Comparisons of the biologically effective spectra for erythema and pre-vitamin D_3 synthesis

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Abstract

This paper has compared the short wavelength cut-off (λ_c) and the wavelength of the maximum spectral UV (λ_{Max}) of the spectral pre-vitamin D_3 effective solar UV irradiances (UV_{D3}) and the spectral erythemal UV (UV_{Ery}) at five minute intervals over a six month period for the range of solar zenith angles (SZA) from 4.7° to 80°. Averaged over the entire period, the λ_c for the UV_{D3} is higher by 1.05 nm than that for UV_{Ery}. The λ_{Max} is higher for the UV_{D3} compared to the UV_{Ery} for SZA less than approximately 50°. For higher SZA (>55°)*, the ratio of the λ_{Max} for UV_{D3} to that for UV_{Ery} is less than one. As the erythemal action spectrum extends into the UVA, the ratio of the UV_{D3} to UV_{Ery} irradiances decreases with increasing SZA, along with the decrease in the ratio of the λ_{Max} for UV_{D3} compared to UV_{Ery}. The changes in λ_c and λ_{Max} influence the respective exposures and to take this into account, a dual calibration technique for polysulphone dosimeters has been developed to simultaneously provide both the personal UV_{D3} exposures and the UV_{Ery} exposures.*
Keywords: pre-vitamin D_3; erythema; UV radiation; SZA; short wavelength cut-off.

1 Introduction

Solar UV exposure increases the risk of skin cancers and sun-related eye disorders, while on the positive side sub-erythemal exposures to the UVB portion (290-330 nm) of the terrestrial UV spectrum are required in order to initiate the synthesis of pre-vitamin D_3. This upper limit of 330 nm is based on the action spectrum for the initiation of synthesis of pre-vitamin D_3 (CIE 2006) which includes an extrapolation past 315 nm to 330 nm. There exists a minimum in the relationship between the burden of UV-related disease and UV exposure (Lucas and Ponsonby 2002). Consequently, it is necessary to optimize the UV exposure of humans and finding a balance between over exposure to solar UV and sufficient solar UVB for the initiation of the production of vitamin D. This requires an understanding of the solar UV environment for humans, along with an understanding of the complex interactions between the factors influencing the solar UV environment.

The biologically effective UV irradiance (UV_{BE}) for a specific process is the product of the UV spectrum, $S(\lambda)$ and the action spectrum, $A(\lambda)$ for the respective process, followed by summation over the UV wavelengths, namely (WHO, 1994):

$$UV_{BE} = \sum_{\lambda} S(\lambda)A(\lambda)\Delta\lambda$$

where $\Delta\lambda$ is the wavelength interval. The action spectrum for erythema (CIE 1987) has a different shape to the action spectrum for the initiation of synthesis of pre-vitamin D_3 (CIE 2006). Consequently, the relative amounts of each of these two types of biologically effective UV will vary as the UV changes with different conditions throughout the day and the year and with different locations.

The short wavelength cut-offs (λ_c) of the spectral biologically effective irradiances has been investigated for the erythemal UV (Kollias et al. 2003) and for pre-vitamin D_3 synthesis (Parisi et al. 2007). The short wavelength cut-off is important as the majority of the action spectra have a higher relative effectiveness at the shorter wavelengths. Consequently any variations in λ_c have the potential to cause a change in the biologically effective irradiance for that process. The wavelength at which the maximum spectral irradiances (λ_{Max}) occur for the spectral biologically effective UV is also important as this influences the overall spectral shape of the spectrum of the biologically effective UV that has an influence on the UV exposures.

The biologically effective UV exposures are the factors that determine the end points of the damaging and beneficial influences on living tissues. At high latitudes above 51^o, it has been reported that during some months there is a vitamin D winter where none is synthesised due to solar UV (Webb 2006; Engelsen et al. 2005). At lower latitudes, the exposure times to solar UV to initiate pre-vitamin D_3 synthesis vary with SZA (Samanek et al. 2006). This requires a technique to measure both the personal erythemal UV exposures and the personal pre-vitamin D_3 effective UV exposures that humans receive during periods outdoors. Polysulphone UV dosimeters have been previously employed to measure either the erythemal UV (Davis et al. 1976) or the pre-vitamin D_3 effective UV exposures (Parisi and Wilson 2005). This research has been extended to provide a technique to determine both the erythemal UV exposures and the pre-vitamin D_3 effective UV exposures from one dosimeter measurement. The aim of this research is to compare the λ_c and the λ_{Max} of the spectral biologically effective UV for pre-vitamin D_3 synthesis and for erythemal UV in order to determine if these have any influence on the change with SZA of the respective biologically effective exposures. In order to take into account the influences on the respective exposures, a dual calibration technique will be provided to simultaneously provide both types of biologically effective UV exposures.

2 Methods

2.1 Spectral UV

The spectral UV was measured on a horizontal plane from 1 January 2003 to 30 June 2003 at the Southern Hemisphere site of Toowoomba, Australia (27.6 °S, 151.9 °E, 693 m above sea level). Over this period the average ozone obtained from the TOMS satellites (http://jwocky.gsfc.nasa.gov/ozone/ozone_v8.html) was 265 Dobson Units (DU) with a range of 241 DU to 302 DU. The average of the fraction of cloud cover as measured automatically at five minute intervals with a total sky imager was 0.42 with a range of 0 to 1. Aerosol levels are assumed to be negligible at the site as Toowoomba is a high altitude region with relatively little anthropogenic pollution output. The albedo is typical of an urban area with a mixture of surfaces, for example building roofs, uncovered ground and grass surfaces and asphalt and concrete surfaces. A UV spectroradiometer with double gratings with 2400 lines/mm blazed at 250 nm and with a 600 mm focal length (model DTM300, Bentham Instruments,

Reading, UK) was employed to collect data at five minute intervals from 280 to 400 nm in 0.5 nm increments between 05:00 and 17:00 Australian Eastern Standard Time (EST). Each spectral scan took approximately two minutes with an additional one minute for initialization and a dark current scan as described elsewhere (Parisi and Downs 2004). The instrument was irradiance calibrated against a 150 W quartz tungsten halogen (QTH) lamp with calibration traceable to the National Physical Laboratory, UK standard and wavelength calibrated against the UV spectral lines of a mercury lamp. The instrument is enclosed in a box sealed from the environment. During the data collection period for this paper, the instrument was not temperature stabilised. The manufacturer supplied temperature coefficient of -0.4% /^{o}C has been applied to temperature correct the spectral irradiance data employed in this research. The wavelength shift due to the temperature range was minimal and no correction was required. The uncertainty of the spectral measurements based on the cosine error and the temporal stability of the spectroradiometer is estimated as ±6% (Parisi and Downs 2004).

2.2 Erythemal and pre-vitamin D_3 synthesis spectra

The action spectrum for the synthesis of pre-vitamin D_3 (CIE 2006) was employed to calculate the horizontal plane spectral pre-vitamin D_3 effective solar UV irradiances (UV_{D3}). The action spectrum was linearly interpolated to 0.5 nm points and each of the UV spectra was weighted accordingly. This action spectrum contains an extrapolation to 330 nm. There is a small influence on the UV_{D3} as a result of the summation being undertaken over more wavelengths. The amount of this influence has been calculated for all of the data in February and the extrapolation of the action spectrum from 315.5 to 330 nm has increased the UV_{D3} by an average of only 7%. However, there is no influence of this extrapolation on the λ_c and λ_{Max}. Each of the UV spectra was also weighted with the erythemal action spectrum (CIE 1987) to calculate the spectral erythemal UV (UV_{Ery}) at each of the times that the spectral UV_{D3} was calculated.

For each biologically effective spectrum, the wavelength of the maximum spectral irradiances (λ_{Max}) was calculated for the UV_{D3} and UV_{Ery}. The short wavelength cut-offs for the spectral UV_{D3} and UV_{Ery} were defined as the wavelengths at which the respective spectral irradiances were 0.1% of the respective maximum biologically effective irradiances for each scan.

2.3 Erythemal and pre-vitamin D_3 exposures

The differences in the action spectra for erythema and pre-vitamin D_3 provide different exposures for UV_{D3} and UV_{Ery} for the same solar spectra. The spectral response of polysulphone is predominantly at the shorter UV wavelengths with no response for wavelengths longer than 330 nm (CIE, 1992). Polysulphone UV dosimeters have been previously employed to measure either the UV_{Ery} exposures or the UV_{D3} exposures. These two measurements have been combined to determine dual

calibrations to simultaneously measure both types of biologically effective UV exposures.

Polysulphone dosimeters produced by the authors at the University of Southern Queensland were exposed on a horizontal plane to a series of UV exposures while the UV spectra were concurrently measured at each five minutes with the UV spectroradiometer. The calibration was undertaken at Toowoomba on 17 July between 9.00 EST (Australian Eastern Standard Time) and 13.00 EST for the SZA range of 65^o and 51^o during a relatively cloud free period. Each spectrum was weighted with the appropriate action spectrum to produce the UV_{D3} and UV_{Ery} irradiances. Simpson's rule (numerical integration) was then employed to calculate the UV_{D3} and UV_{Ery} exposures for each period of exposure for the dosimeters. The change in absorbance (delta A) for each dosimeter after each period of exposure was measured in a UV spectrophotometer (UV1604, Shimadzu Co., Kyoto, Japan) at 330 nm at four locations over the dosimeter. The UV_{D3} and UV_{Ery} exposures for each period were plotted against the corresponding delta A values to provide dual calibration curves that allow determination of both of the UV_{D3} and UV_{Ery} exposures from one delta A measurement of an exposed dosimeter.

3 Results

3.1 Wavelength of maximum

For a solar zenith angle (SZA) of 13.8^o on 12 February 2003 at the cloud free time of 12:00 AEST (Australian Eastern Standard Time), a sample solar UV spectrum and the associated spectral UV_{Ery} and UV_{D3} are provided in Figure 1. The action spectrum for the synthesis of pre-vitamin D_3 (CIE 2006) and the erythemal action spectrum (CIE 1987) are plotted on the axis on the right side. At this SZA of 13.8^o, the λ_{Max} in the spectral UV_{D3} shifts to longer wavelengths compared to that for the spectral UV_{Ery}. The reason for this is that the action spectrum for the synthesis of pre-vitamin D_3 is shifted to longer wavelengths compared to the erythemal action spectrum.

The ratio of the λ_{Max} wavelengths for the UV_{D3} and the corresponding UV_{Ery} over the six month period are provided in Figure 2 for the SZA range from the minimum SZA of 4.7^o to 80^o. The λ_{Max} for each of the UV_{D3} and UV_{Ery} are provided in Table 1. The data is plotted as the average over each of the SZA ranges of less than 10^o, 10.01-20^o, 20.01-30^o, 30.01-40^o, 40.01-50^o, 50.01-60^o, 60.01-70^o and 70.01-80^o. This takes into account the range of atmospheric and cloud conditions encountered over the six month period. The ratio is higher than one for SZA of less than approximately 50^o. As the SZA increases beyond 40^o, the ratio starts reducing and for SZA of higher than 50^o, the ratio is predominantly less than one.

The reason for this can be seen by considering the ratio of the UV_{D3} irradiances to the respective UV_{Ery} irradiances for the different SZA (Figure 3). The ratio is reasonably constant and then starts to reduce for SZA greater than 40^o. This is due to the longer

path through the atmosphere at the higher SZA causing a reduction in the relative proportion of UVB to UVA irradiances. Coupling this with the differences between the two action spectra (Figure 1), where the erythemal action spectrum extends into the UVA, causes the UV_{D3} to UV_{Ery} irradiance ratios to decrease. Furthermore, as UVB is scattered more readily than UVA the diffuse UVB radiation from the sky exceeds the direct UVB from the sun except for a few hours around solar noon. However, the direct component of UVA is greater than the diffuse for most of the day with the exception of a few hours in the early morning and evening.

3.2 Short wavelength cut-off

The variation during the day of the short wavelength cut-offs on 8 January for the UV_{D3} and UV_{Ery} are plotted at each five minute intervals in Figure 4. On this day, the cut-off wavelengths range from 290 nm at noon to 297 nm at 06:00 and 18:00 EST. The differences of λ_c between UV_{D3} and UV_{Ery} are plotted on the right axis. For the UV_{D3}, the λ_c are shifted to higher wavelengths by an average of ~1 nm. The variation in the difference throughout the day is only minimal with the main noticeable difference being that at the higher SZA in the morning and afternoon, the range of differences is higher. A possible reason for this is that at the higher SZA, the signal level is low and the relatively higher noise results in a larger uncertainty and causes the larger range of differences.

The difference of the λ_c for the UV_{D3} compared to those for UV_{Ery} for the range of SZA encountered over the six month period are provided in Figure 5. The data is plotted as the average over each of the SZA ranges. Averaged over the six month period, the difference between the λ_c for UV_{D3} and UV_{Ery} was 1.05 nm. The minimum is 0.91 nm for the 0-10^o range and the maximum is 1.2 nm for the 70.01-80^o range.

3.3 Erythemal and pre-vitamin D_3 exposures

The calibration of the UV dosimeters that provides both the UV_{D3} and UV_{Ery} exposures is provided in Figure 6. This calibration has to be repeated for the conditions that will be encountered during each field campaign to measure the personal UV_{D3} and UV_{Ery} exposures. This calibration is valid only for the conditions at the latitude of the calibration site and the SZA range of 65^o to 51^o encountered during the calibration. The R^2 for each curve that has been fitted is 0.99. Nevertheless by employing this dual calibration technique, one dosimeter can be employed to provide the two types of personal exposures that are simultaneously received to a specific anatomical site.

4 Discussion

This paper has compared the λ_c and the λ_{Max} wavelengths of the UV_{D3} and the UV_{Ery} spectral irradiances at each five minute interval when the equipment was operational between dawn and dusk over a six month period for the range of solar zenith angles from 4.7^o to 80^o. A total of 12,496 spectra were measured. The range covers the

atmospheric and cloud conditions encountered for this period. The λ_c for the UV_{D3} is higher by 1.05 nm than that for UV_{Ery} when averaged over the six month period. Despite the variations in SZA and in the atmospheric and cloud conditions throughout each day over the six month period, the average over each SZA range for the difference between the two λ_c values only varies between 0.91 nm to 1.2 nm.

In comparison, the λ_{Max} varies to a certain extent with SZA. The λ_{Max} is higher for the UV_{D3} compared to the UV_{Ery} for SZA less than approximately 50^o. For higher SZA, the ratio of the λ_{Max} for UV_{D3} to that for UV_{Ery} is less than one. This is due to the influence of the shapes of the action spectra as the action spectrum for the synthesis of pre-vitamin D_3 is shifted to longer wavelengths between 300 and 315 nm compared to the action spectrum for erythema. However as the SZA becomes larger, the longer path through the atmosphere causes a decrease in the relative proportions of UVB to UVA irradiances. As the erythemal action spectrum extends into the UVA a great deal more significantly than that for the vitamin D, the ratio .of the UV_{D3} to UV_{Ery} irradiances decreases, along with the decrease in the ratio of the λ_{Max} for UV_{D3} compared to UV_{Ery}. The consequence of this is that at high latitudes above 51^o, it has been reported that during some times of the year, no pre-vitamin D_3 is synthesised due to the low levels of solar radiation (Webb 2006; Engelsen et al. 2005). However, the λ_c is longer for the UV_{D3} compared to that for the UV_{Ery} for the range of SZA. Consequently, it is the ratio of the two irradiances and the ratio of the λ_{Max} for the two irradiances that changes with SZA. The influences on the UV_{D3} and UV_{Ery} affect the respective exposures and to take this into account, a dual calibration technique has been developed to simultaneously provide both the personal UV_{D3} exposures and the UV_{Ery} exposures. These can be measured from any anatomical site on humans during normal daily activities to simultaneously provide information on both the beneficial and damaging effects of UV exposure. With the appropriate calibration, this can be done for any range of SZA, cloud and atmospheric conditions encountered.

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Table 1 – The average of the λ_{max} in the SZA ranges for each of the UV_{D3} and UV_{Ery}.

SZA range (^{o})	λ_{max} UV_{D3} (nm)	λ_{max} UV_{Ery} (nm)
0-10	306.2	304.0
10.01-20	306.8	303.6
20.01-30	306.9	303.9
30.01-40	307.0	304.9
40.01-50	307.0	307.0
50.01-60	307.1	310.2
60.01-70	309.7	310.5
70.01-80	310.5	312.4

Figure Captions

Figure 1 – (a) The erythemal action spectrum (1) and action spectrum for the synthesis of pre-vitamin D_3 (2) plotted on the right axis, along with a typical UV spectrum at an SZA of 13.8^o plotted on the left axis with the (b) corresponding spectral UV_{Ery} (thin line) and UV_{D3} (thick line).

Figure 2 – The ratio of the λ_{Max} for UV_{D3} compared to that for the corresponding UV_{Ery}, plotted as averages over each of the SZA ranges.

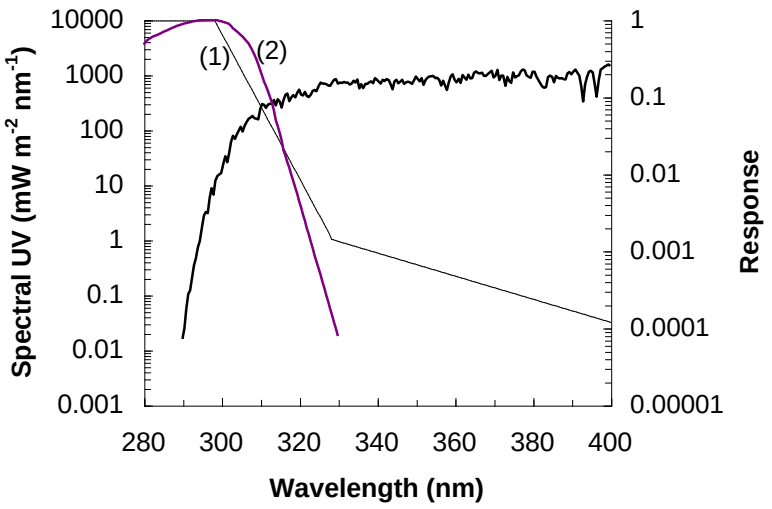
Figure 3 – Ratio of the irradiances for UV_{D3} compared to that for the corresponding UV_{Ery}.

Figure 4 – Short wavelength cut-offs during the day on 8 January for the UV_{D3} (◊) and UV_{Ery} (♦) and the differences (x) plotted on the right axis at each five minute interval.

Figure 5 - The difference of the λ_c for UV_{D3} compared to that for the corresponding UV_{Ery}, plotted as averages over each of the SZA ranges.

Figure 6 – UV dosimeters with a calibration that provides both UV_{Ery} (■) and UV_{D3} (♦) exposures.

(a)



(b)

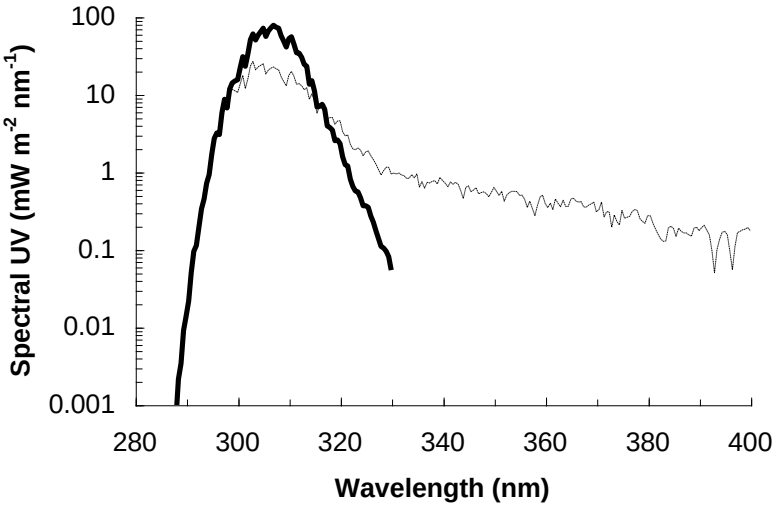


Figure 1 – (a) The erythemal action spectrum (1) and action spectrum for the synthesis of pre-vitamin D_3 (2) plotted on the right axis, along with a typical UV spectrum at an SZA of 13.8^o plotted on the left axis with the (b) corresponding spectral UV_{Ery} (thin line) and UV_{D3} (thick line).

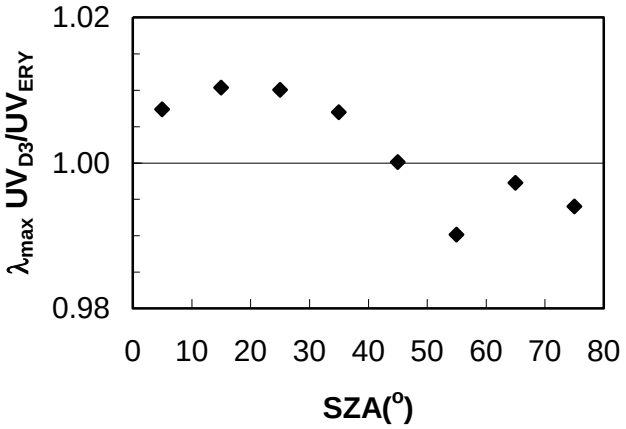


Figure 2 – The ratio of the λ_{Max} for UV_{D3} compared to that for the corresponding UV_{Ery}, plotted as averages over each of the SZA ranges.

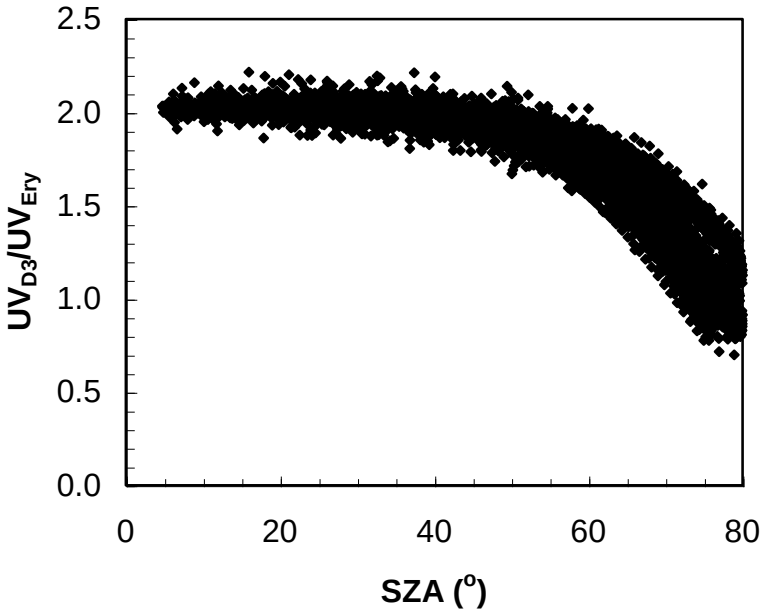


Figure 3 – Ratio of the irradiances for UV_{D3} compared to that for the corresponding UV_{Ery}.

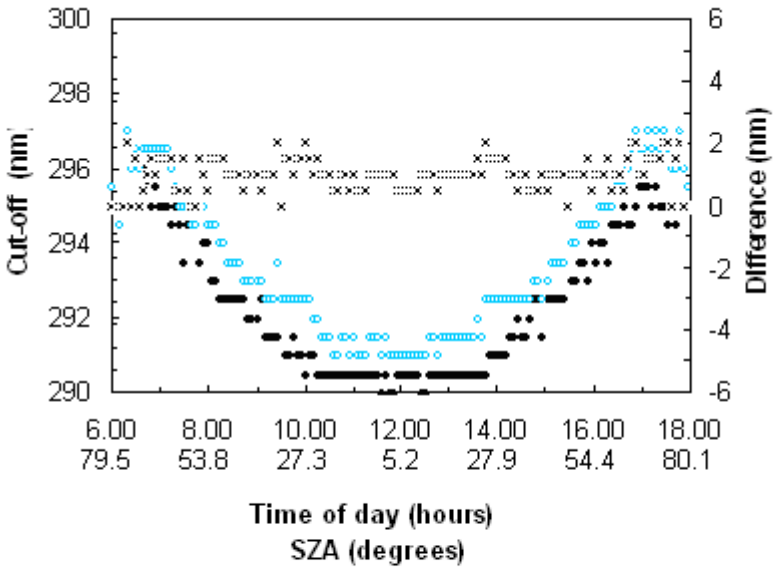


Figure 4 – Short wavelength cut-offs during the day on 8 January for the UV_{D3} (◊) and UV_{Ery} (♦) and the differences (x) plotted on the right axis at each five minute interval. The x axis shows the time of day and the SZA.

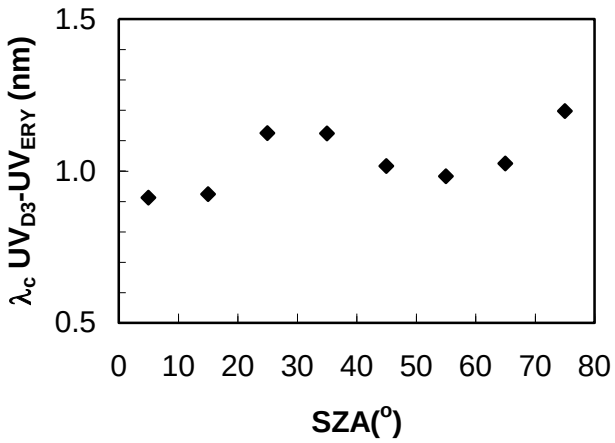


Figure 5 - The difference of the λ_c for UV_{D3} compared to that for the corresponding UV_{Ery}, plotted as averages over each of the SZA ranges.

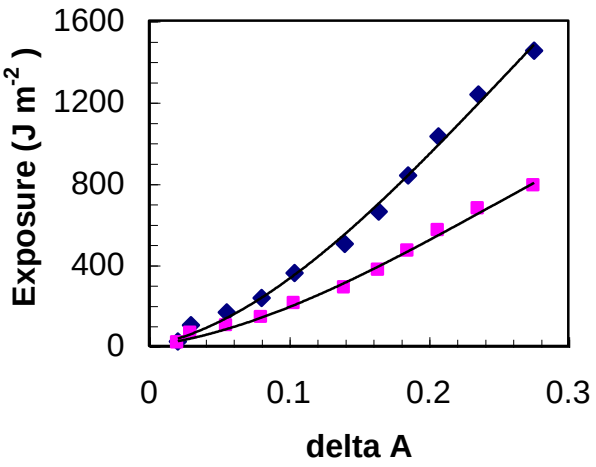


Figure 6 – UV dosimeters with a calibration that provides both UV_{Ery} (■) and UV_{D3} (♦) exposures.