Intercomparison of erythemal broadband calibrations performed by AEMET and INTA laboratories

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1. INTRODUCTION

The aim of this study is to compare the calibration methods of erythemal irradiance radiometers in broadband between the AEMET Radiation Laboratory and the INTA's Atmospheric Sounding Radiometric Station of El Arenosillo, in terms of measures as well as attending to the calculations used to get the calibration factors.

To this end the whole process of calibration of two radiometers YANKEE UVB-1, each one belonging to one of the implied agencies, is carried out in both laboratories during September 2009. This process includes the characterization of each instrument in the laboratory to get its relative spectral and angular response, and their absolute calibration through a spectral reference instrument using the sun as source.

Next step consist of the comparison of the processes, the calibration factors and final data (erythemally weighted irradiance) derived from both laboratories. This work follows the guidelines established by the intercomparison of seven UV calibration laboratories in Europe and USA -Hülsen et al. 2008-, with the European Ultraviolet Calibration Center (EUVC) of PMOD/WRC as reference laboratory and INTA laboratory as one of the participants.

Finally in order to validate the calibration procedure, the erythemally weighted irradiance measured will be compared between the radiometers and the European standard for the spectral UV measurement, QASUME (Quality Assurance of Spectral UV Measurements in Europe). This comparison can be carried out taking advantage of the QASUME visit during the calibration periods (September 2009), both in the AEMET as in El Arenosillo.

2. METHODOLOGY

Broadband radiometers are designed for the measurement of weighted solar irradiance in reference to the erythemal response. The whole calibration of a broadband UVB radiometer consist of obtaining the factors that convert the instrument output signal (measured in volts) into radiometric units (effective erythemal irradiance).

The general calibration equation is given by the expression:

$$E_{CIE} = (U - U_{dark}) Cf_n (SZA, T_{O3}) Coscor \qquad (1)$$

Where

- E_{CIE} is the effective erythemal irradiance

- U_{dark} is the instrument dark signal, and can be calculated daily by averaging the nightly data (SZA>100º)
- $fn(SZA,TO_3)$ is the calibration matrix, which indicates the instrument's sensitivity to changes on ozone and solar zenith angle. This matrix elements are get out from the spectral response obtained in the laboratory and using the radiative transfer model libradtran (Mayer and Killing 2005):

$$f(SZA,TO_3)=\frac{\int E_{rad}\left(SZA,TO_3,\lambda\right)CIE\left(\lambda\right)d\lambda}{\int E_{rad}\left(SZA,TO_3,\lambda\right)RSE\left(\lambda\right)d\lambda} \qquad (2)$$

E_{rad} is the solar spectrum, estimated with the radioactive transfer model for different solar zenith angles (SZA) and ozone column contents (TO_3)
RSE is the radiometer spectral response obtained in the laboratory
CIE is the erythemal action spectrum

This matrix $fn(SZA,TO_3)$ is normalized for SZA=40º and TO_3=300 DU

- $Coscor$ is the cosine correction function, and is calculated as:

$$\cos cor(\theta)=\frac{1}{f_{glo}} \qquad (3)$$

Where f_{glo} is the cosine error of the instrument, which depends on the distribution of the radiation incident direct and diffuse components

$$f_{glo}=f_{dir}\frac{E_{dir}}{E_{glo}}+f_{dif}\frac{E_{dif}}{E_{glo}}$$

f_{dir} represents the direct cosine error and is obtained from the angular response obtained in the laboratory in respect of the ideal response:

$$f_{dir}=\frac{angres(SZA)}{\cos(SZA)} \qquad (4)$$

f_{dif} is the diffuse cosine error calculated by assuming a homogeneous distribution of radiation and integrating over the whole hemisphere.

$$f_{dif}=2\int_0^{\pi/2} angres(\theta)sen\theta d\theta \qquad (5)$$

The direct and diffuse components of radiation (E_{dir} and E_{dif}) are estimated using the same radiative transfer model.

According to the cloud conditions during the measurements, the suitable cosine correction will be:

- For clear skies global correction f_{glo} is applied, and direct and diffuse components are taking into account. This is a function of the SZA.
- For overcast skies or rapid changes in cloud cover the diffuse correction, a constant value independent of the angle, is used.

- C is the absolute calibration factor and is calculated applying the Equation Calibration General (1) for the outdoor measures.

  For each radiometer-spectroradiometer simultaneous observation a constant value is obtained:

$$C_i = \frac{E_i}{U_i - U_{dark}} \frac{1}{Coscor} \frac{1}{f_n(40,300)} \tag{6}$$

E_i is the solar spectrum measured by the spectroradiometer and weighted with the spectral response of the radiometer

U_i is the average of the radiometer signal during the solar spectrum scan

$f_n(40,300)$ is the calibration matrix value for SZA= 40 ° and ozone=300 DU

The calibration factor is calculated as the average value of the Ci obtained during the calibration days, which should be days of clear skies.

3. CALIBRATION IN THE AEMET RADIOMETRIC LABORATORY:

The whole calibration process of the two UVB-1 radiometers (one belonging to AEMET and the other to INTA) is carried out in the AEMET lab.

The INTA radiometer (serial number 990608) arrives at AEMET headquarters on July 13th 2009 from La Rábida. Condensation is observed inside the dome, so in order to make it disappear, desiccant is changed many times with no result. Permission is asked to INTA for open and dry it as well as to change the internal desiccant. Finally condensation is eliminated and the outdoor measurements are checked, seeing those are in the right range.

The AEMET radiometer (serial number 030520) belongs to the Radiometric Laboratory. It has taken part in the UV broadband radiometers intercomparison of El Arenosillo in 2007 and has been taken to Davos in summer 2008 to be calibrated, so reference information concerning its calibration factors has been already provided.

At the end of August, both radiometers are characterized in the laboratory, and on September the 1st they are placed in the roof of the Radiometric Center for their outdoor calibration. Spectral measurements are taken simultaneously with the Bentham DTM300 spectroradiometer and with the Brewer186 spectrophotometer, both owned by AEMET. Besides the equipment also counts on the scans given by the QASUME unit, brought to Madrid for those days to calibrate the UV Bentham DTM3000.

Characterization in the laboratory:

Radiometers are calibrated in the laboratory where they have been connected the previous day in order to ensure their stability. The radiometers inside temperature can not be monitored because the meter used to this end doesn't work well during the characterization. In reference to the AEMET radiometer, days after can be checked that its inside temperature is maintained between 46.8 and 47.0ºC, whereas the INTA's radiometer can not be measured.

a) Spectral response:

The system settled to get the spectral response consist of a Bentham DM150 double monochromator with 2.400 lines/mm diffraction grating, and the slit width chosen produces approximately a 2 nm FWMH. The light source is a Xenon lamp of 150 W. At the monochromator's exit, a beam splitter sends part of the signal to the radiometer settled inside the dark camera, and part to a photodiode that measures the lamp fluctuations in order to correct the measurements. The system's function of transmission has been previously got out from the measurements taken with a photodiode (Bentham DH-Si 7487/4) calibrated at PMOD/WRC.

The BenWin+ software used in this process includes the previous measurement of the dark signal and the correction to every data.

The relative spectral response of the radiometers is obtained in the following terms:

-Range: 270 to 400 nm
-Step: 1nm
-Number of samples for each value: 5
-Normalized for the maximum value

b) Angular Response:

The light source is a 450 W Ozone free Xenon lamp, placed three meters away from the radiometer, which has been settle inside the camera, on a 0.001º angular resolution goniometer. The radiometer is rotated to obtain measurements for different incidence angles. The rotation axis passes through the radiometer's reception plane.

Two angular responses are got with the radiometer orientated in two different positions, in order to obtain the measures for the four quadrants (N, S, E and W), being N the direction of the connector. The response is got:

-Range: -90º to 90º
-Step: 1º
-Number of samples for each value: 5
-Normalized for the normal incidence angle value.

Absolute Calibration:

Absolute calibration is carried out at the AEMET headquarters roof, by comparing the radiometer measurements with a spectral reference instrument using the sun as source. The reference taken is the double monochromator Brewer 186, that has been working during the campaign days in its ordinary measurement schedule such as the rest of the Brewer net of AEMET. This yields about 30 UV daily scans.

The Brewer measures the solar spectra in a range of 286.6 to 363.0 nm, with a step of 0.5 nm, so they must be extended up to 400 nm in order to get the erythemally weighted irradiance. The extrapolation is done with the Martin Stanek UVBrewer software. Besides, it is applied to the Brewer spectra the QASUME calibration gotten by comparison in El Arenosillo (2009), in order to correct the measures with the spectral UV standard.

On September the 1st the radiometers are installed at the roof of the Radiometric Center, close to both spectral instruments.

Measurements are taken between September the 1st and the 5th (244 and 248 julian days). The meteorological conditions on these days are characterized by clear skies with some clouds (especially cirrus) in the afternoon of the 244, 245 and 248. In order to calculate the absolute calibration factor, the chosen measures are those corresponding to the SZA<75º of the two clear days (246 and 247) which yields a dataset of 44 Brewer scan.

Regarding to the radiometers, the data used are the minute averages of measurements taken every ten seconds. The dark signal of the instruments is obtained from the night measurements.

While the Brewer sweeps across the whole measurement range (with a scan duration of 4.5 minutes) the radiometer provides with integrated measures every minute. In order to compare simultaneous measures of both instruments, the radiometer measurements are chosen for each scan at the time of the maximum erythemal effectiveness wavelength. Besides, to obtain the absolute factor, only clear days are chosen to avoid sudden changes in the meteorological conditions that would induce to mistakes in the calculations.

The average daily ozone values (measured with the Brewer186) and meteorological conditions during the outdoor calibration days are as follow:

date	day	ozone average	weather conditions
01/09/2009	244	291	cirrus + cluster from the 15 h
02/09/2009	245	295	cirrus + cluster from the evening
03/09/2009	246	285.7	clear sky, cirrus 8 to 9 h
04/09/2009	247	278.5	clear sky
05/09/2009	248	285.6	clear sky with some clouds

4. CALIBRATION IN THE INTA RADIOMETRIC LABORATORY (EL ARENOSILLO):

The whole calibration process of both radiometers (characterization in the laboratory and outdoor calibration) are carried out in the INTA facilities (El Arenosillo) in September from the 7th up to 13th, just after the same process in Madrid, so the radiometer properties are supposed not to have suffered any change in the time between calibrations.

Characterization in the laboratory:

In order to obtain the spectral response the light source is a 450 W. Xenon lamp linked to a Gemini 180 (FWHM 2nm) monochromator with an integration sphere at its end that provides light to the radiometer as well as to a reference photodiode radiometer calibrated in the PMOD/WRC. Those measurements allow obtaining the radiometer relative spectral response in the range 280 to 400 nm (step 1nm).

About the angular response, the light source is a 1000 W halogen lamp placed on top of a vertical arm and aligned with the radiometer placed over a goniometer that rotates, so measurements are obtained changing the incidence angle of -90º to 90º step 2º. The response is made only in one sense.

Absolute calibration:

To this aim, the chosen reference is the Brewer 150, double monochromator system with a correction introduced to eliminate the cosine effect, placed on the roof of the Atmospheric Sounding Station of El Arenosillo.

During this period, and in coincidence with the Brewer spectrophotometer correcting campaign, the QASUME European standards are taken into account.

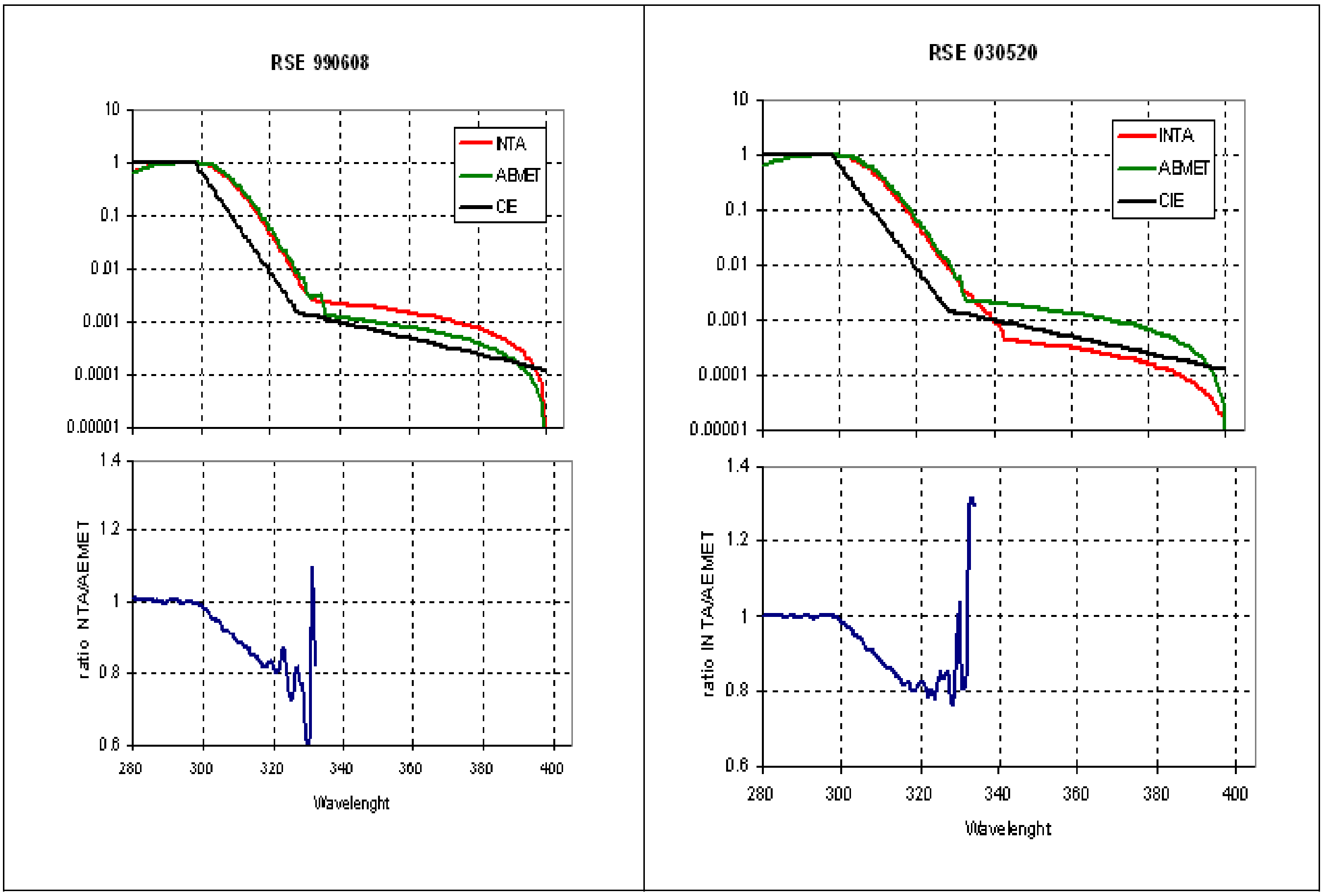
5. INTERCOMPARISON RESULTS:

In this section the results of the calibrations made in both laboratories for each radiometer are showed and compared between themselves, as well as the derived correction factors. Following, the outdoor measurements of each radiometer processed with both calibrations (AEMET and INTA) will be analyzed with respect to the laboratory characterization and compared to the QASUME data to check the consistence of the whole calibration process.

Spectral response and calibration matrix:

Spectral responses obtained in both laboratories accurately reproduce the quick decrease in the instruments response between 300 and 340 nm. At longer wavelengths, the radiometers signal is very low and RSE can’t be accurately measured. Specifically, the high level of noise in the AEMET laboratory makes it impossible to get valid measurements over 336 nm.

Figure 1 shows each radiometer relative spectral response derived by both laboratories as well as the CIE response. At the bottom, it is shown the INTA/AEMET ratio. It is noted that in the 280 to 335 nm interval, the differences between the responses provided by both laboratories do not exceed +/- 20% and would be due to a slight wavelength shift between the two systems. These differences can be considered “consistent” according to the comparison results obtained between different laboratories (Hülsen et al. 2008): “The agreement between the measurements is fairly consistent in the shorter wavelength range up to 340 nm, with deviations not exceeding +/- 20% for most institutes”. The differences found would be due to a slight wavelength shift between the systems that will be investigated.



RSE 990608

RSE 030520

Fig. 1: Relative spectral response as measured in both laboratories and the ratio INTA/AEMET

Anyway, derived calibration matrices (eq. 2), representing the instrument's sensitivity to changes in the ozone level and solar zenith angle (SZA), are also analyzed in respect to the laboratory characterization and the radiative transfer model used.

Figure 2 shows, for each radiometer, the values of the calibration matrices for ozone levels of 200, 300 and 400 DU, and the ratio INTA/AEMET for these same values. It can be noticed that the difference between the matrices calculated in both laboratories increases as well as the SZA increases, and this increase is more significant for higher ozone levels. Analyzing the results for each radiometer it can be seen that:

- For the YES 990608 radiometer the differences between laboratories do not exceed 2% at angles less than 60°and reaches 4% when the SZA = 70º
- For the YES 030520 differences are over 4%, and there are significant differences between 200 and 400 DU

In order to analyze these differences and to check if they are due to differences in the process of the matrix calculation or in the radiative transfer model used to estimate the erythemal irradiance in the different ozone values, the matrix has been calculated through the AEMET model (LibRadtran) and procedure using the spectral response obtained in INTA laboratory. The obtained matrix is identical to the INTA’s matrix, wich indicates that differences between the calibration matrices are originated by differences in the spectral response.

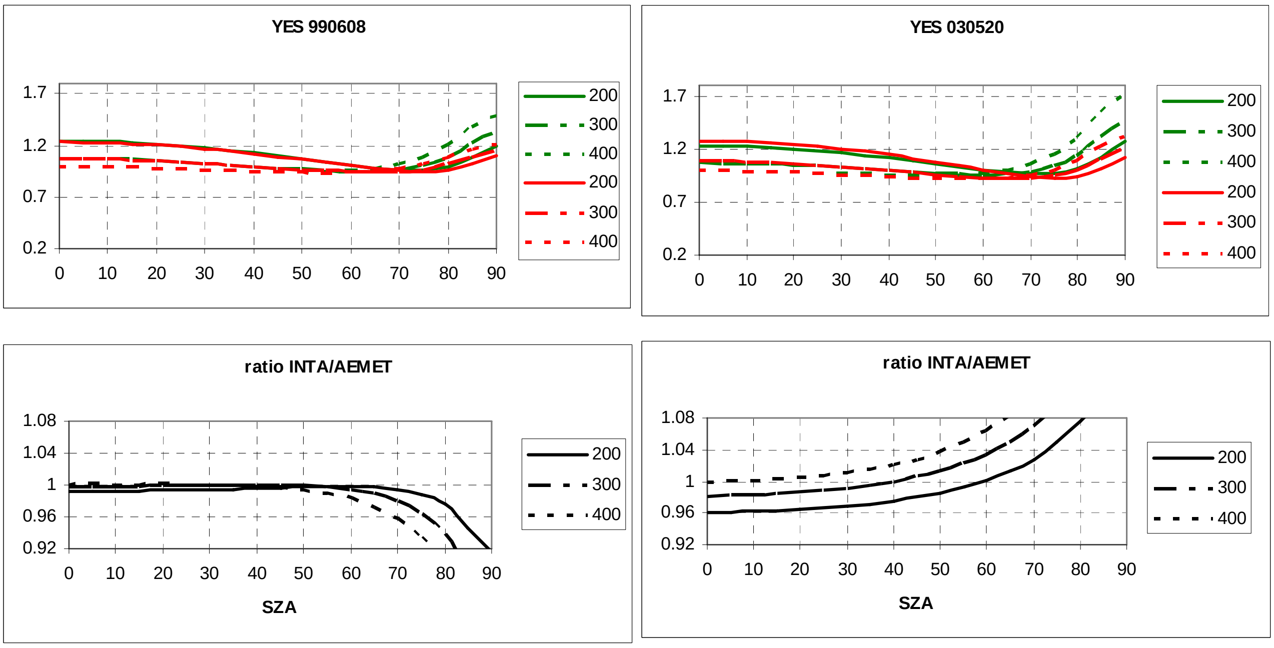


Fig. 2: Calibration matrix *f* in dependence of SZA for 200, 300 and 400 DU calculated using the RSE measured by INTA (red line) and AEMET (green line). The ratios INTA/AEMET are shown in the bottom.

Angular response and cosine correction

Figure 3 shows the average angular response function (ARF) obtained in both laboratories for each radiometer, as well as the ideal cosine response.

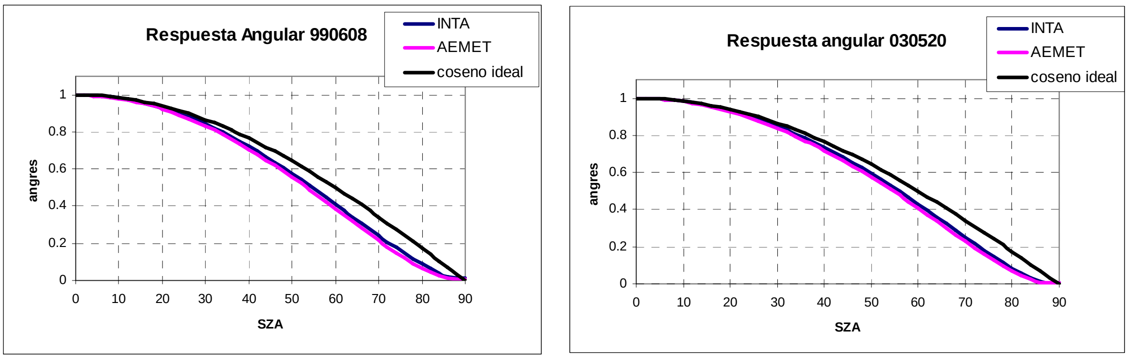


Figure 3: Angular response as measured in both laboratories and ideal response

Figure 4 shows the cosine errors derived from the measured ARF (eq. 4). The differences between the measurement performed at both laboratories do not exceed 5% for zenith angles less than 60º

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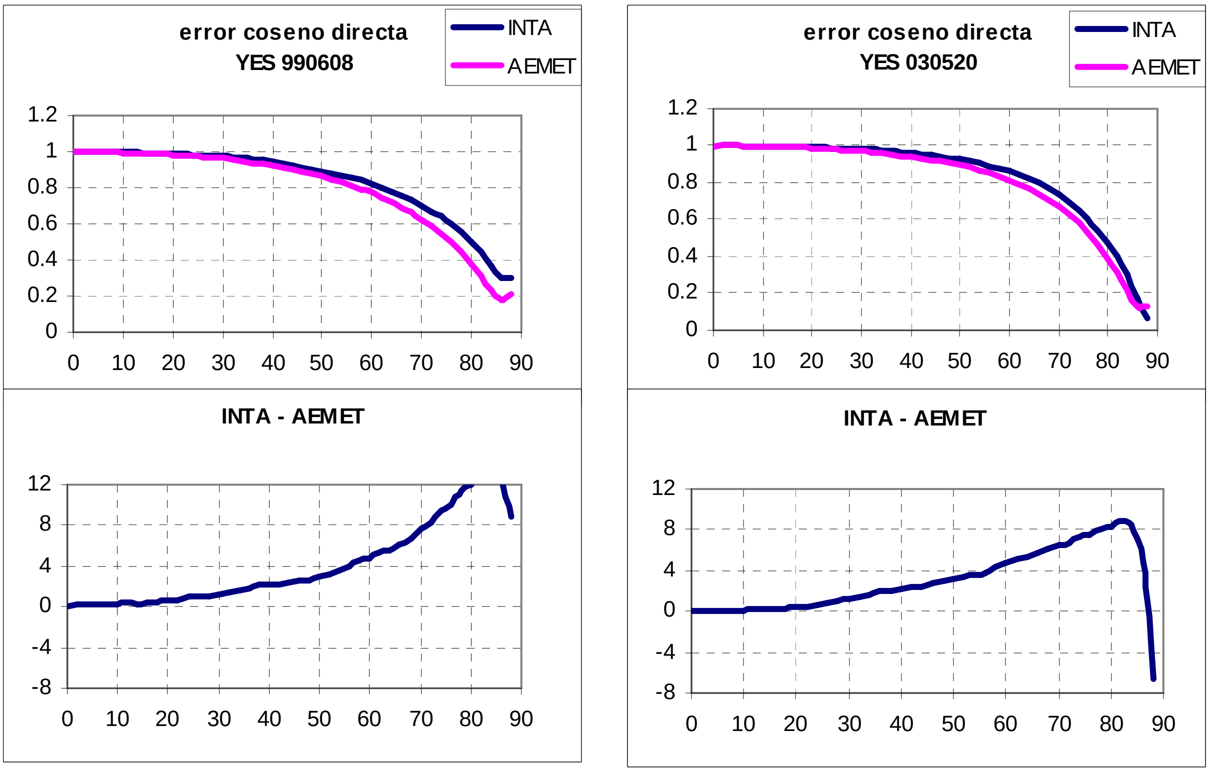


Figure 4: Cosine error derived from ARF and difference INTA-AEMET in percentage

The cosine error for diffuse sky is derived using eq. 5. The results for each radiometer and laboratory are shown in the table 1. The difference between laboratories is approximately 3.5% for both radiometers.

Instrument	INTA	AEMET	INTA/AEMET
990608	0.87	0.84	3.6%
030520	0.89	0.86	3.5%

Table 1: diffuse cosine error

Finally, the cosine correction for clear sky is calculated using eq. 3. This correction is represented in figure 5 in respect to the solar zenith angle.

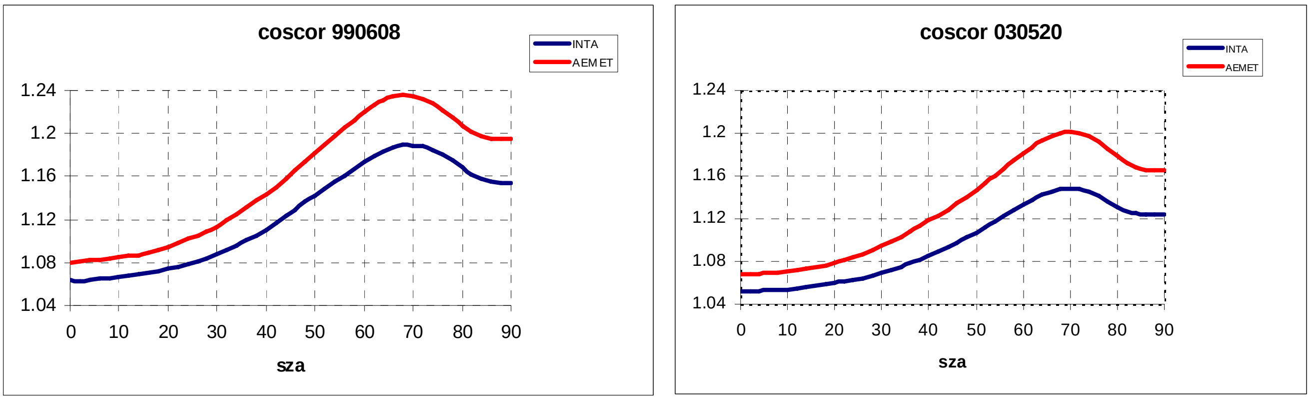


Figure 5: Cosine correction for clear sky conditions

Table 2 shows these cosine corrections at SZA = 40° as derived from each laboratory characterization. The difference between both laboratories (last column of the table) is about 3%, showing that the methods used to obtain the correction cosine are consistent between both of them and are within the framework of the inter-laboratory comparison (Hülsen et al. 2008).

Instrument	INTA	AEMET	INTA/AEMET
990608	1.111	1.144	-2.9%
030520	1.085	1.118	-3.0%

Table 2: Cosine correction factor at SZA = 40º

Absolute calibration factor

The absolute calibration factors *C* derived from the outdoor measurements at each calibration laboratory are given in the table 3, along with the INTA / AEMET ratio. The *C* units are Wm^{-2}/V. As shown in the table, the differences between the two laboratories are under +/- 2%.

Instrument	INTA	AEMET	INTA/AEMET
990608	0.1233	0.1232	0.1%
030520	0.1165	0.1147	1.6%

Table 3: Average absolute calibration factor (at 40° and 300 DU) and ratio INTA/AEMET

6. COMPARISION OF ERYTHEMAL IRRADIANCE AND UVI:

6.1 Comparison between the calibrations at INTA and AEMET laboratories for each radiometer

Since all the above factors (calibration matrix, cosine correction factor and absolute calibration factor) are used in the General Calibration Equation (eq. 1) to convert the radiometer output (Volts) into erythemal irradiance, the whole calibration process performed on both laboratories can be compared by comparing the Erythemal Irradiance derived from these calibrations.

The following figures and tables show the INTA/AEMET ratio calculated for the campaign days (245th -247th julian days in Madrid. and 255th -256th julian days in “El Arenosillo”). The erythemally weighted irradiance values calculated using the INTA calibration are lower than those obtained from AEMET calibration (approximately 3% for YES990608 and 0.3% for YES030520). The jumps in the figures are due to the fact that some of the calibration factors depend on the solar zenith angle, and are calculated every 5º.

Radiometer	ratio INTA/AEMET
YES 990608	0.966 ± 0.009
YES 030520	0.997 ± 0.016

Table 4: Erythemally weighted irradiance INTA/AEMET ratio (average and standard deviation)

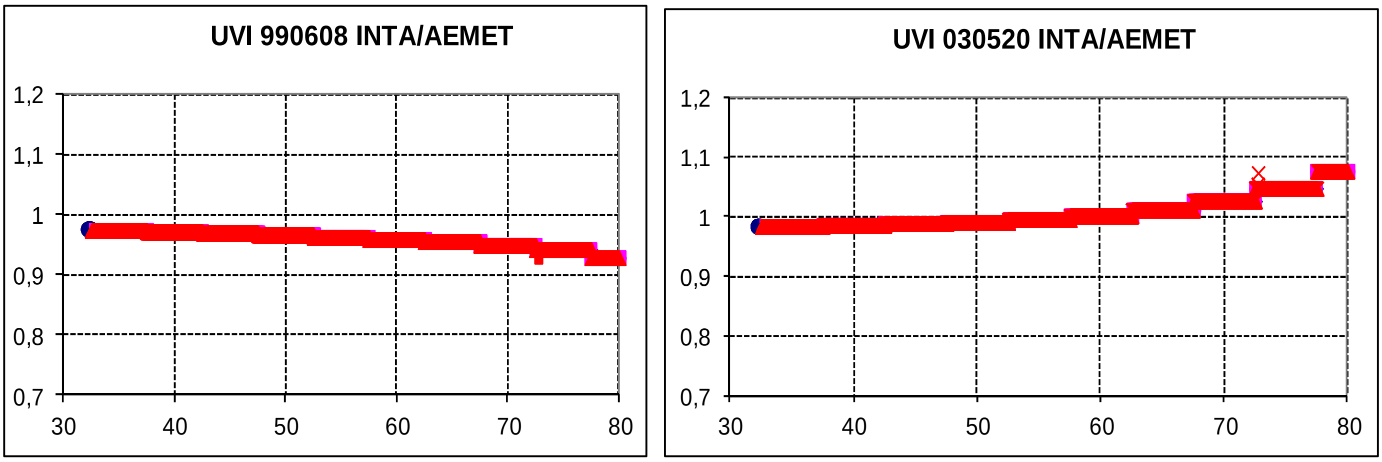


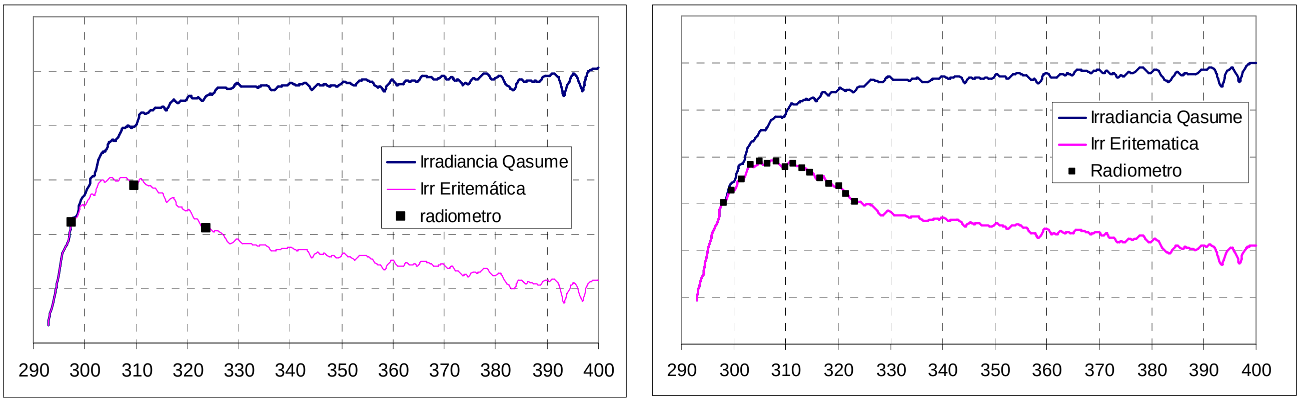
Figure 6: UVI INTA/AEMET ratio in dependence of solar zenith angle

6.2 <u>Comparison respecting to the irradiance measured by the QASUME</u>:

In order to evaluate the radiometers calibrations in respect to a UV reference instrument, for each one the erythemally weighted irradiance derived from both laboratories calibration are compared with the erythemally weighted irradiance obtained from the QASUME unit (Gröbner et al . 2005).

For this propose a total of 98 solar spectra from the QASUME have been obtained during the study: 246th - 247th days (in Madrid) and 255th -256th (in El Arenosillo).

The QASUME observations span a range of 280 to 400 nm with 0.25 nm step. Since during the time of a QASUME spectra observation (ten minutes) radiometers obtain many integrated measures (one every minute at AEMET and one every ten seconds at INTA), to compare with each weighted and integrated QASUME spectrum it is used, for the radiometers, the average of the data measured in the interval corresponding to the maximum erythemal effectiveness wavelength. Next figure shows this choice of simultaneous data.



Madrid (datos integrados minutales)

El Arenosillo (datos integrados cada 10 sg)

Figure 7: radiometer simultaneous data chosen for a QASUME scan

Table 5 shows the results (mean and standard deviation) of the ratio of erythemally weighted irradiance calculated for the radiometers using both calibrations and for the QASUME unit.

Instrument	**INTA/QASUME**	**AEMET/QASUME**
990608	0.949 ± 0.073	0.98317 ± 0.069
030520	0.980 + 0.062	0.982 + 0.073

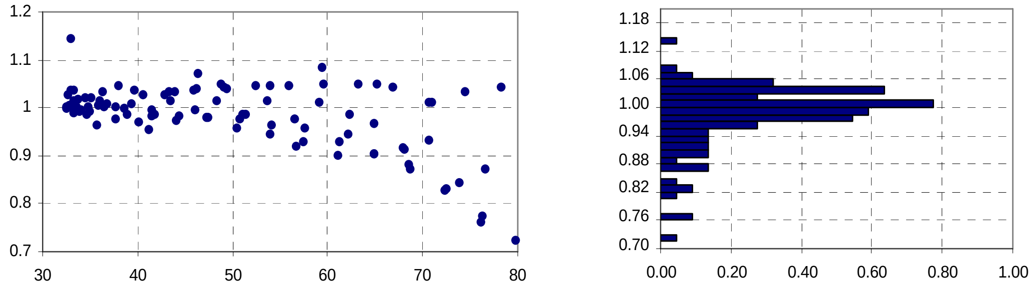
Table 5: Erythemally weighted irradiance ratios radiometer/QASUME
(mean and standard deviation)

Those results are also shown in the following figures in dependence on the solar zenith angle. The right side of each graph includes the frequency histogram normalized to the maximum frequency value.

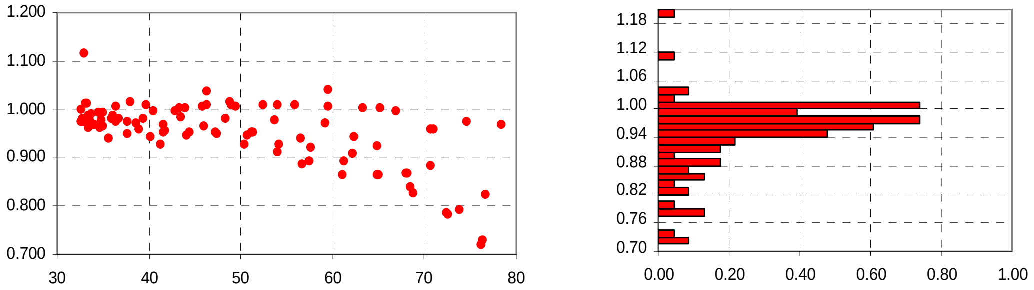
The values represented further away from the average correspond to large SZA values (the Yankee radiometers cosine error is important and produces variability in the measures) or to time intervals with quick changes in cloud conditions that also affect to the measures.

For the YES 030520, using either of the two calibrations, radiometer data differs from QASUME data less than 2%. For the YES 990608 the results are similar with the AEMET calibration, but respecting to the INTA calibration the differences in the erythemallly weighted irradiance are higher (around 6%).

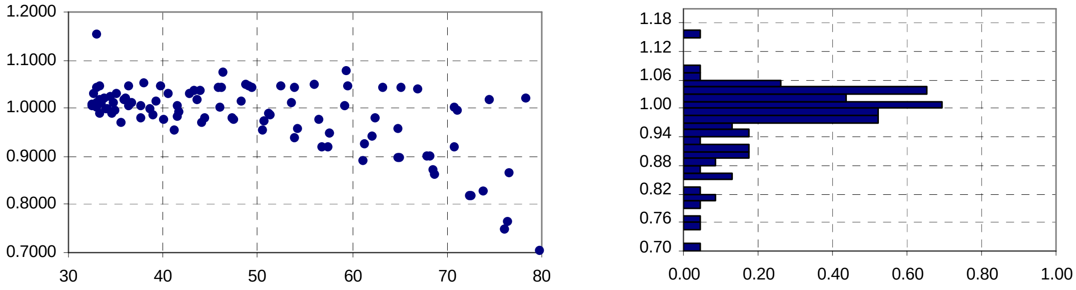
990608 AEMET/QASUME



990608 INTA/QASUME



030520 AEMET/QASUME



030520 INTA/QASUME

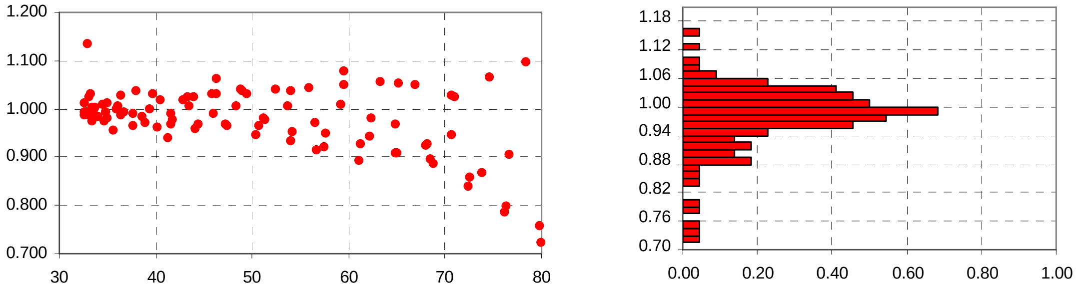


Figure 8:Erythemally weighted irradiance derived by each laboratory relative to the QASUME for 246th - 247th days (Madrid) and 255th -256th (El Arenosillo) in dependence on the SZA.The right side shows the frequency histogram normalized to the maximum frequency value

7. CONCLUSIONS

The intercomparison between the two radiometers and laboratories (AEMET and INTA) has been carried out following the guidelines established by the large scale intercomparison campaign organized by the PMO/ WRC in August 2006 as a part of the activities of COST 726. It consisted on the comparison between the calibrations of 6 broadband UV radiometers carried out by seven laboratories in Europe and in the USA, with the European Ultraviolet Calibration Center (EUVC) of PMOD/WRC as reference laboratory and INTA as one of the participant laboratories.

The results of the referenced intercomparison (Hülsen et al. 2008) were that the characterization of the detectors in the respective laboratories was in good agreement: with deviations in the determination of the angular response below ± 4%, and larger differences in the spectral responses (up to 20%) that do not introduce any significant discrepancies in the resulting calibration. In addition, the intercomparison of erythemally weighted irradiances derived by the respective laboratories and PMOD/WRC showed consistent measurements to within +/- 2% for most of participants. The differences between the different calibrations of the instruments are within the uncertainty of the calibration.

In the current intercomparison INTA-AEMET, as it is shown in the section 5 the differences between the laboratories are within these ranges (not exceeding ± 20% for the spectral response up to 335 nm, below ± 4% for the angular response, and less than 2% for the absolute calibration factor) , so we can deduce that the calibrations are consistent. Also, the intercomparison of the erythemally weighted irradiance derived by both calibrations (table 4) shows differences about 0.3% and 3% for YES030520 and YEST990608, respectively.

Considering also that the comparison of the erythemally weighted irradiances derived by both radiometers calibrated in AEMET and those obtained with the QASUME (European pattern of UV settled by the PMOD/World Radiation Center of Davos, Switzerland), the results (table 5) show measurements to within 2%, concluding that the calibration performed in AEMET is consistent.

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