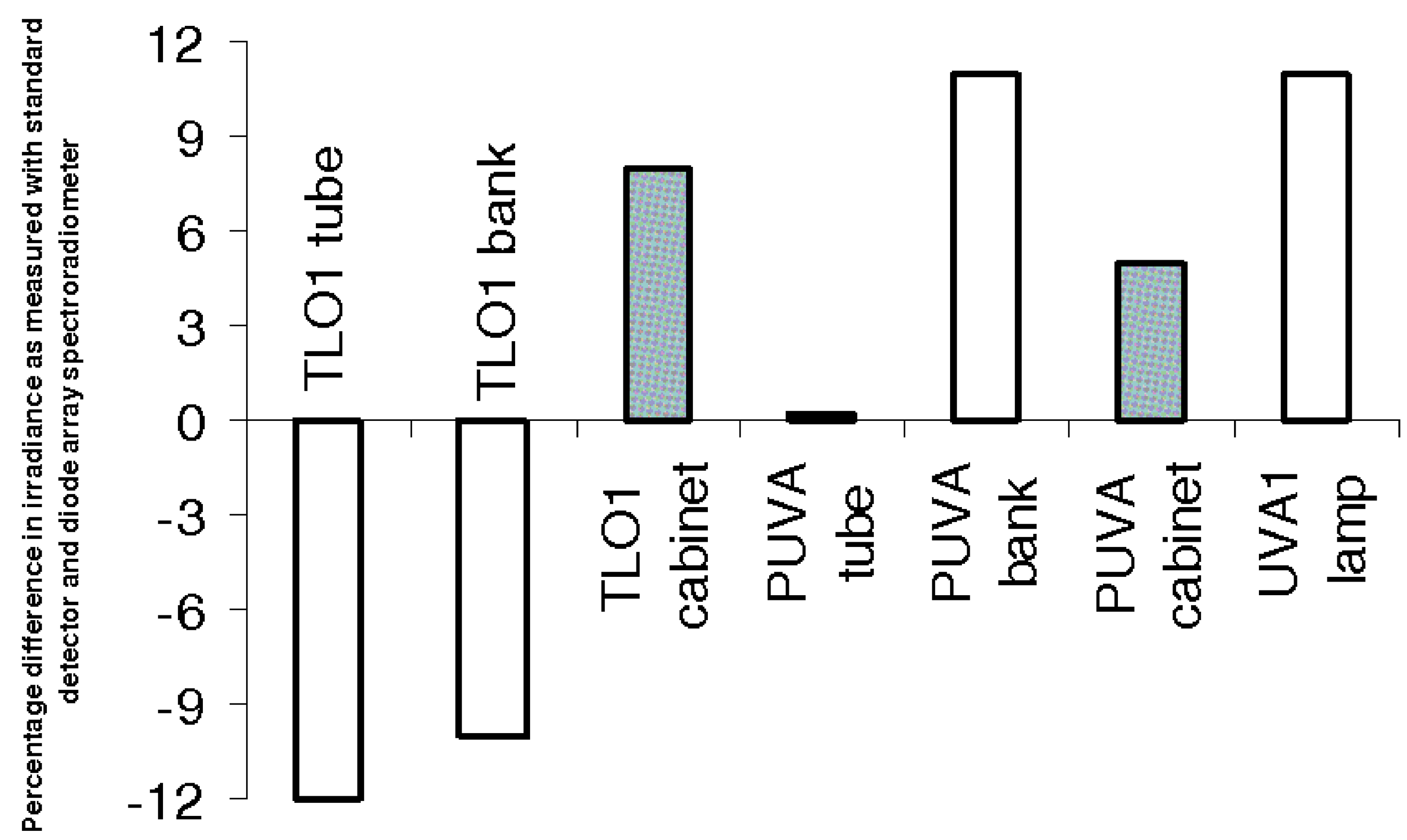

Figure 5. Graph to show the differences in measured irradiances when comparing custom calibrated Sola Scope with Bentham spectroradiometer and, in the case of the cabinets, an IL1400 radiometer. TLO1 values from integrated irradiance 280–315 nm. PUVA and UVA1 from integrated irradiance 315–400 nm.

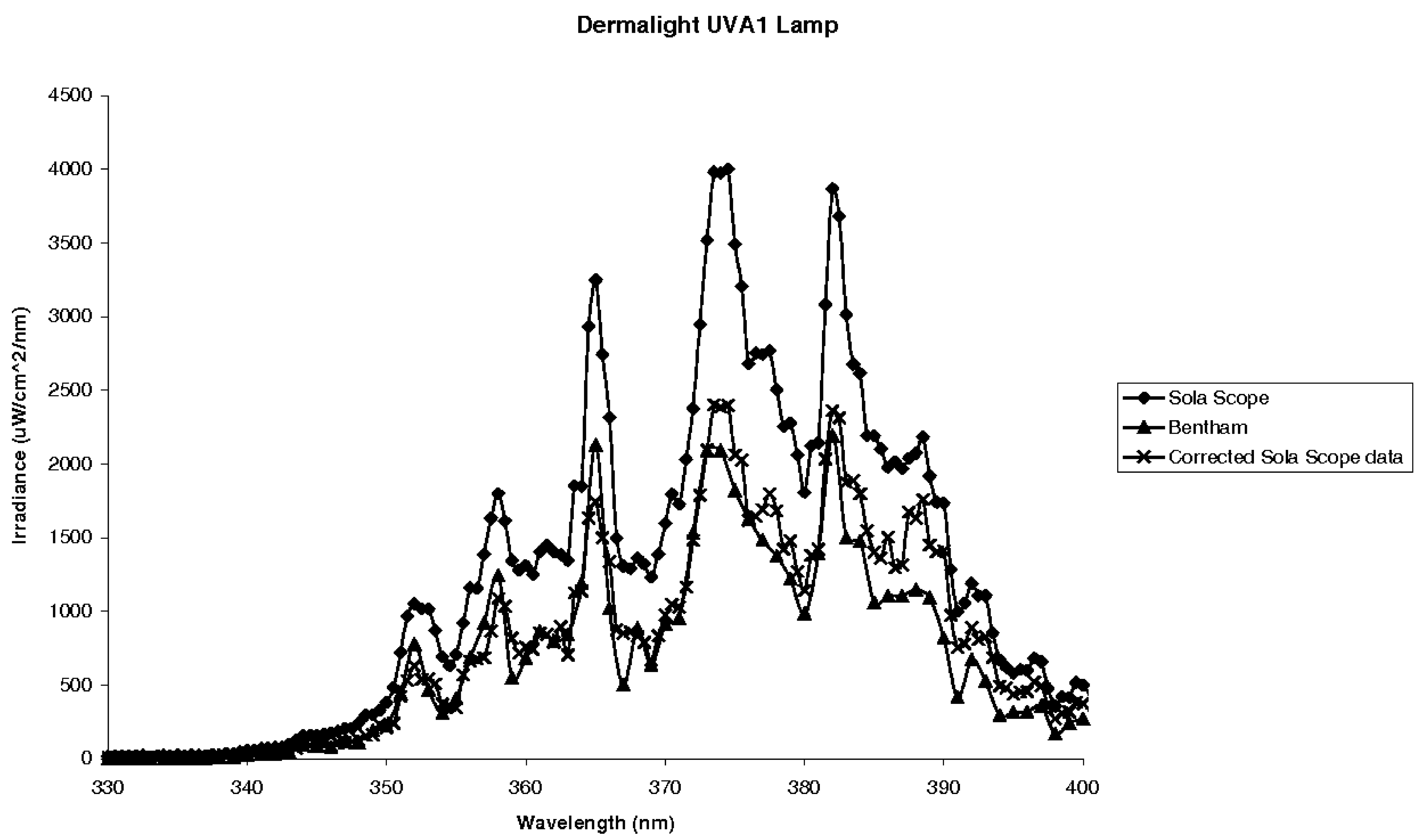

Figure 6. Measurement of a high dose UVA1 source which illustrates the discrepancy that was seen to exist with the Sola Scope's supplied calibration.

3.3. Angular response

The f_2 values for the instruments were both found to be within acceptable limits. For the Sola Scope the value was 5.1% in the plane parallel to its grating and 6.7% in the plane perpendicular to its grating (±60°). This provides an overall f_2 value of 5.9% (±60°). For the Ocean Optics the value was 7.8% (±60°). The cosine responses can also be represented as a polar plot (figure 3).

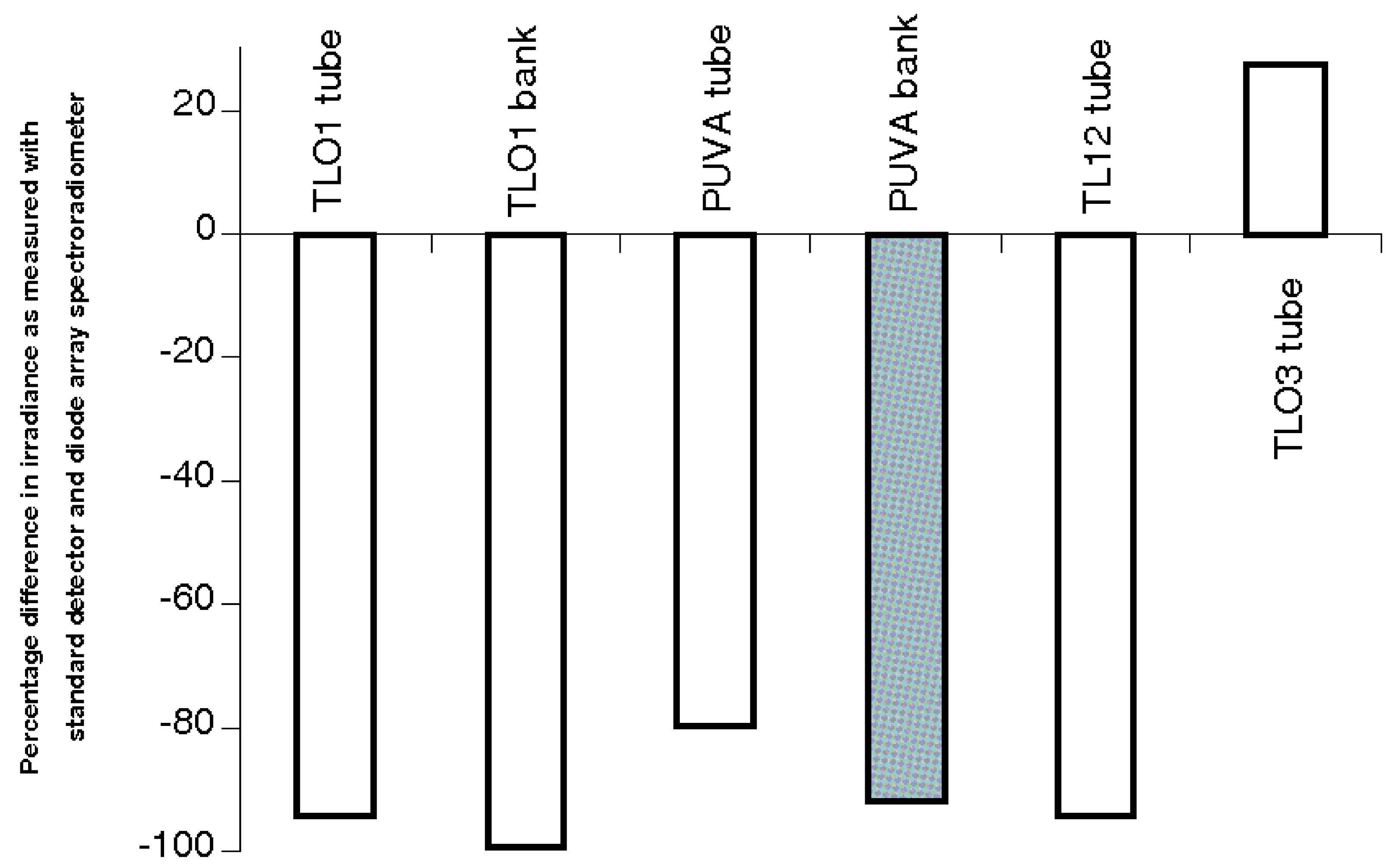

Figure 7. Graph to show the differences in measured irradiances when comparing calibrated Ocean Optics with Bentham spectroradiometer and, in the case of the PUVA bank, an IL1400 radiometer. TLO1 and TL12 values from the integrated irradiance 280–315 nm. PUVA from the integrated irradiance 315–400 nm. TLO3 from the integrated irradiance 400–500 nm.

3.4. Measurement of phototherapy sources

Results from using the Sola Scope revealed wide discrepancies in measured doses when using the supplied calibration (figure 4). The error was most pronounced as an overestimation of the irradiance at the UVA end of the spectrum (see figure 6). Use of the calibration created from measuring the 1 kW FEL lamp reduced these errors significantly (figures 5 and 6).

Measurements of phototherapy sources using the Ocean Optics showed the instrument underestimated the irradiance in all but the cases of a blue light source (figure 7). The recorded spectra were very noisy at low wavelengths and this fact, combined with the low responsivity of the instrument at low wavelengths, produced errors of the magnitudes seen and illustrates that this instrument is not at present sensitive enough to be used for UV radiation dosimetry.

4. Discussion and conclusion

This type of spectroradiometer potentially represents a welcome addition to the instrumentation available to the medical physicist. The portability of the instruments is certainly a very attractive quality and the relative speed and ease of acquiring spectral data is also desirable. However, the potential for inaccuracies in dosimetry has been shown to be significant.

One major issue encountered when calibrating both the instruments was the sensitivity of the detector arrays. Neither instrument proved to have sufficient sensitivity to detect the transfer standards usually employed in the department (see section 3.4). CIE guidelines (1984) recommend that detectors are calibrated against sources with a known spectral intensity and distribution that is similar to or the same as the source to be measured. Thus, the 1 kW FEL lamp employed was not ideal for UVB measurements but the instruments were not sufficiently sensitive to allow the use of a deuterium lamp. The deuterium discharge lamp is also a good approximation of a point source, and would normally be used for measuring the cosine response of any radiometer (Pye and Martin 2000). A xenon arc lamp was a second choice for this measurement but did, however, demonstrate that the f_2 values of both instruments were acceptable.

The Sola Scope is supplied with a calibration derived from a deuterium source but we found that the instrument was not sensitive enough to detect the output from such a lamp. It transpires that the calibration is performed without the cosine diffuser attached to the sensor and a convolution of the transmittance of the diffuser and the responsivity of the detector array is then performed in order to give the final calibration (Ridyard 2002, personal communication). It is possible that uncertainties inherent in this calibration method lead to the error seen in the supplied calibration and subsequent errors when measuring phototherapy sources (see figures 5 and 7). Calibration of the intact instrument using the 1 kW FEL lamp was sufficient to reduce the error in the readings from the instrument to within 12% (figure 5). A calibration method such as this, keeping the instrument intact, would certainly be necessary for any clinical application. Errors of the magnitude that the supplied calibration was producing could certainly lead to patients receiving the wrong dose.

The UV responsivity of the Ocean Optics meant that even using the 1 kW calibration source, recorded spectra were similar to the noise inherent in the instrument. This meant that all the phototherapy sources measured were too low in intensity to give a discernible spectral output and it was only with a largely visible source that the signal was discernible (TLO3). This occurred despite the instrument supposedly being optimized for UV and visible wavelengths. This instrument could have potential in the clinical environment if its quantum efficiency in the UV were increased substantially. The calibration method for this instrument should also be revised. Very few light sources, and certainly not phototherapy sources, match the black body emission spectral profile. Convolution of some calibration source to this emission spectrum, based on colour temperature immediately introduces error into the calibration. The method that was used with the 1 kW FEL lamp would certainly be more satisfactory if the sensitivity issue is addressed.

The stray light levels in measurements from these instruments were high, as expected. It has been shown, however, that it is possible to compensate for the stray light by one of the two methods. An orange glass filter can be used to find the stray light profile for any source being measured and the 'profile' then subtracted from any final spectrum. Alternatively the stray light can be calibrated by including stray light in any spectrum of a calibration source and, therefore, including stray light in the sensitivity factor (SF_λ). The first method is the most favourable because it takes into account different spectral profiles of any source, although it requires two scans of any source to be made which can have potential exposure risks when measuring phototherapy sources.

The Sola Scope instrument currently shows significant potential for use in a clinical environment. The calibration supplied by the manufacturer was unsatisfactory but this could be improved using a high output source and stray light correction. With these modifications in place the errors in measuring phototherapy sources were calculated as being up to 12%, in line with errors inherent in filtered radiometer readings.

The Ocean Optics device should have its sensitivity increased and its calibration protocol re-written before it should be considered for phototherapy dosimetry.

Although there is potential benefit associated with this type of instrument, caution should be advised in its use within a clinical environment. Calibration issues surrounding this type of instrument have not yet been adequately addressed by manufacturers to advocate the replacement of the filtered radiometer in the photomedicine clinic with a device such as this. There would be particular concern over the use of a device such as this by non-specialist staff since errors can be considerable. An erroneous reading of the magnitudes reported in this paper could easily lead to a patient being burned.

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